

## **Ocean Acidification and Warming**

*The economic toll and implications for the social cost of carbon*

John Talberth

President and Senior Economist  
Center for Sustainable Economy  
16869 SW 65th Avenue, Suite 493  
Lake Oswego, Oregon 97035-7865  
[jtalberth@sustainable-economy.org](mailto:jtalberth@sustainable-economy.org)  
(Corresponding author)

Ernie Niemi

Natural Resource Economics  
1430 Willamette St., Suite 553  
Eugene, Oregon 97401-4049  
[ernie.niemi@nreconomics.com](mailto:ernie.niemi@nreconomics.com)

### **Abstract**

Mounting evidence indicates ocean acidification and warming (OAW) pose significant risks of systemic collapse of many critical ocean and coastal ecosystem services. Attention has focused on drastic reductions, if not extinction, of coral reefs, inundation of coastlines, massive ocean dead zones, collapse of both capture and subsistence fisheries in highly dependent regions and significant disruption of the ocean's carbon sequestration capacity. The economic costs of OAW have yet to be adequately researched or included in estimates of the social cost of carbon (SCC). This paper summarizes current knowledge about the economic costs of OAW and suggests alternative approaches for incorporating these costs into the federal government's SCC. Preliminary results suggest that accounting for OAW would raise SCC 1.5 to 4.7 times higher than the current federal rate, to \$60–\$200 per metric ton CO<sub>2</sub>-e.

### **Keywords**

Ocean acidification, Ocean warming, Sea level rise, Social cost of carbon, Risk aversion

## 1.0 Introduction

Among the most startling manifestations of the Anthropocene is the widespread degradation and collapse of ocean and coastal ecosystems already underway as a result of symbiotic interactions between climate change, pollution, habitat destruction and overexploitation of fisheries. Over 90% of large game fish species have disappeared as a result of factory trawling and other industrial fishing methods (Myers and Worm 2003). Roughly 20-25% percent of all marine species are at risk of extinction (Webb and Mindel 2015). One fifth of all mangrove forests have been destroyed since 1980, primarily from aquaculture, agriculture and urban land uses (Spalding et al. 2010). Marine dead zones caused by nutrient runoff have spread exponentially since the 1960s and now encompass over 245,000 km<sup>2</sup> (Diaz and Rosenberg 2008). Enormous quantities of marine debris, mostly plastic, are found floating in all the world's oceans and litter both the seabed and coastlines. At least 267 different species are known to have suffered from entanglement or ingestion of this debris (Allsopp et al. 2006). Alarming as these effects are, they are likely to be eclipsed by climate change.

Climate change has the potential to disrupt ocean and coastal ecosystems on a scale that is difficult to grasp. There are two interrelated processes at work: ocean acidification and ocean warming (OAW). Oceans have absorbed roughly half of all anthropogenic emissions of carbon dioxide (Sabine et al. 2004). Acidification occurs as the absorption of CO<sub>2</sub> triggers a series of chemical reactions that increase the acidity and decrease the concentration of carbonate ions in the water. So far, absorption of CO<sub>2</sub> has increased acidity of surface waters by about 30% and, if current trends in atmospheric CO<sub>2</sub> continue, by 2100 these waters could be “nearly 150 percent more acidic, resulting in a pH that the oceans haven't experienced for more than 20 million years” (PMEL). Among the dire predictions associated with acidification include dramatic reductions in populations of some calcifying species, including oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton – the latter effect putting the entire marine food chain at risk. Some models suggest that ocean carbonate saturation levels could drop below those required to sustain coral reef accretion by 2050 (Hoegh-Guldberg, et al. 2007).

The second process is ocean warming. The mechanisms of ocean warming are complex, and include heat transfer from the atmosphere, downwelling infrared radiation, stratification, reductions in mixing, changes in ocean currents, and changes in cloud cover patterns (Hoegh-Guldberg 2014). Already, the global average sea surface temperature (SST) has risen by over 2.0 °F since the post-industrial revolution low point in 1909 (EPA). Sea level rise is one of the most conspicuous effects with potentially catastrophic consequences. Models that account for collapse of Antarctic ice sheets from processes driven by both atmospheric and ocean warming indicate sea level rise may top one meter by 2100 and put vast areas of coastal infrastructure at risk (DeConto and Pollard 2016).

Obviously, all these physical effects have enormous economic consequences, yet relatively little research has been completed to date on their expected magnitude, timing, and distribution. Indeed, as late as 2012, several prominent climate researchers concluded that economic assessments of the effects of ocean acidification “are currently almost absent” (Narita et al. 2012). This relative lack of understanding has, in turn, translated into a lack of policy mechanisms and research focused on OAW (Billé et al. 2013). One of the policy mechanisms where OAW costs are notably absent is the social cost of carbon (SCC) – an increasingly popular regulatory tool for assessing both the costs of greenhouse gas emissions and the benefits of actions to limit emissions. Ostensibly, the SCC includes all known market and non-market costs, yet there are many categories missing or incomplete (Howard 2014). One of the bigger holes is OAW and one of the

justifications for its absence is the relative dearth of methods or data to quantify economic consequences and the assumption that such impacts are minor enough that society will be able to adapt (Howard 2014). Here, we argue that such barriers need not restrain the government agencies participating in the SCC's development and application from incorporating estimates for OAW based on the best available information and inclusive of high-impact but low probability scenarios – two factors that are baked into the regulatory framework for the SCC.

