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Accounting for risk transitions of ocean ecosystems under climate change: an economic justification for more ambitious policy responses

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Abstract
Despite the ocean's role in regulating the climate and providing ecosystem services, the importance of the ocean has only recently gained appropriate attention in the context of international climate change policies. This concerns the impacts of climate change on ocean ecosystems and the role of the ocean in climate change mitigation. Since impacts can be cumulative, future climate risks for the ocean and dependent human communities emphasize the need to reduce greenhouse gas emissions. Here, we make the case that assessing these impacts and their consequences for human welfare would provide not only an ethical but also an economic justification for strengthening policy responses to a substantial degree.

Keywords Climate change · Ocean change · Climate policy · Ocean acidification · The social cost of carbon · Integrated Assessment Models (IAMs) · Risk transition

Large proportions of carbon dioxide (CO_2) emitted by human activities accumulate in the atmosphere, and the resultant changes of the climate system cause climate impacts both on land and in the ocean. For about 30 years, the Intergovernmental Panel on Climate Change (IPCC) has systematically assessed the evidence of climate change, its impacts, and potential policy implications. The importance of climate action was taken up by the United Nations'

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Sustainable Development Goals (SDGs) where the urgency to combat climate change and its impacts is included as one of the 17 goals (United Nations 2015). A Special Report of the IPCC on global warming of 1.5 °C (Masson-Delmotte et al., IPCC 2018) stressed the critical importance of the next 10 years in limiting climate change, emphasized most recently by an IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Pörtner et al., IPCC 2019).

Despite the ocean's role in regulating the climate and providing ecosystem services, the importance of the ocean has thus only recently gained importance in the discussion of climate change policies, considering impacts of sea level rise as well as climate change impacts on ocean biology and fisheries in the context of impacts at global and regional scales (e.g., Pörtner et al. 2014, 2019, Hoegh-Guldberg et al. 2014, 2018, Gattuso et al. 2015, 2018, Gallo et al. 2017). Since the greenhouse effect is accumulative by nature, climate risks for the ocean have immediate relevance for the need to reduce greenhouse gas emissions. In the following, we make the case that assessing these impacts and their consequences for human welfare would provide not only an ethical but also an economic justification for strengthening policy responses to a substantial degree. Overall, ocean-based economic activities generate hundreds of millions of jobs and trillions of USD (Bindoff et al. 2019).

Primary physical and chemical impacts of climate change on the ocean include ocean warming, ocean acidification, deoxygenation (hypoxia), and sea level rise (see Fig. 1). These primary changes, either from individual or combined factors, lead to secondary impacts including those on marine biology and ecosystems (such as decreased ocean productivity, reduced species abundance, changes in species distributions and food web dynamics, and greater disease incidence; see Hoegh-Guldberg and Bruno 2010, and Doney et al. 2012, as well as IPCC reports cited above, for a review). These changes are likely to have an impact on ecosystems and human well-being through a change in ecosystem services, including coastal protection, seafood production, tourism, and human health and are also likely to cause wider economic and social impacts through, for example, effects on national labor markets by changing employment opportunities in the fisheries sector (e.g., Lam et al. 2016).

