

Ocean Acidification: Scientific Surges, Lagging Law and Policy Responses*

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Introduction

The increasing acidity of the world's oceans, linked to elevated carbon dioxide levels in the atmosphere from anthropogenic CO₂ emissions, is capturing more and more scientific and political attention. The scientific literature has exploded with a fifteen-fold increase in the number of ocean acidification publications from 2004 to 2012¹ and the number of multi-national and national ocean acidification research projects are ever expanding.² The need to mitigate and adapt to ocean acidification has been highlighted in recent UN General Assembly resolutions,³ and new Sustainable Development Goals agreed to in 2014 include a specific political target to minimize and address the impacts of ocean acidification including through enhanced scientific cooperation.⁴

Getting a regulatory grip on ocean acidification has not been easy. No international agreement has been negotiated to specifically address ocean acidification.⁵ A fragmented array of international agreements, documents and initiatives has emerged having relevance to climate change and ocean acidification.⁶ International negotiation efforts for a new agreement by 2015 to control global greenhouse gas emissions have focused on the need to address climate change and rising atmospheric temperatures rather than ocean acidification.⁷

This chapter reviews both the scientific and international law and policy dimensions of ocean acidification. Part 1 highlights the surging scientific reality. After reviewing the basic chemistry of ocean acidification, it summarizes the extensive scientific information regarding biological effects and ecosystem-level responses and the numerous scientific uncertainties and information gaps still remaining. Part 2 surveys the international law and policy seascape relevant to ocean acidification and the lagging nature of the regulatory framework to date. Five global dimensions are described and assessed: the UN Convention on the Law of the Sea (LOSC);⁸ the UN climate change regime; marine pollution control instruments; the Convention on Biological Diversity;⁹ and relevant UN General Assembly resolutions and processes. The chapter concludes with thoughts on future directions for international law and policy responses to ocean acidification and a summary of key questions looming on the horizon. A review of regional,¹⁰ national¹¹ and local responses¹² to ocean acidification is beyond the scope of this chapter.

Surging ocean acidification science

Ocean chemistry and “man’s greatest geophysical experiment”

Ocean acidification most commonly refers to the long-term increase in ocean acidity caused by the ocean’s uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere, although the ocean’s acidity can increase due to other processes as well, e.g. acid rain and decomposition of organic material. Since the industrial revolution human activities have led to the emission of roughly 590 Gt of carbon, primarily due to fossil fuel combustion and land use changes.¹³ As a result atmospheric CO_2 has increased dramatically from a pre-industrial value of 280 parts per million by volume (ppmv) to 400 ppmv in 2014 with an accelerating rate.¹⁴ By the year 2100 atmospheric CO_2 may reach levels 900 ppmv unless CO_2 emissions are reduced dramatically.¹⁵

The ocean is taking up about 2 Gt of anthropogenic carbon per year.¹⁶ Cumulatively the ocean has taken up a quarter to a third of anthropogenic CO_2 ¹⁷ and is thus mitigating human-induced global warming; however, this massive uptake of CO_2 affects the ocean’s chemistry. When CO_2 is taken up by the ocean it does not merely dissolve in seawater; instead most of the dissolving CO_2 reacts with water to form carbonic acid (H_2CO_3) which then dissociates to form bicarbonate ions (HCO_3^-), carbonate ions (CO_3^{2-}) and hydrogen ions (H^+).¹⁸ The fraction of inorganic carbon that remains in the form of CO_2 molecules is referred to as aqueous CO_2 . The combination of all inorganic carbon forms, i.e. aqueous CO_2 , carbonic acid, carbonate ions and bicarbonate ions, is referred to as Dissolved Inorganic Carbon (DIC). Only the small fraction of aqueous CO_2 can be used directly by photosynthetic organisms.¹⁹ The addition of anthropogenic CO_2 to the ocean shifts the equilibrium between aqueous CO_2 , carbonate and bicarbonate such that the concentrations of CO_2 , hydrogen and bicarbonate ions increase compared to preindustrial concentrations (the increase in hydrogen ions is synonymous with increasing acidity) while the concentration of carbonate ions decreases. These chemical reactions are well understood and quantified.

It is important to note that the uptake of anthropogenic CO_2 by the ocean (i.e. a net flux into the ocean) is the relatively small residual of much larger, spatially and temporally varying CO_2 fluxes into and out of the ocean (IPCC 2001 estimated that roughly 90 Gt C/yr are exchanged between ocean and atmosphere).²⁰ Some ocean regions are continuous sources of CO_2 to the atmosphere, e.g., the upwelling region in the eastern tropical Pacific Ocean where a combination of wind patterns and the Coriolis force exerted by earth’s rotation lead to perpetual upwelling of deep ocean water that is supersaturated in DIC. Other regions are continuous sinks of atmospheric CO_2 or switch seasonally between acting as a sink and source. Switches between uptake and outgassing of CO_2 can be driven by local processes such as surface water cooling and warming (since the solubility of CO_2 is temperature-dependent) and photosynthetic production and respiration of organic matter (since CO_2 is consumed and produced by these processes, respectively) and by remotely driven changes in surface ocean pCO_2 such as variations in the horizontal import of high or low DIC waters by ocean currents. Ocean DIC concentrations increase in the vertical direction with increasing water depth, primarily because a portion of the organic matter that is produced by photosynthesis in the surface ocean sinks and is respired at depth by microbes that consume oxygen and produce CO_2 . This process, referred to as the biological pump, contributes to the storage of inorganic carbon in the deep ocean.

The acidity of seawater refers to its concentration of hydrogen ions and is expressed in pH, defined as the negative logarithm of hydrogen ion concentration. Because of this convention a decrease in pH refers to an increase in acidity, and a change by one pH unit corresponds to a

change in hydrogen ion concentration by a factor of 10. Solutions with pH values less than 7.0 are said to be acidic; solutions with pH values larger than 7.0 are alkaline. Surface ocean water is weakly alkaline with an average pre-industrial pH of 8.2. Surface water pH has already fallen to 8.1²¹ which corresponds to an increase in surface ocean acidity by 26 per cent. By the year 2100, pH values are projected to drop to 7.8 or 7.9,²² which would represent a doubling in acidity. While most of the surface ocean is still far from becoming truly acidic (pH < 7.0), the term acidification refers to the ongoing shift toward acidic conditions.