We do so by demonstrating three basic approaches rooted in standard microeconomic models of externalities, capital investment, and risk aversion. The first is based on federal agencies' current approach for quantifying externalities from GHG emissions using the Dynamic Integrated Climate-Economy (DICE) integrated assessment model and economic damage functions suggested by existing literature. The second is a replacement or adaptation cost approach, which views SCC as a current capital investment liability that can be amortized over the adaptation time horizon. The third is an averted-risk approach based on willingness to pay to eliminate the risk of catastrophic changes, an approach that seems most compatible with worst-case scenario requirements under existing law.

In Section 2, we review the recent literature on the valuation of ocean and coastal ecosystems. In Section 3, we discuss what portion of this value is at risk from OAW including a set of plausible high-impact scenarios. In Section 4, we discuss the current regulatory approach and methods for estimating the SCC, and demonstrate three alternative models for incorporating the effects of OAW. In Section 5, we offer concluding thoughts and recommendations for further research and data gathering.

## **2.0 The value of ocean and coastal ecosystem services**

Ocean and coastal ecosystems provide goods and services worth many trillions of dollars each year to the global economy. The concept of ecosystem services provides a comprehensive framework for valuation that incorporates both market and non-market benefits. Table 1 provides a partial list of important ecosystem services using the standard four-tier typology for these services including provisioning, regulating, cultural and supporting.  
<Table1 goes here>

Many of these services generate multidimensional economic benefits. Fish and shellfish for human consumption, for example, typically provide high-value protein with essential micronutrients (vitamins, minerals, polyunsaturated omega-3 fatty acids) but low levels of saturated fats, carbohydrates, and cholesterol (World Bank 2013). The oceans play key roles in limiting the multiple costs of climate change by absorbing more than 90% of the thermal energy accumulated because of GHGs in the atmosphere, and about 30% of the emitted anthropogenic CO<sub>2</sub> (IPCC 2014). Subsistence fish can embody many benefits besides nutrition: aesthetic, place/heritage, activity, spiritual, inspiration, knowledge, existence/bequest, option, social capital/cohesion, identity, and employment (Chan et al. 2012).

Costanza et al. (2014) updated their groundbreaking 1997 study on the value of the world's natural capital and ecosystem services to account for changes in both the area of marine and terrestrial ecosystems and their unit values. The total estimated value for marine ecosystems was found to be over \$57.4 trillion per year in 2016 dollars. This stream of benefits was further subdivided into those provided by open oceans (\$25.3 trillion/yr), estuaries (\$6.0 trillion/yr), seagrass and algae beds (\$7.9 trillion/yr), coral reefs (\$11.4 trillion/yr) and continental shelves (\$6.8 trillion/yr). The total value of all marine and terrestrial ecosystem services was estimated to exceed \$144.2 trillion/yr. Of particular note is that this aggregate global value is roughly twice

that of gross world product (\$75 trillion in 2015), and encompasses valuable functions – like maintenance of the atmospheric gas balance that enables us to breathe – that cannot be captured in market-based transactions.

### **3.0 Values at risk from OAW and plausible scenarios**

OAW presents a significant threat to ocean and coastal ecosystem services. The literature paints an alarming portrait of large-scale adverse changes to ocean processes and marine habitats and organisms (Table 2). Key processes at risk include carbon sequestration and storage, production of atmospheric oxygen, nutrient cycling, heat transfer, regulation of acidity, and regulation of weather patterns. Among the most disconcerting risks is to the ocean's capacity to produce atmospheric oxygen. If the oceans were to warm by more than 6 °C, disruption of oxygen production by phytoplankton could cause the atmospheric oxygen concentration to fall below the level most organisms require for respiration (Sekerci and Petrovskii 2015).

<Table 2 goes here>

Key biological impacts include loss of habitat, increase in marine hypoxic dead zones, reduced primary production, extinction of sea-ice dependent species and declining abundance and distribution of species with thresholds for acidity or temperature. The disappearance of all the world's coral reefs is one particularly worrisome scenario ~~that may already be manifesting in places~~. A somewhat sensational article declared that the Great Barrier Reef was dead for all practical purposes from warming-related bleaching and acidification after a 25 million year reign as one of the world's most concentrated hotspots of biological diversity (Jacobsen 2016).

A few studies predict economic losses from OAW, but mostly for just one ecosystem good or service and for either warming or acidification but not for the two effects together (Table 3). Most of these studies concentrate on impacts to one or more region, with a focus on commercial seafood production. Notable exceptions, though, address widespread global ecosystem service costs. For example, Brander et al. (2012) shows the global costs from lost recreational opportunities associated with coral reef loss could top \$1.2 trillion/yr by 2100. By 2200, costs associated with warming-induced release of stored methane from methane clathrate, or hydrate, gas (CH<sub>4</sub>) trapped in ice under the East Siberian Arctic Sea could reach \$60 trillion as flooding, drought, severe heat stress and other climate disasters worsen (Whiteman et al. 2013). Most global losses of ecosystem services remain unaddressed, however, largely because the economic valuation literature has not yet caught up with the relatively fast proliferation of research on the physical dimension of OAW.

<Table 3 goes here>

Practically all of the physical effects can nonetheless be quantified, at least in a preliminary sense, with standard valuation methods applicable to both market and nonmarket dimensions of economic welfare. Here, we demonstrate by discussing seven distinct high-impact/low probability outcomes of OAW by 2100 or earlier and making preliminary estimates of economic values at risk suggested by existing research and relevant methods (Table 4). Existing values at risk do not represent the cost of losing a key good or service in the year of the loss, but only what is at risk on today's terms.