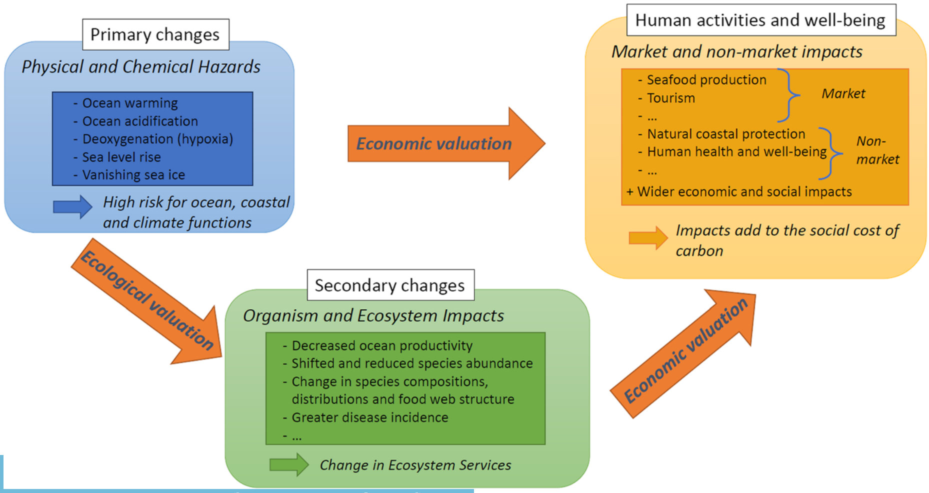

Fig. 1 Impacts of climate change on the ocean and its consequences for human welfare (cf. Pörtner et al. 2019)

Among the primary climate related changes in the ocean, ocean acidification is the one currently being most recognized and the only one being mentioned in SDG 14 (United Nations 2015). Further, in addition to ocean warming, marine heat waves, and ocean hypoxia, acidification is a key ocean issue that has been included in international policy discussions on climate change within the United Nations Framework Convention on Climate Change. This process started with individual countries or states referring to ocean acidification and its implications for marine ecosystems and fisheries in their national climate change plans and strategies (Harrould-Kolieb and Herr 2012; Gallo et al. 2017). Some of these countries and states are particularly concerned about regional vulnerability and local adaptation options (e.g., Schmutter et al. 2017; NOAA Ocean Acidification Program; California's Assembly Bill 2139). This might be one reason why the secondary changes including impacts on ecosystems and on human well-being are most comprehensively being investigated for ocean acidification, among the other ocean impacts of climate change (e.g., IPCC 2014a; Secretariat of the Convention on Biological Diversity 2014; Gattuso et al. 2015).

The focus on the ocean acidification problem does not imply that policies can neglect the other important changes in the oceans, namely warming including heat waves as well as ambient hypoxia (Pörtner et al. 2014, 2017, 2019). Laboratory studies and consecutive meta-analyses have revealed vulnerability of marine fauna to warming, extreme hypoxia, and ocean acidification, with extreme hypoxia impacting ocean life as strongly as temperature at extremes outside of the thermal range of species. Temperature and hypoxia extremes are thus prime candidates to cause short term lethal impacts (Reddin et al. 2020), whereas ocean acidification may often have longer term consequences. The combination of the three drivers may synergistically constrain ocean life even further (Pörtner et al. 2017; Tripp-Valdez et al. 2017).

Since ocean impacts are caused mostly by an increase in atmospheric CO_2, which is driven by its human emissions, impacts of all climate drivers in the ocean are ultimately controlled mainly by a reduction of human CO_2 emissions (Gattuso et al. 2018). This also means that the costs of ocean impacts, which would be an integral part of the costs of climate change, would emphasize the need to reduce and eventually stop CO_2 emissions. The current policy debates tend to equate the costs of climate change with those only on land, but these ocean-related costs also need to be considered in international policy discussion. In fact, preconditions for reaching the UN SDGs include keeping global warming at 1.5 °C, a key conclusion of the IPCC 1.5 report (Masson-Delmotte et al. 2018). Through associated emission reductions, this climate target would help eliminate or minimize such costs of ocean impacts.

1 The social cost of carbon: an indicator to link scientific evidence of ocean impacts of human CO_2 emissions to international policy-making

The concept of the social cost of carbon (SCC) is used in policy-making, exemplified by the attempts of the US government under the Obama administration (e.g., Interagency Working Group on Social Cost of Carbon 2010, 2013, 2016; National Academies of Sciences 2017; see also Pizer et al. 2014). It reflects the per-unit benefit of CO_2 emission reduction (i.e., the monetary-equivalent value of climate change damage avoided by a unit amount of CO_2 emission reduction) and hence of climate change mitigation (see Box 1 for details). The SCC corresponds to a socially optimal price of CO_2 emissions (which may take a form of a carbon tax or price of emission permits, both of which discourage emissions). At this price, emission reduction yields the best possible net benefit for society, where the benefit is defined as the avoided negative impacts of climate change. In other words, CO_2 emission reduction, which is costly, would socially be justified as long as its unit costs are less than the level of the SCC. Since the SCC encompasses all climate change damages, the long-term risk of ocean impacts should in principle be included in the SCC.