As mentioned above, an increase in acidity coincides with a decrease in carbonate ion concentration. Lowering of the carbonate ion concentration makes seawater more corrosive to calcium carbonate minerals, which are major building blocks of the shells and skeletons of many marine organisms. From the pre-industrial time to 2007 the solubility of calcium carbonate has increased by about 20 per cent and is projected to increase by another 40 per cent by the year 2100.²³

The chemistry of ocean acidification as outlined above is well understood. Already more than 50 years ago the chemist Roger Revelle referred to the accelerating human CO₂ emissions as an unprecedented “large scale geophysical experiment” anticipating its fundamental effects on ocean chemistry.²⁴ There is observational evidence documenting ongoing trends in acidification from time-series stations in the open ocean.²⁵ These trends are consistent with the rate of increase in atmospheric CO₂. Hydrographic and biogeochemical properties have been measured at the Bermuda Atlantic Time-series Study (BATS) station, a site in the subtropical North Atlantic Ocean near Bermuda, since 1983 with more regular, monthly measurements beginning in 1988²⁶ and at the Hawaii Ocean Time-series (HOT) station in the subtropical Pacific Ocean near Hawaii since October 1988.²⁷ Surface ocean pCO₂ at these two stations is shown in comparison with atmospheric CO₂ in Figure 20.1. Acidity derived from these measurements is shown in Figure 20.2.

The time-series show recurring seasonal variations in atmospheric CO₂ (due to the seasonal greening of forests in the northern hemisphere) and in surface ocean pH and pCO₂ superimposed on a clear long-term trend.²⁸ The seasonal cycle in seawater pCO₂ and pH is largely driven by seasonal warming (cooling) of seawater, which decreases (increases) the solubility of CO₂ leading to outgassing (uptake) of CO₂ to (from) the atmosphere. The recurring seasonal pattern of planktonic photosynthesis and respiration of organic matter contributes also to the seasonal cycle in pH and pCO₂. Inter-annual differences occur at both the Hawaii and the Bermuda station due to various episodic events.²⁹ However, the trends of pCO₂ increase (1.91 and 1.89 ppm/yr at HOT and BATS, respectively) are consistent with the trend in atmospheric pCO₂ (1.87 ppm/yr after 1990).

The seasonal fluctuations and long-term trends in pH that are observed in open ocean waters are much smaller than those in coastal waters. For example, an 11-year record of high-resolution pH measurements obtained annually from late spring or early summer to late summer is available from Tatoosh Island at the coast of Washington State (USA) in the northeast Pacific Ocean.³⁰ At Tatoosh Island, pH exhibits a pronounced daily oscillation, substantial fluctuations over a range of longer timescales (days to seasons) and a clear long-term trend.³¹ The daily cycle has a typical amplitude of 0.24 pH units; in other words, pH changes within 24 hours by more than twice the change that has occurred from preindustrial times to the present in the surface open ocean. The daily oscillation is due to the day-night cycle of photosynthesis (which consumes CO₂ thus increasing pH) in combination with continuous respiration (which produces CO₂ thus lowering pH). The seasonal pH fluctuations are more extreme, for example, in 2007 pH changed by more

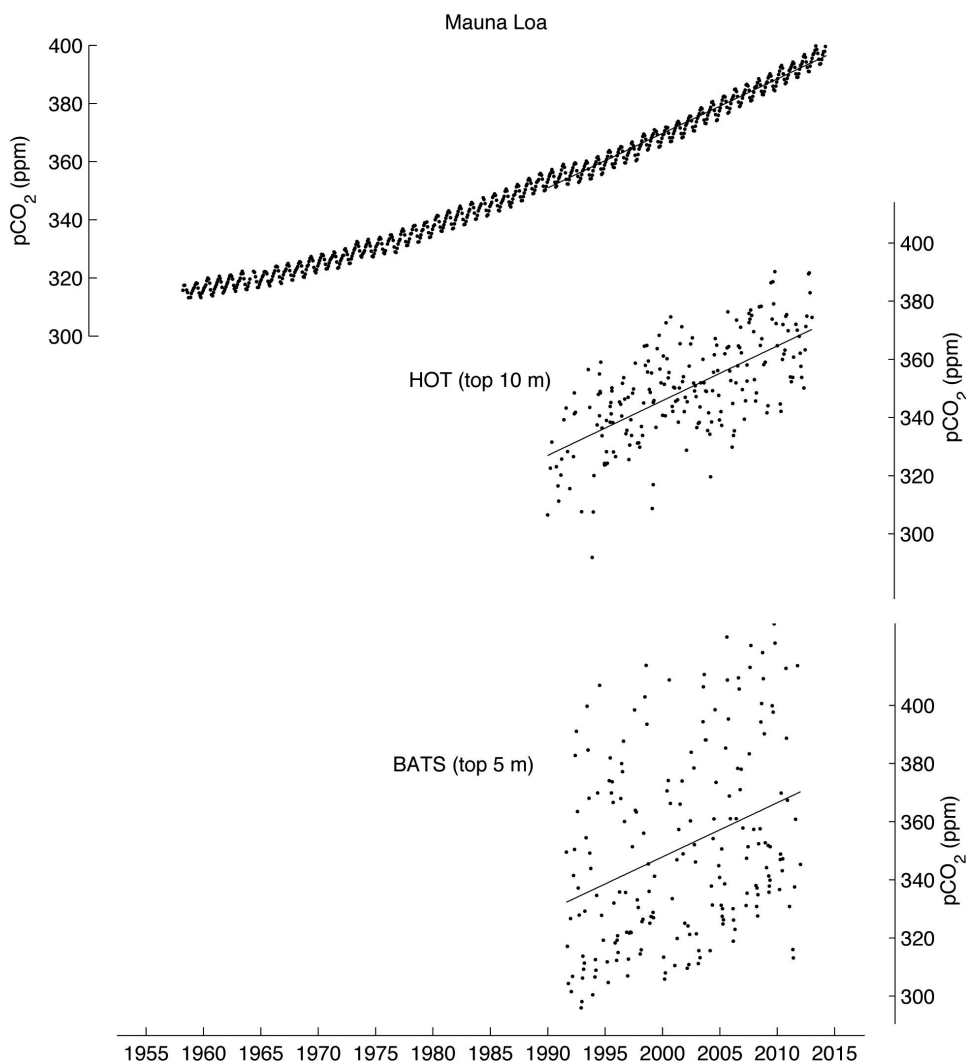


Figure 20.1 Atmospheric CO₂ concentrations measured at the Mauna Loa observatory in Hawaii from 1958 onward, and surface ocean concentrations of dissolved CO₂ (gas phase only in partial pressure) from the HOT station near Hawaii and the BATS station near Bermuda. Observations are shown as black dots; black lines indicate linear trends after 1990. Atmospheric pCO₂ increased by 1.87 ppm per year; surface ocean pCO₂ increased by 1.91 and 1.89 ppm per year at the HOT and BATS stations, respectively.

than 1 pH unit; this is more than twice the estimated pH change between preindustrial and year 2100 conditions in the surface open ocean. Superimposed on these signals is a long-term decline of 0.065 pH units per year³².