<Table 4 goes here>

#### **3.1 Decrease in net primary production by 16%**

Primary production is the production of chemical energy in organic compounds by living organisms, or more simply the rate of accumulation of biomass. Some of this biomass is used in respiration, and so net primary production measures what is left over. Contributing roughly half of the biosphere's net primary production (NPP), photosynthesis by oceanic phytoplankton contributes roughly half of the biosphere's net primary production (NPP) and, as such, is a vital link in the cycling of carbon between living and inorganic stocks. In many climate models, NPP will fall dramatically because of the effects of OAW on phytoplankton productivity. Worst-case scenarios predict a global average decline in NPP of 41% by 2100, although a range of 2% to 16% is regarded as more plausible (Randerson and Moore 2015). A preliminary valuation of the top of this range (16%) is relatively straightforward, since NPP is a widely accepted proxy for the total ecosystem service value of marine ecosystems – something valued by Costanza et al. (2014) at \$57.4 trillion/yr through calibration of 14 separate studies. A 16% decline in ocean NPP translates into a values-at-risk estimate of over \$9.2 trillion.

### 3.2 Loss of half of all coral reefs

The bleaching and death of coral reef ecosystems from OAW is already underway. As previously noted, the Great Barrier Reef has lost extensive areas due to the combined effects of warming and acidity and some models predict that the process of coral reef accretion may entirely halt by 2050 for many reefs. In particular, models show that increases in atmospheric CO<sub>2</sub> above 500 parts per million and a sea surface temperature rise of over 2°C relative to today will push carbonate-ion concentrations well below levels needed to sustain the accretion process and “reduce coral reef ecosystems to crumbling frameworks with few calcareous corals” (Hoegh-Guldberg et al. 2007). Less pessimistically, but only addressing the acidification effect, Brander et al. (2012) predict losses in 2100 to range between 16% and 27%. Given this, we split the difference and adopt a plausible scenario of a 50% loss of current coral reef ecosystem extent (14 million hectares) by 2100. Applying the mean value of ecosystem services from coral reefs, \$404,407 per hectare, Costanza et al. (2014) suggests a current values-at-risk estimate of roughly \$5.7 trillion/yr.

### 3.3 Additional sea level rise of one meter due to Antarctic ice sheet collapse

Current climate models used in calculating SCC depict a sea level rise of roughly 0.55 meters by 2100. But new research suggests a much more dire situation due to the effects of ocean warming on Antarctic ice sheets. Through a process known as basal melting from below, the collapse of marine-terminating ice cliffs in Antarctica could contribute more than a meter to sea level rise by 2100 (Deconto and Pollard 2016). To translate this into an economic loss estimate, we first calculated the additional land area inundated by sea level rise of 1.55 meters (vs. 0.55 meters) for various regions including the US, southeast Asia and north Australia, the Mediterranean, northwest Europe, the Amazon Delta, east Asia, and south Asia primarily using figures published by Rowley et al. (2007). The research also reported population affected in these newly inundated areas.

We use gross domestic product (GDP) per capita to develop an initial estimate of potential economic losses without adaptation from these areas– at least for market-based transactions. (Below, we show an alternative approach, based on adaptation cost.) Using region-specific GDP per capita figures, we estimate a global values-at-risk from newly inundated areas of about \$3.6 trillion/yr should the additional meter of sea level rise occur.

### 3.4 At least 25% of all charismatic marine species go extinct

People of all nationalities and income groups place a value on sustaining the existence of whales, dolphins, polar bears, salmon and other charismatic marine species. The loss of this “existence value” is thus an important category of OAW costs to consider. OAW is likely to cause many treasured species – like the polar bear – to slip into extinction as sea ice, coral reefs, and mangroves are reduced and food chains disrupted. One model predicts that 37% of all marine mammals are at risk of extinction from climate change and other synergistic effects (Davidson et al. 2012). Others predict that the extinction risk is in the 20% to 25% range.

We can derive a ballpark estimate of worst-case global costs by making different assumptions about the share of global income people are willing to pay (WTP) to prevent these outcomes. The range of WTP reported in the literature generally varies from <1% to about 5% for conservation and humanitarian causes. Using the upper bound figure suggests a values-at-risk of >\$1.1 trillion/yr as marine species people value for their existence decline or go extinct from OAW.

### 3.5 Carbon sequestration capacity of the oceans declines by 50%

Currently the oceans absorb 25–30% of anthropogenic carbon dioxide emissions, and they have taken up almost half of accumulated emissions since the industrial revolution. Basic physics and standard climate models suggest this capacity will increase in the future simply as a result of the differences between the partial pressure of CO<sub>2</sub> in the atmosphere (higher) relative to the ocean surface (lower) and the resulting diffusion into water ~~that results~~. But OAW will compromise the oceans’ future ability to capture and store emissions through a complex set of factors, including warming sea surface temperatures, changing wind patterns, changes in ocean currents, and reduction of ventilation or mixing of surface and deep ocean layers. In the North Atlantic, researchers have noted an absolute 50% reduction of CO<sub>2</sub> uptake from the mid-1990s to 2002–2005, at least partially in response to these climate change dynamics (Schuster and Watson 2007). Other research has predicted a reduction in cumulative CO<sub>2</sub> uptake of 38% and 49% for a doubling and quadrupling of atmospheric CO<sub>2</sub> concentrations relative to 1996 levels, respectively (Sarmiento and Le Quéré 1996).