Box 1 What is the social cost of carbon (SCC)?

> As defined by the US Interagency Working Group (2010), the Social Cost of Carbon (SCC) is "an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year." From a regulatory perspective, the SCC is useful for cost-benefit evaluation of a policy involving carbon dioxide emission reduction. The "damages" here include various negative consequences of climate change on human life and economic activities, such as productivity losses in agriculture and property damages due to increased flood risk (see also text). The SCC is estimated to be the difference of monetary-equivalent climate change damages between two sets of climate and socioeconomic paths differing in 1 ton of carbon dioxide emissions in a particular year. The climate change damages considered here are the time-discounted sum of all climate change damages toward the future caused by carbon dioxide emitted in a base year. Such estimations are often made by using Integrated Assessment Models (see Box 2 and also text). The SCC is often evaluated as a global value, but some studies have also attempted its estimations on a country-by-country basis (Ricke et al., 2018; Tol, 2019).

The value of the SCC is estimated by integrated assessment models (IAMs; see Box 2 for details). Climate-economy IAMs calculate optimal paths of climate policy and carbon price by weighing the costs of CO_2 emission reduction and the costs of long-term climate change caused by anthropogenic CO_2 emissions. More precisely, they incorporate the economic damages of climate change in the IAM in the form of a damage function, which is represented by the sum of sectoral economic losses caused by climate change. These damages reflect the potential welfare losses (inclusive of adaptation costs) due to climate change impacts on market goods and services in sectors such as agriculture (e.g., through losses in productivity), energy use, and infrastructure development (such as those related to enhanced extreme weathers). In addition, IAMs have made some effort to include non-market values of ecosystem services as an element in their damage function, although their approach tends to be indirect and crude (see Box 3 for more information on ecosystem services; Box 4 provides details on market and non-market values). For example, a major IAM, the FUND model (whose estimation approach of climate change damages is described by Tol 2002), treats the costs of climate change on ecosystem services to be the same as people's willingness to pay generally for a good cause (reflecting the "warm-glow" effect, that is, a utility gain due to positive feelings people get from an act of giving). In other words, its estimation of climate change costs associated with ecosystem services does not reflect actual mechanisms of how ecosystem functions could respond to climate change and, consecutively, of how changes in ecosystem services could affect human life.

Box 2 What are integrated assessment models (IAMs)?

A definition of the Integrated Assessment Models is that they are “approaches that integrate knowledge from two or more domains such as climate and economy into a single framework” (Nordhaus, 2013). In the context of the estimation of the SCC, IAMs play a more specific role. The IAMs that estimate the SCC combine an economic model with a model of the atmosphere and ocean. They embody modules that simulate the carbon cycles in the atmospheric and oceanic systems and the climate, where CO_2 and greenhouse gases emitted by humans influence the behavior of the systems. Emissions of greenhouse gases are produced from economic activities, and policies affect those emissions. Examples of IAMs are DICE, FUND and PAGE (see, e.g., Interagency Working Group on Social Cost of Carbon, 2010). In terms of formulating the climate-damage relationship, these three models all take stylized, reduced-form approach. In principle, all these models are equally able to incorporate components of climate change impacts, including those concerning the oceans. Main differences among the models lie in basic representations of how exactly the temporal changes of the climate affect the temporal changes of economic outcomes. Specifically, in PAGE, the level of consumption-equivalent damage from climate change is linked to the average temperature of the current period, while in FUND, the damage is affected also by the average temperature of the previous period. In DICE, the current average temperature influences both consumption and investment but the effects of previous periods are not considered (Interagency Working Group on Social Cost of Carbon, 2010).

Box 3 What are ecosystem services?

Ecosystem services are the components of nature that (actively or passively) help create human well-being and economic wealth (Fisher et al., 2009). Society is dependent upon them as a life support system as well as for enhancing its well-being. At a general level, ecosystem services can be categorized into four distinct groups (MEA, 2003): provisioning services; regulating services; cultural services; and supporting services. They form the basis of the recently proposed NCP concept, nature’s contribution to people (Diaz et al, 2018) which includes social sciences and humanities aspects Kadykalo et al. (2019).