The likely reason for the faster rate of acidification observed at the coast of Washington State is that it is an upwelling region where prevalent wind patterns lead to transport of carbon-rich, low-pH water from the deep ocean to the surface. The upwelling phenomenon combined with

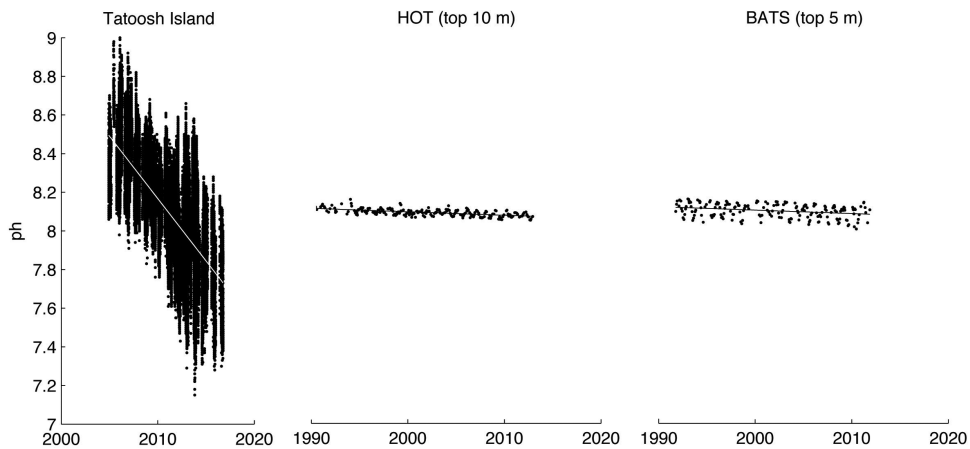


Figure 20.2 Ocean pH in surface waters at Tatoosh Island (left), at the HOT station near Hawaii (middle), and at the BATS station near Bermuda (right). pH measurements are shown as black dots; solid white and black lines indicate linear trends. At the two open ocean sites (HOT and BATS) pH is declining at a rate of 0.002 pH units per year. At Tatoosh Island (Washington State) pH is declining at a much faster rate of 0.065 pH units per year, and pH is exhibiting extreme fluctuations.[12]

the anthropogenic carbon addition to the ocean is making the coasts Washington State, Oregon (USA) and British Columbia (Canada) more susceptible to acidification than subtropical and temperate open ocean regions. Other susceptible regions include coastal waters that are impacted by heavy nutrient loads from land (for example, the coastal northern Gulf of Mexico, which receives massive nutrient inputs from the Mississippi River)³³, subsurface oxygen minimum zones in the open ocean and the polar oceans.³⁴ Oxygen minimum zones and polar oceans have naturally elevated DIC and low pH because of accumulation of microbially respired carbon in the former and because cold water holds more CO₂ in the latter.

Biological effects of ocean acidification

Ocean acidification will affect marine organisms in a number of ways. Direct effects include changes in solubility of calcium carbonate (the material of shells and hard skeletons in many marine organisms), stimulation of photosynthesis due to increases in the concentration of aqueous CO₂ and bicarbonate ions, and disturbance of the acid-base balance of animals because many physiological processes require the pH in body fluids and within cells to be regulated within narrow limits. The direct effects may have repercussions far beyond changes in abundance of individual species potentially leading to reorganizations of whole ecosystems and affecting the ocean's ability to export carbon through biological mechanisms.

Direct effects

Ocean acidification is expected to directly affect the process of calcification (the biologically mediated precipitation of calcium carbonate); hence, early studies have primarily focused on the responses of calcifying phytoplankton and invertebrate species (calcifying or calcareous organisms are those with calcium carbonate shells or skeletons). Examples include benthic

invertebrates such as corals, clams, mussels, oysters, crabs, lobsters and sea urchins, and planktonic organisms such as coccolithophores and foraminifera. There are two common forms of calcium carbonate: aragonite, which is built by corals and many molluscs and is relatively soluble, and calcite, which is less soluble and built by coccolithophores, foraminifera and some molluscs. Acidification increases the solubility of these bio-minerals because fewer carbonate ions are available in solution.

Studies on corals have consistently shown decreasing rates of calcification when aragonite solubility increases following acidification.³⁵ In a study on two coral species Fine and Tchernov³⁶ have shown that corals can lose their skeletons completely in highly acidified water, but that the coral polyps remain healthy in a controlled environment and able to regrow their skeletons when exposed again to normal pH conditions. In natural coral reefs the naked polyps would be subject to predation and likely not viable for long. There are many other benthic invertebrates with calcareous parts, but responses to acidification have been studied only in a few. Examples include the study by Gazeau et al.,³⁷ which showed decreasing calcification rates in a mussel and an oyster species, and by Shirayama and Thornton,³⁸ which documented reduced shell growth in a gastropod and two sea urchin species following acidification. In addition to decreasing calcification rates, the early development of benthic invertebrates can be affected by acidification with reduced rates of fertilization success and development, and smaller larval sizes.³⁹ Although few calcareous organisms can tolerate pH that is significantly below present levels, there are exceptions. Tunnicliffe et al.⁴⁰ observed dense clusters of mussels near a deep ocean hydrothermal vent in the Mariana arc (western equatorial Pacific) where liquid CO₂ and hydrogen sulphide emerge from the vent. The vent fluids reduce pH in surrounding waters to between 5.4 and 7.3. Despite these acidic conditions the vent mussels are able to precipitate shells, albeit at reduced rates and with thinner shell walls indicating that calcification under these low pH conditions comes at a metabolic cost. Many studies have also found decreased calcification rates and thinner shells in the major calcareous plankton groups coccolithophores and foraminifera,⁴¹ although there are exceptions as well. For example, Iglesias-Rodríguez et al.⁴² found a significant increase in shell thickness of a coccolithophore under high CO₂, while its growth rate decreased.

The above examples illustrate that, for a variety of calcareous organisms, calcification rates are reduced following acidification, but the sensitivity to decreasing pH varies among species and some show the counterintuitive response of increased calcification. These complications arise because calcification is a biologically mediated process regulated by the organism to varying degrees. Organismal compensation and acclimation mechanisms affecting the calcification process are not sufficiently understood as of yet to explain the observed species-to-species differences.