Society’s WTP for carbon sequestration provides the basis for valuing this loss. Kotchen et al. (2013) found that that households are, on average, willing to pay between \$79 and \$89 per year in support of reducing domestic greenhouse gas (GHG) emissions 17% by 2020 – the current US target. This translates into a mean WTP of \$134.56 per metric ton CO<sub>2</sub>, and we use this amount to represent the global value of sequestration. We then apply this amount within a plausible scenario that assumes the ocean’s annual sequestration will decline by 4.8 billion metric tons CO<sub>2</sub> (about half of the current annual sequestration) by 2100 to arrive at a values-at-risk of roughly \$641 billion/yr.

### 3.6 Loss of at least 15% of current mangrove area

The World Bank has recently modeled the expected loss of mangrove habitat as climate change unfolds. Inundation from sea level rise and an increase in storm intensity are the key drivers. Modeled losses include 100% of coastal mangroves in Mexico, 85% in the Philippines,

59% in Venezuela, 31% in Papua New Guinea and 27% in Myanmar (Blankespoor et al. 2016). These and other regional estimates support a global loss range of 10%–15%, the upper bound being equivalent to a loss of 2.2 million hectares. The mean value of lost ecosystem services, \$130,736 per hectare (Costanza et al. 2014), indicates a global values-at-risk of about \$287 billion per year.

### 3.7 400 million people suffer increased risk of food insecurity

Observations and forecasts suggest that OAW will disrupt the supply of food from the sea in many regions and increase the number of food insecurities. The combination of water surface warming, the spread of low oxygen zones and increasing acidity due to decreasing pH values is altering the body size of individual animals. This is shifting the habitat ranges of whole stocks and influencing species abundance and composition, food chain linkages and the dynamics of interactions between individuals within and among species. Potential losses in the ocean's yield of shellfish, mollusks, and fish for both commercial and subsistence uses have been relatively well studied in the literature (Table 3).

According to the IPCC, climate change puts the 400 million people who depend heavily on fish for food at risk, especially small-scale fishermen in the tropics (Holmyard 2014). That's because yields are expected to fall by 40% to 60% in that region. Widespread increases in starvation and malnutrition will materialize unless food distribution systems are expanded to bring replacement food to affected communities without delay when seafood catches decline. And while seafood yields may increase in the high latitudes, it will not solve the food security issue unless there is a way for fishing infrastructure and associated distribution systems to migrate to those areas as well and unless the subsistence catch in seafood-dependent regions is replaced with other sources of nutrition.

The welfare loss associated with putting 400 million at increased risk of food security can also be evaluated from a WTP standpoint. People care about starvation, and regularly donate to organizations feeding the hungry. Globally, studies have consistently documented willingness to pay values of 1% or more of income to cut hunger in half. Globally, there are about 800 million affected by hunger, and so the 1% figure is a good proxy for the welfare loss associated with having 400 million people more at risk from OAW. This translates into a global annual values-at-risk of about \$246 billion/yr should the scenario unfold.

### 3.8 Marine dead zones expand in area by 50%

The term “dead zone” is a common term for hypoxic (low oxygen) areas in the world's oceans and lakes caused mainly by nitrogen and phosphorous pollution from human agricultural lands and settlements and the burning of fossil fuels. Within these dead zones, the oxygen consumed by algae that thrive in polluted waters depletes that required to sustain most other forms of marine life. Diaz and Rosenberg (2008) estimated the global extent at 245,000 square kilometers. Continued growth of these marine dead zones undermines global biodiversity conservation goals and poses a significant challenge to meeting the world's increasing demands for capture fisheries and aquaculture.

CO<sub>2</sub> emissions have the potential to increase the extent of oxygen-depleted water by 50%, or 12,250,000 ha by 2100 (Oschlies et al. 2008). This depletion would occur independent of, but compounded by the impacts of other pollutants. So the 50% figure seems reasonable as a basis for assessing the risk. The mean value of services derived from marine ecosystems is

\$10,271/ha/yr (Costanza et al. 2014). Assuming that this value would fall to zero in the new dead zones, the resulting values-at-risk would be about \$127 billion per year.

#### **4.0 Alternative approaches for incorporating values at risk into the SCC**

The social cost of carbon (SCC) represents the increase in net global economic damage expected to result from an increase in atmospheric greenhouse gases (GHGs) equivalent to one metric ton of carbon dioxide (tCO<sub>2</sub>-e). A reliable monetary estimate of the SCC is essential for measuring, in economic terms, the potential harm from actions that would increase emissions of greenhouse gases or slow their sequestration, and the benefit of actions that would have the opposite effect. It also can broaden public understanding of the risks associated with greenhouse gas emissions by translating scientific descriptions of these risks, such as decreases in arctic ice or reductions in biodiversity, into more familiar, economic terms.

An Interagency Working Group (IWG 2016) of U.S. federal agencies has developed partial estimates of the SCC, focusing on potential costs arising from the effects of climate change on terrestrial portions of the globe: changes in agricultural production, flooding, wildfire, human health, water supply, drought, and the like. With various assumptions about discount rates and other modeling factors, IWG (2016) estimates that emissions over the next few years will have an SCC of about \$42 (tCO<sub>2</sub>-e)<sup>-1</sup>. This and other efforts to quantify the SCC have not incorporated the social costs of OAW (Howard 2014). As noted in Section 3, these changes in ocean conditions are likely to have profound economic consequences for billions of people, especially the world's poorest. As such, efforts to integrate OAW costs into the SCC will provide a much better signal of the benefits of climate action and costs of business as usual.