Box 4 Market and non-market values

The total economic value (TEV; Pearce and Turner 1990) is useful for categorizing how changes in the environment (e.g. through climate change) impact ecosystem goods and services and the benefits they create for humans. The TEV framework includes goods and services that are not traded on markets such as storm and flood control or marine biodiversity. For example, many marine habitats and ecosystems (e.g., tropical coral reefs, mangroves, seagrass meadows and bivalve beds) significantly dissipate the energy in waves reaching the coast, increasing sedimentation rates and decreasing coastal erosion. Their economic value, which is how much people would be willing to pay for them, is not made explicit in markets but people have preferences for the provisioning of these non-market goods and services nevertheless. Non-market valuation methods can be applied to estimate people’s preferences for their protection. TEVs are mostly not included in assessments of SCC.

With respect to the focus of this commentary, current IAMs generally do not take into account the importance of the ocean for human welfare, as impacts neither on market goods nor on non-market goods. An exception is the impact of sea level rise due to climate change, which is included. IAMs estimate economic impacts of sea level rise by methods consistent with those described by Nicholls et al. (2011), which utilize empirical relationships of the costs of population displacement and adaptation in the face of enhanced coastal erosion and increased flood risks (Interagency Working Group on Social Cost of Carbon 2013). This means that the models only include consequences of sea level rise on land and not those on marine ecosystems. Ocean impacts are excluded from the assessment not because they are regarded as unimportant but because solid quantitative estimates of losses, which can be utilized by IAMs, are scarce. In fact, US's Interagency Working Group on Social Cost of Carbon (2010, p29) mention that "(c)urrent IAMs do not assign value to all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature… because of lack of precise information on the nature of damages and because the science incorporated into these models understandably lags behind the most recent research." A later assessment by the National Academies of Sciences (2017) also recognizes the lack of OA impacts in SCC estimations, pointing out that "the Interagency Working Group should adopt or develop a surface ocean pH component" within the climate module of its models (p. 118 Recommendation 4-4). It is also important to note that as indicated by the IPCC (Masson-Delmotte et al. 2018, Chapter 5), the ocean is associated with various aspects of economic and human development. Mitigation measures of climate change, which are normally seen as costs, may in fact help achieve goals of development. These possibilities of synergies are also not considered in the current evaluations of the SCC.

2 Economic valuation of ocean impacts of climate change: ocean acidification as an example

Potential impacts of climate change on ocean ecosystem services and human well-being, such as those on seafood production, tourism, health, and subjective well-being, can be individually assessed in monetary-equivalent units in the framework of economic analysis. Economic studies of these ocean impacts are scarce, except for some economic assessments of ocean acidification impacts (Brander et al. 2014 review the economic literature until 2013; see also Supplementary Table 1). Overall, the existing economic studies on ocean acidification show that the long-run global costs of ocean acidification are rather small relative to other types of climate change impacts. For example, Brander et al. (2012) conclude that the costs of ocean acidification impacts on coral reef ecosystems, primarily harming tourism, will be one order of magnitude smaller than the total damages of climate change globally. Narita et al. (2012) estimate that the global costs of ocean acidification on shellfish fisheries will be 1–1.5% of the total global economic impacts of climate change.

However, to infer from these studies that the long-run costs of ocean acidification are minor is misleading. These studies deal with only one specific type of ocean acidification impacts, the disturbance of calcification, and not with the combined effect of warming, acidification, and in some cases, hypoxia. Further, the role of calcified systems such as coral reefs in disaster risk reduction (coastal protection) and the non-market losses (e.g., cultural and regulating ocean services) associated with ocean acidification has not been included. Current IPCC projections indicate that global warming to 1.5 °C will cause 70 to 90% loss of warm water reefs, with these values increasing to 99% at 2 °C (Hoegh-Guldberg et al. 2018). These numbers would justify a holistic assessment of the loss of coral reefs. The synergistic effect of ocean acidification with warming, and where applicable hypoxia, will reflect the full set of damages to ecosystems and their services.