Acidification is expected to increase rates of photosynthesis because the process uses aqueous CO₂ rather than the more abundant bicarbonate ions.⁴³ Aqueous CO₂ makes up only a small fraction of DIC, but this fraction increases with falling pH. Marine photosynthetic organisms (the most important of which are phytoplankton) have to expend energy on internally concentrating CO₂ at their sites of photosynthesis. With falling pH, photosynthesizers will have to spend less energy on concentrating CO₂ and photosynthetic rates should increase. Indeed this stimulating effect on photosynthesis has been shown to occur in a variety of phytoplankton species, but not all, and for natural plankton assemblages, although the effect is relatively small.⁴⁴ The stimulation of photosynthesis does not necessarily lead to increased rates of cell division; instead it appears to be limited to producing larger cells with relatively more intracellular carbon relative to other elements.⁴⁵ In contrast to planktonic photosynthesizers, seagrasses consistently show dramatic increases in their photosynthetic rate when the concentration of aqueous CO₂ increases.⁴⁶

Decreasing ocean pH may not only affect calcifying organisms but may also have detrimental effects on the survival, growth and reproduction of marine animals in general. For example, fishes require their blood pH to remain within tight limits. Disturbances of blood pH are known to impair oxygen transport by the circulatory system and thus overall fitness of the animal. Information to date suggests that most marine fishes can effectively maintain their blood pH even at extreme ambient pH levels (regulation involves the excretion of acid primarily through gills but also kidneys and gut as compensatory mechanism)⁴⁷. However, the energetic costs associated with pH regulation may impair other energy-demanding bodily functions such as swimming, immune defense, digestion, reproduction and growth, and thus overall fitness.⁴⁸ Responses of fishes to acidification will be species-specific. Most temperate fish species, including Atlantic cod,⁴⁹ appear to be well adapted to handle pH variations in ambient water.⁵⁰ A notable exception are two species of cardinal fish from a tropical coral reef which suffered a significant decrease in their capacity to swim and carry out other vital functions in response to decreasing pH levels.⁵¹ Only few species have been studied systematically in terms of their response to decreasing pH and detailed understanding of physiological compensation mechanisms is too limited at present to explain species-to-species differences and make projections about how fish will respond to acidification.

Ecosystem-level responses

As discussed above, ocean acidification will directly affect the physiology and growth of marine organisms in various ways. Acidification is also likely to alter biogeochemical processes with potential feedbacks on climate. The direct organismal responses to acidification will likely alter ecological relationships and trophic dynamics, which determine the flow of energy and nutrients through the marine food web. Changes in acidity affect different species differently, which will result in perturbations of individual ecosystem components that can have cascading effects across the food web. Major reorganizations of pelagic and benthic ecosystems may lie ahead, but projecting such ecosystem-level responses is extremely difficult because single-species laboratory experiments and multi-species mesocosm manipulations are not easily extrapolated to natural systems or the whole ecosystem, and because cascading effects are notoriously difficult to predict.

A slowdown of calcification may reduce the ability of calcifying organisms to compete with those that do not. Reductions in the abundance of those calcifying organisms that act as important trophic links (e.g. pteropods can be an important food source for Pacific salmon)⁵² may interrupt feeding relationships and result in broad ecosystem responses. Loss of calcium carbonate structures in coral reefs, although not immediately fatal to corals in controlled environments, would remove their protective structures making them susceptible to predation, and would remove the habitat of the whole, diverse reef community. Increased dissolution of calcium carbonate in the water column of the open ocean may decrease the ballasting of sinking organic matter, resulting in shallower re-mineralization and less efficient biological carbon export with potential feedbacks on climate.

Photosynthesis in planktonic ecosystems will likely be stimulated, but responses will almost certainly be species-specific with organisms thereby altering competitive relationships.⁵³ The elemental composition of photosynthetically produced organic matter will likely shift toward more carbon per atom of nitrogen, potentially lowering the food quality for consumers but possibly increasing the efficiency of biological carbon export. To date there is no solid observational

evidence for acidification-induced species shifts in planktonic open-ocean ecosystems, which may in part be due to the fact that these systems are chronically under-sampled and, in part, because the changes may be subtle and hard to detect. Tatoosh Island is a rare example where community level shifts have been observed in an intertidal community and attributed to pH changes. More specifically, Wootton et al.⁵⁴ have shown that calcareous species performed poorly compared to non-calcareous species when pH was low.

The difficulty in projecting how ecosystems may reorganize is further complicated by the fact that marine species will adapt to changing environments to some degree. Ocean pH has varied over various timescales in the geological past, the massive carbon release during the Paleocene-Eocene Thermal Maximum (PETM) about 55 million years ago probably being the closest known analog to the present anthropogenic acidification.⁵⁵ Despite many similarities between the anthropogenic carbon release and the PETM, the latter is an imperfect analog to current changes because climatic and carbon cycle background conditions were different then (for example, the continental plate configuration was different and ice sheets in land were absent) and because carbon release was slower than the rate of the present anthropogenic release.⁵⁶ While the PETM can provide valuable information about the response of ocean carbon chemistry to a massive and sudden input of carbon,⁵⁷ responses of marine species and ecosystems are again difficult to infer given the limits of paleontological records. The potential for marine organisms to adapt to higher levels of CO₂ is presently not known.

In summary, the details and significance of ecosystem-level effects remain largely speculative. It is also important to note that ocean acidification is not the only stressor affecting marine ecosystems. Ocean warming and de-oxygenation will act synergistically with acidification.

Lagging law and policy responses

UN Convention on the Law of the Sea

Although LOSC was concluded in 1982 and thus predates global concerns over climate change and ocean acidification, the Convention contains general provisions that may be applicable to the threats of ocean acidification.⁵⁸ Pursuant to Article 192, States have the general obligation to protect and preserve the marine environment. States must also take all measures necessary to ensure that activities under their jurisdiction or control do not cause damage by pollution to other States and their environment (Art. 194(2)). States must further take necessary measures to protect and preserve rare or fragile ecosystems as well as the habitat of depleted, threatened or endangered species and other forms of marine life (Art. 194(5)). States must also adopt laws and regulations to prevent, reduce and control pollution from or through the atmosphere (Art. 212(1)).