##### 4.1 Regulatory mandate

Incorporating the economic costs of OAW into the SCC is of interest not just from the perspective of improving the SCC's rigor. It also is strongly suggested by the regulatory framework governing federal agencies' use of the SCC in decision-making. There are seven cabinet-level agencies or departments participating in the IWG that are already using or planning to incorporate the SCC into regulatory-impact analysis, including the Environmental Protection Agency and the departments of Energy, Agriculture, and Interior. All of these agencies are bound by statutes, regulations, and rules governing economic and environmental analysis that require use of best available science, attention to all known benefits and costs of agency actions including non-market effects, treatment of uncertainty, and worst-case scenarios.

For example, Circular A-94, which provides guidance for all federal agencies conducting economic analysis, requires consideration of externalities, monetization of all benefits and costs to the extent practicable, and treatment of uncertainty through the use of expected values (OMB 1992). Executive Order (EO) 12866 as amended by EO 13563 direct agencies conducting benefit-cost analysis "to use the best available techniques to quantify anticipated present and future benefits and costs as accurately as possible." Regulations for implementing the National Environmental Policy Act, an often-used venue for SCC, require consideration of worst-case scenarios that have "catastrophic consequences, even if their probability is low" (40 CFR §1502.22). In the following sections, we offer three possible paths forward for meeting these mandates and present the results of some preliminary estimates of what they imply for the SCC.

##### 4.2 Damage function approach

The IWG’s current approach to calculating the SCC relies on three integrated assessment models (IAM) known as DICE, Policy Analysis of the Greenhouse Effect (PAGE), and Framework for Uncertainty, Negotiation and Distribution (FUND) (IWG 2016). These models calculate SCC in five-year increments through 2200 based on functions that express economic costs as a fraction of gross world product in each year that would be enjoyed in the absence of climate change. In other words, the models compare gross world product with and without climate change. The IWG then divides the present (discounted) value of this difference as it unfolds in five-year increments through 2300 by the increase in cumulative emissions in the prior period to arrive at the marginal SCC estimate. The damage function itself is based on the following relationship, as reported by Ackerman and Stanton (2012):

$$[1] R_t = [1+(T_t 18.8^{-1})^2]^{-1}$$

In this quadratic equation, the term  $R$  represents the share of gross global product remaining at year  $t$  after accounting for damages  $D$  (so that  $R_t = 1 - D_t$ ) and is solely a function of temperature  $T$  expressed as an increase in degrees Celsius over pre-industrial levels. The basic function has been often criticized not only for excluding major categories of damage but also because it leads to absurd results in the long run. In particular, at an increase of 12 °C the model suggests that economic damages would only amount to 30% of gross world product, when in fact at this temperature most life on Earth, much less the human economy, may not exist. For this reason, several alternative damage functions have been proposed to account for catastrophic outcomes. These alternatives suggest that the SCC could be almost \$900 (tCO<sub>2</sub>-e)<sup>-1</sup> for emissions in 2010, rising to \$1,500 (tCO<sub>2</sub>-e)<sup>-1</sup> by 2050 (Ackerman and Stanton 2012).

Regardless of the relevant form of the SCC damage function, incorporating OAW costs into the framework requires recalibrating damages at each point in time ( $D_t$ ), re-estimating equation [1], and then running the IAMs to produce new SCC results. The full impacts on the SCC can be determined when the IWG updates its estimates. For the purposes of this paper, we use a short cut to illustrate what the effects on SCC likely would be. The short cut involves using a simple linear regression on IAM model outputs with  $D_t$  as the independent variable and SCC as the dependent variable and then using the resulting equations to solve for SCC at OAW-adjusted levels of  $D_t$ . Using 2013 public access versions of DICE, we first estimated two equations based on separate runs of the model (called the ‘Copenhagen Accords’ and ‘Limit of 2 °C’ scenarios) and then used the resulting equations – both of which fit well ( $R^2 > 0.80$ ) as linear models through 2100 – to suggest what SCC would be in various years if OAW costs were included. We based the OAW-adjusted level of damages ( $D_t$ ) at 5-year increments through 2100 on the assumption that damages by 2100 would amount to \$20 trillion per year, but with a relatively low probability (25%) of occurring. The \$20 trillion figure is within the range suggested by Table 4. The expected value – \$5 trillion/yr by 2100 on top of the IWG’s baseline estimates – was assumed to increase from zero in 2015 at a constant rate until 2100. We then plugged the resulting baseline plus OAW damage figures into the regression equations to translate them into increments to the IWG’s published SCC estimates.

The results of this simplified approach are reported in Table 5. Column one reports the IWG’s baseline SCC figures at a 3% discount rate in 2007 dollars. Column two adds modeled increments to the SCC to account for OAW using the Copenhagen scenario of DICE while column three uses the Limit2 scenario. The former suggests an SCC rising from \$60 (tCO<sub>2</sub>-e)<sup>-1</sup> in 2015 to \$101 (tCO<sub>2</sub>-e)<sup>-1</sup> in 2100. The latter suggests a range of \$96 (tCO<sub>2</sub>-e)<sup>-1</sup> to \$281 (tCO<sub>2</sub>-e)<sup>-1</sup>.