Comparing the existing studies on ocean acidification, the majority of them has taken a narrow look at the impact on marine and coastal ecosystem services focusing on a particular country or region. The focus on provisioning services can largely be ascribed to the emerging scientific understanding of the impacts of ocean acidification on shellfish and finfish and the economic data available for these sectors rather than the other sectors. These studies have their merit particularly in informing local decision-makers and stakeholders about local and direct economic costs of ocean impacts, so far focusing on impacts of ocean acidification. Such costs of ocean acidification include losses in mollusk fisheries in areas where ocean circulations bring about locally low pH levels or losses in tourism revenues due to damaged coral reefs. Ocean acidification would cause both of them in combination with other stressors such as temperature changes and pollution. Further, since serious effects of ocean changes are likely to occur in the longer term, economic assessments should consider not only the future changes in the environment but also possible future changes in consumer preferences.

Compared with losses in market values, losses of non-market ocean services, such as cultural and regulating ocean services (e.g., loss of value for tourism or disaster mitigation caused by the loss of coral reefs), are much more challenging to estimate from an economic perspective, even if scientific evidence would be more solid.

3 Ocean impacts as an economic risk: making CO_2 emission reduction even more urgent

The existing economic studies of ocean acidification discussed above all use deterministic economic models that ignore the probabilistic aspects of the problem, i.e., future changes in ecosystems that may or may not occur in accordance with ocean acidification. But, as discussed below, some forms of ocean impacts of climate change, or climate change impacts in general, could result from risks of irreversible systemic changes induced by climate change. The current estimates of the SCC do not take such risks into account, but in principle, such effects could be incorporated in the framework. Since humans are risk-averse, inclusion of risk features in computation by using stochastic modeling techniques could substantially increase the effective level of the SCC (discussed in Metcalf and Stock 2017).

Indeed, some ocean impacts of climate change possess some identifiable characteristics of threshold risks. For example, as emphasized by Rockström et al.'s (2009) discussion of the Planetary Boundaries and also by the IPCC SR1.5 °C (Masson-Delmotte et al. 2018), some key marine organisms such as corals and mollusks have their shells in the form of aragonite, a relatively soluble crystal form of calcium carbonate. Aragonite shells dissolve below an aragonite saturation state (Ω_{arag}) of unity unless the organisms have developed a special protective mechanism such as shell coating. Once reaching that saturation level, ocean ecosystems would likely go through a disruptive change that is irreversible. While Ω_{ara} is still far above 1 globally (currently $\Omega_{arag} = 2.9$ at the surface ocean), the threshold value of 1 may be crossed in some regions even with relatively low atmospheric CO_2 levels due to the local pattern of ocean circulation (e.g., upwelling) or at cold temperatures. Note also that many ocean organisms do not live near the surface but at lower depths that might already be in undersaturated conditions.

While using water Ω_{arag} as a metric of risk is numerically appealing, it only provides information on the fate of existing unprotected shells and hence is overly simplistic—it does not consider further physiological principles of CO_2/acidification impacts on living organisms including their mechanisms of shell construction (Wittmann and Pörtner 2013). From this point of view, water CO_2 levels are driving the impacts of ocean acidification on marine fauna and also define the fraction of species in key phyla negatively affected by acidification. Considering that ocean acidification acts together with ocean warming and, in some regions, hypoxia, this observation led to the notion that the combined impacts of warming and OA could bring increments in risk levels from moderate (at the present level of global warming) to high (between 1.5 and 2 °C mean global warming) or to very high risk (for levels greater than 2 °C) (cf. IPCC 2014b; O'Neill et al. 2017). Such risk thresholds (cf. O'Neill et al. 2017) might become a guiding principle in adjusting incremental levels of the SCC depending on the climate target reached.