The Convention's definition of pollution found in Article 1(4) appears broad enough to cover CO₂ emissions that are eventually absorbed into the oceans contributing to acidification.⁵⁹ Pollution is defined as the introduction by man, directly or indirectly of substances or energy into the marine environment which results in or is likely to result in deleterious effects, such as harm to living resources and hindrances to fishing and other legitimate uses of the sea.

The Convention also imposes a general environmental impact assessment responsibility that may be interpreted to cover proposed projects and activities at the national level that may contribute substantial CO₂ emissions and thus lead indirectly to ocean acidification. Article 206 requires States to undertake environmental impact assessments for planned activities under their

jurisdiction or control that may cause substantial pollution or significant and harmful changes to the marine environment.

LOSC also contains aspirational provisions encouraging States to further develop global and regional standards to control pollution of the marine environment from various sources. Such standards are urged for land-based pollution (Art. 207), seabed activities (Art. 208) and atmospheric pollution (Art. 212). Article 211 requires the further development of international rules and standards to prevent and control vessel-source pollution. While the aspirational provisions do not specifically mention the control of pollutants contributing to ocean acidification, they offer a reminder of the need to address the multiple sources of marine pollution, for example, not just CO₂ emissions from ships but also from offshore petroleum operations and land-based burning of fossil fuels.

LOSC also contains dispute resolution procedures that might be used to place the legal spotlight on the failure of States to adequately address climate change and ocean acidification threats to the oceans.⁶⁰ Part XV of LOSC, establishing a rather complicated set of dispute settlement rules,⁶¹ includes Article 297 which allows a case to be brought against a coastal State for contravening international rules and standards for the protection and preservation of the marine environment. The Convention also established the International Tribunal for the Law of the Sea (ITLOS) and ITLOS through its Rules of Procedure has opened the door for advisory opinions to be sought.⁶² An advisory opinion has already been given on state responsibilities relating to deep-seabed mineral activities⁶³ and one could foresee a similar type of case being brought to seek advice as to state responsibilities to protect the marine environment from ocean acidification.

Whether future cases will be brought relating to climate change or ocean acidification remains highly doubtful. Adversarial litigation would depend on finding a plaintiff State willing to devote the time and money to contest the excessive CO₂ emissions of another State and major doctrinal hurdles would be faced including the need to establish a breach of an international legal obligation and to prove causation.⁶⁴ The breadth of ITLOS advisory opinion jurisdiction remains in question and the LOSC itself only explicitly bestowed a limited advisory role for ITLOS to address legal questions surrounding deep seabed activities (Art. 191).⁶⁵

Climate change regime

The two global climate change agreements, the UN Framework Convention on Climate Change and the Kyoto Protocol, are obviously relevant to ocean acidification but in limited ways. Neither agreement mentions ocean acidification and their overall focus is on addressing the atmospheric aspects of climate change.⁶⁶

The UNFCCC calls for the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Since climate system is defined broadly to cover “the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions”,⁶⁷ the need to consider ocean impacts of greenhouse gas emissions seems called for.⁶⁸ What constitutes dangerous interference is left open to interpretation.⁶⁹ The stabilization level for concentrations should allow ecosystems to adapt naturally, ensure food production is not threatened and allow economic development to proceed in a sustainable manner.⁷⁰

The UNFCCC actually promotes the idea of enhancing the use of the oceans as sinks and reservoirs of greenhouse gases, including CO₂, which is the main contributor to ocean acidification.⁷¹ Article 4(1)(d) requires Parties to promote and cooperate in the conservation and

enhancement of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol including forests, oceans and other coastal and marine ecosystems.

The Kyoto Protocol also displays substantial limitations as an avenue to address ocean acidification. The Protocol does not actually require reduction of CO₂ emissions. Industrialized countries listed in Annex I do have overall reduction targets for greenhouse emissions based on CO₂ equivalence,⁷² but countries may choose not to give priority to reducing CO₂ emissions in favour of reducing emissions of one or more of the other five listed greenhouse gases: methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride.⁷³ The Protocol does not require emission reductions for developing countries and key developed countries, including Japan, New Zealand and the Russian Federation, have not agreed to emission reductions for a second commitment period.⁷⁴ Canada and the United States are not Parties.⁷⁵

The fifth assessment reports of the Intergovernmental Panel on Climate Change (IPCC), published in 2013–2014, have given increased attention to ocean acidification but policy-related advice remains quite weak. Working Group I, examining the physical science of climate change, highlighted the increase in carbon dioxide concentrations by 40 per cent since pre-industrial times with the ocean absorbing about 30 per cent of emitted anthropogenic CO₂, causing ocean acidification.⁷⁶ The decrease in pH of ocean surface water by 0.1 since the beginning of the industrial era was also noted corresponding to a 26 per cent increase in ocean acidity.⁷⁷ Working Group II, addressing impacts and adaptations to climate change, emphasized that for medium and high-emission scenarios, ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs.⁷⁸ The Working Group listed key adaptation options to reduce other stresses in an acidifying ocean environment, such as enhancing water quality and limiting pressures from tourism and fishing.⁷⁹

The IPCC's Working Group III, addressing mitigation of climate change, did not address ocean acidification specifically but emphasized the overall needs to reduce greenhouse gas emissions. To keep temperature change below 2°C relative to pre-industrial levels, the Working Group suggested the need for substantial GHG emission reductions, 40 to 70 per cent lower in 2050 than in 2010 and emission levels near zero or below by 2100.⁸⁰

Negotiations for a post-Kyoto regime have not paid much attention to ocean acidification threats.⁸¹ Political attention has been focused on obtaining enhanced commitments by countries to reduce GHG emissions but with a focus on controlling global temperature increases.⁸² At the UN Climate Change Conference in Cancun in 2010, Parties agreed to a long-term goal of limiting global temperature increase to no more than 2°C above pre-industrial levels with a further review on the need for a strengthened goal (1.5°C) to be concluded by 2015.⁸³

At the 2011 Climate Change Conference in Durban, countries agreed to launch a process to develop a protocol, another legal instrument or an agreed outcome with legal force applicable by all Parties. Negotiations are expected to be concluded in 2015 with entry into force and implementation in 2020.⁸⁴ Consideration of oceans and ocean acidification in the flurry of negotiations in the wake of the Durban decision has continued to lag.⁸⁵

Marine pollution control instruments

Three marine pollution control instruments are especially relevant to ocean acidification. Two key international agreements are the 1996 Protocol to the London Convention,⁸⁶ which addresses ocean fertilization and its possible contribution to acidity increases, and the International Convention for the Prevention of Pollution from Ships (MARPOL)⁸⁷ which has partly

addressed CO₂ emissions from ships. The Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA),⁸⁸ a legally non-binding document, is relevant for its supportive role in reducing the stresses from land-based marine pollution.