Respectively, these columns suggest that adding OAW costs would yield an SCC 1.5 to 4.0 times greater than the existing federal baseline.

<Table 5 goes here>

#### 4.2 Replacement or adaptation cost approach

An entirely different approach that may be more amenable to the damages associated with OAW is one based on the replacement or adaptation cost associated with losing key ecosystem goods and services and replacing infrastructure. Thus, as food from the sea declines there will be a replacement cost associated with providing alternative nutrition sources from the land. The tally of costs should include both the financial outlays needed as well as any additional external damages that may be associated with the substitutes. Increasing agricultural output to make up for declining seafood consumption, for instance, may come at a steep cost to remaining native terrestrial ecosystems and the goods and services they provide if additional land needs to be put into production.

Current replacement or adaptation cost figures – and these may certainly change over time as new information permits more refined estimates – can then be used as date-certain investment targets achieved by a stream of annual investments that begins today. Dividing the necessary level of investment by emissions in a given year then represents what charge needs to be made on each ton of carbon dioxide released in order to eliminate the externalized cost burden. This approach may be better suited for costs of OAW because most of the costs are non-market in nature. It is easier to figure out the cost of replacing these lost services than the existing economic damage their loss generates simply due to the inherent uncertainty associated with non-market valuation techniques.

As an example, consider coastal infrastructure that will need to be abandoned and replaced if sea level were to rise 1.55 meters by 2100 (See Section 3.3). As previously noted, this scenario entails a risk of losses of \$3.6 trillion/yr – a figure that reflects the current value of GDP in areas that would be newly inundated above and beyond a sea level rise of 0.55 meters, the baseline IWG assumption. As a general rule of thumb, economists assume that the value of the underlying capital stock is roughly ten times the annual GDP produced by a given area. In this case, the challenge would be replacing roughly \$36 trillion in infrastructure.

If we select 2100 as the date-certain when these investments need to be completed, it implies an annualized investment stream now until that date of \$2.5 trillion/yr taking into account an opportunity cost of capital (OCC) of 7% - the standard now used by many public agencies when making large-scale infrastructure investment decisions. The OCC is used to reflect the opportunity of taking capital out of more productive investments elsewhere. Dividing this annual investment need by current global emissions suggests an increment of about \$70 to the current SCC to account for the externalized debt obligation associated with replacing coastal infrastructure at a sea level rise of 1.55 meters rather than 0.55 meters by 2100. Additional replacement cost increments to SCC can be made for dwindling supplies of food from the sea, lost carbon sequestration capacity (the alternative here may be reforestation), and perhaps other ecosystem services that have functional replacement that are relatively easy to identify and cost out. Adding in these other replacement cost figures would likely justify an increase of SCC by a factor of two or more.

## 4.2 Averted risk approach

People pay to reduce risk. Of course, this is the bread and butter of the insurance industry. But it is also one of the most basic themes in welfare economics, in particular, the branch of economics related to risk and uncertainty. Models of decision making under risk and uncertainty, including the payments of premiums to avoid or reduce risks, may be an extremely fruitful approach to the SCC since so many of the damages expected are potentially catastrophic but highly uncertain (Botzen 2013). An averted risk approach would peg the SCC to what society is willing to pay today (WTP) to reduce the risk of future economic damages. Stated as a cost, it represents the welfare loss associated with having a large share of economic activity at risk from climate change.

Basing SCC on WTP to avert or reduce risk has advantages over damage function based approaches. For example, current damage function models are based on certainty equivalents, when in reality uncertainty over whether or not a specific damage (i.e. catastrophic sea level rise associated with the collapse of West Antarctic ice sheets) will occur as well as the magnitude of such damages is the norm. Of course this trades one complex task for another – modeling probabilities rather than damages – but nonetheless is more tractable, especially if the probabilities are based on subjective expert assessments. In this way, the averted risk approach need not be nearly as sophisticated or complex as the existing IAMs.

The standard method for determining WTP to reduce risk is based on expected utility theory. Figure 1 illustrates calculation of the risk premium an individual is willing to pay, shown as the line connecting points  $c$  and  $d$ , or  $Y_3$ - $Y_4$ . It involves three key steps. First, it requires an assumption regarding the shape of an individual's (or in our case, society's) utility function. Utility is an economic concept that hypothetically measures the enjoyment, or wellbeing associated with a given level of income, wealth, or quantity of a good or service. For our purposes, we adopt one of the standard forms depicting the utility function of a risk-averse person or population:  $U = \ln(W)$ , where  $W$  is wealth (y-axis) and  $U$  the level of utility associated with that level of wealth (x-axis). The declining marginal utility of wealth is reflected by the concave shape of the curve, and is a graphical representation of the fact that as wealth increases, a given increment to wealth has less of an impact on wellbeing.

<Figure 1 goes here>

The second step depicts the loss scenario, should it unfold. The person currently enjoys a level of wealth  $W$  and utility  $U_1$ , but faces a 50/50 chance that a catastrophic event will reduce her wealth by  $L$  to the point  $W-L$  with a utility of  $U_2$ . Given this risk, the expected wealth and utility in the next time period is given by the points  $Y_3$  and  $U_4$ . This is simply a weighted average assigning equal probability to the two outcomes of next period wealth. The third step calculates the risk premium. The risk premium reflects what society is willing to pay to have an intermediate level of wealth in the next period ( $Y_4$ ) for certain rather than an uncertain  $W$ . The calculations are relatively straightforward, and the results vary with the shape of the assumed utility function, probability of loss, and magnitude of loss.