If characterized by such risk thresholds, ocean impacts of climate change could be a component that significantly raises the SCC even if its market-based economic impacts would be small. Some recent studies of the economics of climate change use modeling methods of stochastic optimization (Cai et al. 2015, 2016; Lontzek et al. 2015; Lemoine and Traeger 2016; Cai and Lontzek 2019). They use essentially the same basic modeling framework as that of the deterministic IAMs in estimating the SCC. The inclusion of threshold risks in these stochastic models tends to produce results to justify more stringent efforts of CO_2 reduction than the deterministic IAM studies. This reflects the large cumulative costs of an irreversible change of a climatic, natural, or economic system, which persists once a transitional shift sets in, e.g., the projected marginalization of warm-water coral reefs and the associated loss of coastal protection or fisheries resources or the surpassing of risk thresholds associated with sea-level rise at low-lying islands and coasts (Pörtner et al. 2019). These studies show that significantly higher SCC levels than the currently discussed ones are estimated if potential risk thresholds are taken into consideration. This is a reflection of purely rational economic decision-making, akin to a purchase of an insurance policy for possible future property losses. Inclusion of only a few well-recognized processes, such as the disintegration of the West Antarctic ice sheets, could more than double the SCC levels reflecting resultant risks for the human population such as those associated with sea level rise (Cai and Lontzek 2019, Cai et al. 2016, Lemoine and Traeger 2016). Further, SCC levels could increase even more if the estimation takes into account the realistic condition that climate-impacted ecosystem services cannot be perfectly substituted by human-made goods and services (Cai et al. 2015). Examples include the poor quality of potential human-made substitutes for esthetic benefits of oceans or for supporting ecosystem services of the oceans regarding element and nutrient cycling. If ecosystem services were reduced, their relative prices would increase, resulting in relatively large impacts on well-being even if their decrease is not large. Additional processes of risk transitions could be incorporated into the IAM framework if reliable quantification is made about the likelihood of each scenario of all possible risk transitions, potential ecological and economic consequences under the scenarios, and alternative policy paths of emission reduction in anticipation of these possible but unknown futures. IAMs are able to evaluate and compare all these possible futures by using a monetary metric, and consequently, they identify optimal policy paths and also the SCC inclusive of risk-related processes.

None of the existing studies in the literature of stochastic IAMs explicitly models the risks associated with ocean change or includes it as a part of the overall risk of climate change. However, it is reasonable to assume that the consideration of even a small risk for ecosystems and associated human well-being from serious disruption of global marine ecosystem services due to ocean change has a significant influence on the estimates of the SCC. Excluding any ocean-related risk thresholds, the above-cited report of the Interagency Working Group on the Social Cost of Carbon (2016) estimates SCC levels at \$42/tCO_2 and \$50/tCO_2 for the years 2020 and 2030 (3%/

year time-discounting case). Meanwhile, the abovementioned literature of stochastic IAMs indicates that the real levels of SCCs may be more than twice as high, and their analyses still exclude ocean-related risks apart from those of sea level rise. A doubling to \$84 to 100/tCO_2 would fall in the range of the carbon price levels required to achieve the 1.5 °C long-term temperature target (i.e., in the order of \$100/tCO_2 in 2030), as assessed by the IPCC 1.5 °C Report (Rogelj et al. 2018, Figure 2.26). The inclusion of ocean-related risks and associated costs of adaptation would raise the SCC even further. The features of ocean impacts that have been described above suggest that the real impact of ocean change on the SCC is possibly substantial and worth serious efforts of further scientific investigation.

As a corollary, in IAMs, ocean acidification should not be considered alone but together with other key drivers such as ocean warming including heat waves, as well as ocean deoxygenation (Pörtner et al. 2017, 2019). Some key ecosystems are on the verge of responding to the combined action of these drivers, for example, Eastern Boundary Upwelling Systems such as the Humboldt Current. Its total economic value has been estimated to be US\$19.45 billion per year. Within decades, the Humboldt Current is projected to experience aragonite undersaturation and, thereby, negative impacts on calcified organisms, exacerbated by ocean deoxygenation and warming (Bindoff et al. 2019). Such projections imply economic damages of unknown magnitude, emphasizing the need to quantify the impacts and associated risk thresholds as well as the consequences for the social cost of carbon not only for this but also for all valuable ocean ecosystems.

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