1996 Protocol to the London Convention

The 1996 Protocol, adopting a precautionary approach to ocean dumping where only wastes listed on a global “safe list” may be disposed of at sea,⁸⁹ is relevant to ocean acidification in two main ways. First, it addresses the potential sequestration of CO₂ into the ocean, for example, from offshore hydrocarbon operations. Sequestration of CO₂ into the seabed is one of the accepted disposal options under the Protocol.⁹⁰ Such sequestration would be subject to permit and waste assessment requirements.⁹¹ Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations, adopted in November 2012, flesh out various considerations that decision makers should evaluate when deciding whether to authorize seabed sequestration, for example the availability of other disposal options, potential migration and leakage pathways and potential environmental effects of escaped carbon dioxide in the overlying water including changes in pH.⁹² The Protocol prohibits the sequestration of CO₂ into the water column.⁹³

A second relevance of the Protocol is the placing of strict limitations on proposed ocean fertilization activities, another potential contributor to ocean acidification.⁹⁴ Through amendments to the Protocol, adopted in October 2013,⁹⁵ an ocean fertilization activity may only be considered for a permit if it is assessed as constituting legitimate scientific research taking into account any specific placement assessment framework.⁹⁶ A new Annex 5 to the Protocol sets out details on how proposed ocean fertilization projects should be assessed and clarifies what constitutes legitimate scientific research.⁹⁷ Permits are only to be issued if an assessment determines that pollution of the marine environment is as far as practicable prevented or reduced to a minimum.⁹⁸ Additional geoengineering activities could also be subject to control under the Protocol if they are added to Annex 4.

MARPOL

Addressing CO₂ emissions from ships is another important component of the global fight against ocean acidification. The latest IMO study on GHG emissions from ships estimates that for the period 2007–2012, on average, shipping accounted for 3.1 per cent of annual global CO₂ emissions.⁹⁹ Maritime CO₂ emissions are projected to increase significantly in the coming decades with increases of 50 to 250 per cent predicted by 2050.¹⁰⁰

The MARPOL Convention has only partly addressed the emission of carbon dioxide from ships. In July 2011 initial steps were taken to address GHG emissions from ships through amendments to Annex VI of MARPOL. A new chapter 4 was added establishing energy efficiency requirements.¹⁰¹ New ships will be obligated to meet Energy Efficiency Design Index (EEDI) requirements.¹⁰² Each ship, including existing ships, will be required to develop a Ship Energy Efficiency Management Plan (SEEMP).¹⁰³

Possible additional measures on GHG emissions have been controversial.¹⁰⁴ Tensions have arisen over whether a common but differentiated principle should apply in the shipping context. Debates have also occurred over whether market-based measures (MBM), for example, applying a levy on fossil fuel use and setting emission reduction targets should be adopted. The

IMO's Marine Environment Protection Committee at its May 2013 meeting agreed to suspend discussion of MBM issues to a future session.¹⁰⁵

Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (GPA)

The GPA is relevant to ocean acidification since it calls for the development and strengthening of national and regional programmes of action to prevent and control land-based sources of marine pollution.¹⁰⁶ Reducing land-based marine pollution is one of the key adaptation measures for responding to ocean acidification. Controlling the discharges of sewage and nutrients into the marine environment are two of the nine source categories targeted by the GPA and both sewage and nutrient discharges may enhance ocean acidification. The GPA's programme of work for 2012–2016 is focused on wastewater and nutrient management as two priorities in addition to marine litter.¹⁰⁷ Global partnerships have been formed to further address wastewater and nutrient pollution.¹⁰⁸

However, the GPA has not effectively countered ocean acidification. CO₂ emissions are not listed as one of the nine source categories of land-based marine pollution to be addressed. The GPA might be described as “limping along” with substantial limitations. The GPA is a soft law document and has struggled with limited funding support.¹⁰⁹ There appears to be waning political support for GPA implementation.¹¹⁰

Convention on Biological Diversity

The CBD has been relevant to ocean acidification in four main ways.¹¹¹ First, the CBD has played a central role in tracking and summarizing the state of scientific knowledge on ocean acidification and its impacts on biodiversity. Two synthesis reports on the impacts of ocean acidification on marine biodiversity have been prepared, the first in 2009¹¹² and the second in 2014.¹¹³

A second CBD role has been to highlight the need for taking adaptation measures to counter ocean acidification. The CBD's Strategic Action Plan for Biodiversity 2011–2020, adopted through decision X/2 at the 10th Conference of the Parties in 2010,¹¹⁴ sets out 20 “Aichi targets” with three particularly pushing for adaptation actions. Target 10 expressly mentions ocean acidification: “By 2015, the multiple anthropogenic pressures on coral reefs and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized, so as to maintain their integrity and functioning.”¹¹⁵

The other two targets important for adapting to ocean acidification are Target 6 and Target 11. Target 6 urges that by 2020 all fish and invertebrate stocks are managed sustainably and applying ecosystem approaches, so that overfishing is avoided and recovery plan and measures are in place for all depleted species.¹¹⁶ Target 11 calls for at least 10 per cent of coastal and marine areas to be conserved through ecologically representative and well connected systems of protected areas and other effective area-based conservation measures by 2020.¹¹⁷

A third relevance of the CBD has been to emphasize the need for mitigation measures to counter climate change. For example, decision X/33, adopted at the 10th COP, calls for ecosystem-approaches to mitigation, through such means as protection of natural forests, sustainable wetland management, and conservation of salt marshes and seagrass beds.¹¹⁸

A fourth role of the CBD has been to collect information on climate-related geo-engineering prospects and to encourage a precautionary approach to future geo-engineering projects. A technical and regulatory report on geo-engineering and potential impacts on biodiversity was published in 2012¹¹⁹ and a further interim update was issued in 2014.¹²⁰ Through decision IX/16C in 2008, the Conference of the Parties called for a precautionary approach to ocean fertilization activities whereby such activities should not be allowed, except for small scale scientific research studies within coastal waters, until there is an adequate scientific basis for justification, and a global and effective regulatory mechanism to cover those activities.¹²¹ Through decision XI/20 in 2012, the COP noted the lack of science-based, global, transparent and effective control and regulatory mechanisms for climate-related geo-engineering and the need for a precautionary approach to addressing future geo-engineering activities.¹²² The COP also emphasized that climate change should be primarily addressed by reducing anthropogenic emissions of greenhouse gases and by increasing their removal by sinks.¹²³