<Table 6 goes here>

Table 6 shows the result of this simplified analysis for three loss scenarios, each with OAW losses of \$20 trillion (as suggested by Table 4) but with different assumptions about when that loss will occur, the social discount rate (converting future losses into present values), and the probability of the loss. The resulting risk premiums, in trillions per year, are then divided by current emissions to suggest what the SCC increment should be today to internalize the welfare loss associated with the risk of catastrophic damages associated with OAW by 2050 or 2100. The

results justify an increment of \$33.96 to \$155.66 to the SCC, for emissions over the next few years, to account for this welfare loss. This translates into an SCC that is 1.8 to 4.7 times higher than the current federal estimate.

## 5.0 Conclusions

Ocean acidification and warming (OAW) has the potential to put the livelihoods of billions of people at risk, accelerate the extinction of marine species, and damage critical life support systems of the planet, including the production of adequate levels of oxygen for life on Earth to exist. Literature on the economic toll of OAW is relatively sparse compared with other aspects of climate change. As a result, past efforts to estimate SCC have excluded these costs by treating them as zero. Here, we argue that there now exists sufficient information to develop non-zero estimates of the OAW component of the SCC. Moreover, incorporating such estimates would be consistent with regulatory requirements to use best available science and take note of high-impact/low probability scenarios.

There are at least three approaches for doing so. The first is simply to fit plausible scenarios of OAW and the likely magnitude of economic costs into integrated assessment models (IAMs) used by federal agencies. The IAMs model year-by-year net economic damages as a quadratic function of temperature and then translate the present value damage stream into an estimate of the SCC for emissions today and in future years. The key conclusion we offer here is that while OAW damages are highly uncertain, they can nonetheless be input into the IAM framework as expected (probability-weighted) values. The second is an entirely different approach that requires maintaining an ongoing inventory of necessary capital investments needed to replace or adapt to ecosystem goods, services, and infrastructure likely to be lost to OAW. Under this approach, the SCC would reflect what amount ought to be charged to emissions, beginning now, to generate an annual investment stream needed to meet long term replacement or adaptation goals. If adaptation planning is begun in earnest today, there is no reason why this approach could not supplement the SCC's damage function basis.

The third mimics the insurance industry to estimate society's willingness to pay to reduce or eliminate future OAW risks. We find that this approach is, perhaps, the most suitable for OAW given the fact that economic costs are potentially catastrophic in value but highly uncertain. Standard expected utility theory provides the basis for current estimates of WTP and resulting increments to SCC needed to capture the welfare losses associated with having these economic risks on the books. Taken together, our preliminary results suggest that SCC should be 1.5 to 4.7 times the current federal rate, or in the \$60 to \$200 per metric ton CO<sub>2</sub>-e range, just to account for the costs of OAW.

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## Figures and Tables

**Table 1: Typology of ocean and coastal ecosystem services**

<b>Provisioning goods and services</b>	<b>Regulating goods and services</b>
<ul style="list-style-type: none"> <li>• Human food (calories, protein, essential micronutrients)</li> <li>• Livestock food</li> <li>• Pharmaceutical and cosmetic compounds</li> <li>• Fertilizer</li> <li>• Water for desalination and industrial cooling</li> <li>• Construction materials</li> <li>• Commercial products (jewelry, curios, ornamental fish)</li> </ul>	<ul style="list-style-type: none"> <li>• Energy storage</li> <li>• Carbon sequestration and storage</li> <li>• Oxygen production</li> <li>• Filtration of runoff by sea grasses</li> <li>• Bioremediation of waste</li> <li>• Biological control of harmful algal blooms</li> <li>• Shoreline protection</li> </ul>
<b>Cultural goods and services</b>	<b>Supporting goods and services</b>
<ul style="list-style-type: none"> <li>• Subsistence</li> <li>• Cultural and scientific education</li> <li>• Recreation opportunities</li> <li>• Tourism opportunities</li> <li>• Intrinsic values for threatened and endangered species</li> <li>• Sense of place for coastal communities</li> <li>• Cultural identity for coastal communities</li> <li>• Research opportunities</li> </ul>	<ul style="list-style-type: none"> <li>• Biological primary and secondary production</li> <li>• Biological diversity</li> <li>• Habitat/refugia</li> <li>• Nutrient cycling</li> </ul>

**Table 2: Risks associated with ecological and biogeochemical systems**

<b>Key processes at risk</b>	<b>Key risks to marine habitats and organisms</b>
<ul style="list-style-type: none"> <li>• Increase in acidity of sea water</li> <li>• Increase in sea temperature down to 1km</li> <li>• Changes in ocean currents</li> <li>• Release of seafloor methane to atmosphere</li> <li>• Intensification of extremes in El Nino/Southern Oscillation and weather events</li> <li>• Poleward movement of storm tracks and changes in monsoons</li> <li>• Decline in phytoplankton's production of atmospheric oxygen</li> <li>• Changes in nutrient cycling</li> <li>• Slowdown of the Biological Pump (transfer of atmospheric CO<sub>2</sub> to the ocean floor)</li> <li>• Discharge into the atmosphere of heat and CO<sub>2</sub> previously absorbed by the oceans</li> <li>• Intensification of global hydrological cycle</li> <li>• Rising sea levels from heat expansion of sea water</li> </ul>	<ul style="list-style-type: none"> <li>• Melting of Arctic summer sea ice</li> <li>• Increased incidence of harmful species and toxic compounds</li> <li>• Negative effects on growth, survival, fitness, calcification, and development of marine organisms</li> <li>• Changes in metabolic pathways and biological processes</li> <li>• Global redistribution of marine biodiversity</li> <li>• Evolution of some organisms towards smaller size</li> <li>• Reduction in primary production of some marine ecosystems</li> <li>• Expanding deoxygenation, with shift away from species not adapted to hypoxia</li> <li>• Spreading anoxic dead zones and toxic blooms</li> <li>• Changes in food-web dynamics</li> <li>• Contraction of metabolically viable habitats of marine animals</li> <li>• Synergistic interactions with other stressors (pollution, etc.) of marine ecosystems</li> </ul>

**Table 3: Potential economic cost of lost ecosystem services due to ocean warming (OW) and/or acidification (OA)**

Lost ecosystem service	Source	Estimated Cost	
		Location, Year	Estimate
Coral reef recreational value (OA)	Brander et al. (2012)	Global, 2100	\$1.2T/yr
Shellfish landings (OA)	Turley et al. (2009)	UK, 2006	\$52–131M/yr
Mollusk catch and aquaculture (OA)	Narita et al. (2012)	Global, 2100	\$7-101B/yr
Mollusk catch and aquaculture (OA)	Narita et al. (2012)	USA, 2100	\$436M/yr
Fish, mollusks/bivalves, crustaceans, aquaculture (OA)	Armstrong et al. (2012)	Norway, 2010-2110	\$360M
Carbon sequestration (OA)	Armstrong et al. (2012)	Norway, 2010-2110	\$114B
Shellfish production (OA)	Hilmi et al. (2015)	Global, 2100	\$2.3B/yr
Sardine catch (OW)	Garza-Gil et al. (2015)	Spain, 2036	\$17M/yr
Fish catch (OW)	Jones et al. (2014)	UK, 2005-2050	\$0.44B
Methane storage East Siberian Sea (OW)	Whiteman et al. (2013)	Global, thru 2200	\$60T

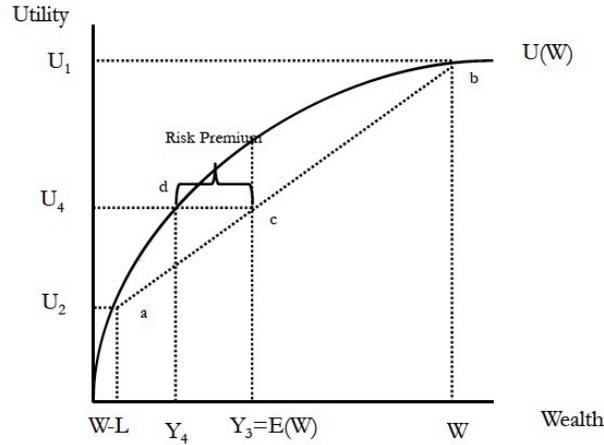
**Table 4: Plausible worst-case scenarios and values at risk from OAW**

Resource or service at risk	Scenario	Values at risk
		(\$2016 billions/yr)
Net primary productivity	Ocean net primary productivity reduced by 16%	\$9,232.00
Coral reefs	Loss of at least 50% of current coral reef area	\$5,661.70
Coastal infrastructure	Additional SLR of 3 meters via WAIS collapse	\$3,561.69
Charismatic species	25% of charismatic marine species go extinct	\$1,104.08
Carbon sequestration	50% loss of ocean CO <sub>2</sub> uptake	\$641.16
Mangroves	Loss of at least 15% of current mangrove area	\$287.42
Fisheries	400 million at significantly increased risk of hunger	\$245.74
Coastal ecosystems	Marine dead zones expand in area by 50%	\$126.82

**Table 5: Social cost of carbon – modified damage function approach (\$2007, 3% discount rate, OAW damages at \$20 trillion in 2100 with probability=0.25)**

Year	IWG baseline (\$/mt CO <sub>2</sub> )	OAW/DICE Limit2 (\$/mt CO <sub>2</sub> )	OAW/DICE Copen (\$/mt CO <sub>2</sub> )
2015	\$36	\$96	\$60
2020	\$42	\$161	\$75
2025	\$46	\$205	\$84
2030	\$50	\$235	\$91
2035	\$55	\$256	\$96
2040	\$60	\$269	\$98
2045	\$64	\$277	\$100
2050	\$69	\$281	\$101

**Figure 1: Willingness to pay to avert risk – standard expected utility model**



**U=utility, W=wealth, Y=expected wealth**

**Table 6: Willingness to pay to avoid catastrophic OAW scenarios**  
*(Based on a social utility function of  $y=ln(w)$ )*

Parameters	Scenario1	Scenario2	Scenario 3
Existing wealth (GWP - \$trillions)	\$75.80	\$75.80	\$75.80
Nominal loss from OAW (\$trillions/yr)	\$20.00	\$20.00	\$20.00
Year of loss	2050	2100	2100
Discount rate	0%	1%	3%
Present value loss (\$trillions/yr)	\$20.00	\$8.58	\$1.62
Risk of loss	0.25	0.50	0.75
Expected utility	4.25	4.27	4.31
Certainty equivalent wealth (\$trillions)	\$70.21	\$71.38	\$74.58
Risk premium (\$trillions)	\$5.59	\$4.42	\$1.22
SCC increment	\$155.66	\$123.15	\$33.96