General Assembly resolutions and processes

UN General Assembly resolutions have also begun to address ocean acidification. For example, Resolution 68/70 on Oceans and Law of the Sea of December 2013 encourages States, international organizations and other relevant institutions to urgently pursue further research on ocean acidification and to increase national, regional and global efforts to address levels of ocean acidity and the negative impact of acidity on vulnerable marine ecosystems, particularly coral reefs.¹²⁴ The resolution expressed a General Assembly commitment to continue paying attention to ocean acidification and to take into account the first global integrated marine assessment and the ongoing work of the recently established Ocean Acidification International Coordination Centre of the International Atomic Energy Agency.¹²⁵

The General Assembly's sustainable fisheries resolution of December 2013 also gave attention to ocean acidification.¹²⁶ The resolution urges States to intensify efforts to assess and address the impacts of global climate change and ocean acidification on the sustainability of fish stocks and their habitats.¹²⁷ The resolution emphasizes the importance of developing adaptive marine resource management strategies and enhancing capacity-building to implement such strategies so as to enhance the resilience of marine ecosystems to the impacts of ocean acidification.¹²⁸

Processes occurring under the auspices of the UN General Assembly have also addressed ocean acidification. The UN Open-ended Informal Consultative Process on Oceans and Law of the Sea devoted its 14th meeting in June 2013 to the topic of ocean acidification, and the meeting emphasized the need to address the issue through both mitigation and adaptation.¹²⁹ Regarding mitigation, delegations stressed the principal mitigation measure must be reduction of CO₂ emissions but also noted the potential for other mitigation methods, such as carbon capture and storage.¹³⁰ The importance of reducing energy demands and developing renewable energy sources was also emphasized.¹³¹ Regarding adaptation, the report of the meeting highlighted the need to reduce the multiple stressors on the marine environment including pollution, coastal erosion, destructive fishing practices and overfishing.¹³² The importance of key management tools to assist with adaptation was noted including environmental impact assessment, marine protected areas and marine spatial planning.¹³³

Two other General Assembly related processes have also addressed ocean acidification. The UN Conference on Sustainable Development (2012) and its outcome document, 'The future we want', reiterated the need to work collectively to prevent further ocean acidification and called

for enhanced international cooperation in marine scientific research, monitoring and observation of ocean acidification.¹³⁴ The Open Working Group on Sustainable Development Goals, established to develop a set of sustainable development goals for consideration and appropriate action by the General Assembly at its 68th session, in its 2014 outcome document includes a goal on conserving and sustainably using the oceans and marine resources for sustainable development.¹³⁵ One of the targets under the goal is to minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels.¹³⁶

Conclusion: future directions and key questions

Negotiating a new international agreement to specifically address ocean acidification has been suggested by various authors as a possible future course,¹³⁷ but prospects do not look good due to various factors. They include the lack of a political champion and most importantly the presence of existing international fora, described above, that have or are beginning to address ocean acidification.¹³⁸

The main global response route for curbing ocean acidification is obviously pursuant to the UNFCCC regime.¹³⁹ While the extent to which CO₂ emissions will be further mitigated under the UNFCCC regime remains uncertain as negotiations for a new post-Kyoto agreement are still ongoing, future ways forward stand out that could be realized through a new agreement and/or a COP decision. First might be the adoption of a pH level target for the oceans.¹⁴⁰ The setting of a global average temperature target of not going above 2°C from pre-industrial levels establishes a type of precedent. However, getting international agreement on the appropriate pH level or range might be difficult in light of the highly variable nature of ocean acidity locally and regionally.¹⁴¹ Setting a reasonable minimum pH level is further complicated by inertia in the global carbon system (even if CO₂ emissions were halted completely, ocean pH would continue to fall for at least decades). A second future course might be the establishment of a fund or giving funding priority under the climate change framework to support States in conserving critical coastal sinks for carbon, including mangroves, saltmarshes and seagrass beds.¹⁴² UNEPs Blue Carbon report has already called for the protection of at least 80 per cent of such areas.¹⁴³ Perhaps the most straightforward and effective measure would be to set a CO₂ atmospheric level benchmark that would address both climate change and ocean acidification concerns.¹⁴⁴

Future steps to address ocean acidification will have to extend on many fronts beyond the UNFCCC regime. The CBD will certainly continue to be an important international venue for further synthesizing scientific knowledge on the impacts of ocean acidity on marine biodiversity and for further raising, through CBD decisions relating to marine and coastal diversity, the need for mitigative and adaptive actions.¹⁴⁵ Reducing the multiple stressors on marine ecosystems, such as overfishing, deoxygenation and pollutants, are key adaptation strategies needing implementation at both regional and national levels.¹⁴⁶

Numerous law and policy questions loom on the horizon. Key questions at the global level include:

- Should the GPA be strengthened to better address climate change and ocean acidification?
- Should the world community move from a 'soft law' approach towards land-based marine pollution to a legally binding treaty?¹⁴⁷
- Should the CBD target of protecting 10 per cent of marine areas by 2020 be substantially raised in light of the need to adapt to ocean acidification?

- Will there be further need to regulate marine geo-engineering proposals beyond ocean fertilization projects?¹⁴⁸
- What role should UN General Assembly resolutions play in further addressing ocean fertilization acidification?

At the regional level, key questions include:

- Are regional fisheries management organizations (RFMOs) and regional sea programmes adequately responding to the threats of ocean acidification and will they do so in the future?¹⁴⁹
- To what extent might ocean acidification be mitigated at the regional level?
- Will governance arrangements in polar regions be up to the task of addressing the serious threats of ocean acidification in polar waters?¹⁵⁰

Questions also abound at the national level. For example:

- Is there sufficient political, financial and human resource support for scientific research relating to ocean acidification?
- Are national CO₂ mitigation commitments and implementation efforts adequate in light of climate change and ocean acidification threats?
- What are the national adaptation implications of ocean acidification for fisheries management, aquaculture development and regulation, pollution standards, marine species at risk protection and marine protected area establishment?¹⁵¹

One thing is clear about the future regulation of human activities that contribute to ocean acidification and the degradation of marine ecosystems. It will remain a work in progress for decades to come. Mitigation not adaptation must be the global mantra. The work has hardly begun.

Notes

- * This chapter attempts to be accurate as of 15 September 2014.
- ** The authors would like to acknowledge the research assistance of Emily Adams, JD candidate (2015), Schulich School of Law, and the research support of the Marine Environmental Observation Prediction and Response Network (MEOPAR), based at Dalhousie University and funded by the Government of Canada's Network of Centres of Excellence Program. The support of the Social Sciences and Humanities Research Council of Canada is also gratefully acknowledged.
- 1 The number of peer-reviewed papers grew from 18 in 2004 to 356 in 2012. Secretariat of the Convention on Biological Diversity, *An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*, UNEP/CBD/SBSTTA/18/INF/6 (19 June 2014), p. 16.
- 2 For a detailed review, see *ibid.*, pp. 16–18.
- 3 See section 'General Assembly resolutions and processes' below.
- 4 Target 14.3 as agreed to by the Open Working Group on Sustainable Development Goals in its *Outcome Document* (2014), submitted for consideration by the 68th session of the UN General Assembly. Available <<http://www.sustainabledevelopment.un.org>> (accessed 7 September 2014).
- 5 M. Simons and T. Stephens, 'Ocean Acidification: Addressing the other CO₂ Problem', *Asia Pacific Journal of Environmental Law* 12, 2009, 1–17.
- 6 A. Proelss and M. Krivickaite, 'Marine Biodiversity and Climate Change', *Carbon & Climate Law Review* 4, 2009, 437–445; Y. Downing, 'Ocean Acidification and Protection under International Law from Negative Effects: A Burning Issue Amongst a Sea of Regimes?', *Cambridge Journal of International and Comparative Law* 2, 2013, 242–273.

- 7 G. Galland, E. Harrould-Kolieb and D. Herr, 'The ocean and climate change policy', *Climate Policy* 12, 2012, 764–771.
- 8 United Nations Convention on the Law of the Sea, 10 December 1982, 1933 U.N.T.S. 3.
- 9 June 5, 1992, 1760 U.N.T.S. 79.
- 10 For a review of regional efforts to study and address ocean acidification, including for polar regions with the Arctic Council's 2013 *Arctic Ocean Acidification Assessment* being central, see T. Stephens, 'Ocean Acidification, in R. Rayfuse (ed.), *Research Handbook on International Marine Environmental Law*, Cheltenham, UK; Edward Elgar, forthcoming 2015, chapter 26 and D. Herr, K. Isensee and C. Turley, 'Ocean acidification: Overview of the international policy landscape and activities on ocean acidification', *White Paper*, Gland Switzerland: IUCN, 2013.
- 11 For reviews of how climate change and ocean acidification might be addressed at the national and sub-national levels in the United States, see R.P. Kelly and M.R. Caldwell, 'Ten Ways States Can Combat Ocean Acidification (And Why They Should)', *Harvard Environmental Law Review* 37 (2013), 57–103 and J. Thaler and P. Lyons, 'The Seas Are Changing: It's Time to Use Ocean-based Renewable Energy, the Public Trust Doctrine, and a Green Thumb to Protect Seas from Our Changing Climate', *Ocean and Coastal Law Journal* 19, 2014, 72–132.
- 12 J. Gupta, K. Van Der Leeuw and H. De Moel, 'Climate change: a 'global' problem requiring 'glocal' action', *Environmental Science* 4(3), 2007, 139–148; C. Turley and J.P. Gattuso, 'Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications', *Current Opinion in Environmental Sustainability* 4, 2012, 278–286; and R.P. Kelly et al., 'Mitigating Local Causes of Acidification within Existing Laws', *Science* 332, 2011, 1036–1037.
- 13 C. Le Quéré et al., 'Global carbon budget 2013', *Earth Systems Science Data* 6, 2014, 235–263. The authors estimate that between 1750 and 2012 385±20 Gt C were emitted due to fossil fuel burning and cement production and 205±70 Gt C due to land use changes.
- 14 Figure 20.1.
- 15 D.P. van Vuuren et al., 'The representative concentration pathways: an overview', *Climatic Change* 109, 2011, 5–31. See representative concentration pathways 8.5.
- 16 Le Quéré et al., 'Global carbon budget 2013', 235–263.
- 17 C.L. Sabine and T. Tanhua, 'Estimation of anthropogenic CO₂ inventories in the ocean', *Annual Review of Marine Science*, 2, 2010, 175–98.
- 18 R.E. Zeebe and Wolf-Gladrow, *CO₂ in Seawater: Equilibrium, Kinetics, Isotopes*, Amsterdam: Elsevier Oceanography Series, Vol. 65, 2001, pp. 346.
- 19 J.R. Reinfelder, 'Carbon Concentrating Mechanisms in Eukaryotic Marine Phytoplankton', *Annual Review of Marine Science* 3, 2011, 291–315.
- 20 IPCC Third Assessment Report 'The scientific basis', 2001. Chapter 3, p. 188.
- 21 J.-P. Gattuso and H. Lavigne, 'Technical Note: Approaches and software tools to investigate the impact of ocean acidification', *Biogeosciences* 6, 2009, 2121–2133.
- 22 J.C. Orr et al., 'Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms', *Nature* 437(7059), 2005, 681–686.; L. Bopp et al., 'Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models', *Biogeosciences* 10, doi:10.5194/bg-10-6225-2013, 2013, 6225–6245.
- 23 Gattuso and Lavigne, 'Technical Note', 2121–2133.
- 24 R. Revelle and H.E. Suess, 'Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO₂ during the past decades', *Tellus* 9, 1957, 18–27.
- 25 Figure 1.
- 26 N.R. Bates, 'Interannual variability of the oceanic CO₂ sink in the subtropical gyre of the North Atlantic Ocean over the last 2 decades', *Journal of Geophysical Research* 112, C09013, doi:10.1029/2006JC003759, 2007.
- 27 J.E. Dore et al., 'Physical and biogeochemical modulation of ocean acidification in the central North Pacific', *Proceedings of the National Academy of Sciences* 106(30), 2009, 12235–12240.
- 28 Figures 20.1 and 20.2.
- 29 Dore et al., 'Physical and biogeochemical modulation of ocean acidification in the central North Pacific' 12235–240; Bates, 'Interannual variability of the oceanic CO₂ sink in the subtropical gyre of the North Atlantic Ocean over the last 2 decades'.
- 30 J.T. Wootton, C.A. Pfister and J.D. Forester, 'Dynamical patterns and ecological impacts of changing ocean pH in a high-resolution multiyear dataset', *Proceedings of the National Academy of Sciences*

- 105, 2008, 18848–853; J.T. Wootton and C.A. Pfister, 'Carbon system measurements and potential climatic drivers at a site of rapidly declining ocean pH', *PLoS ONE* 7(12), e53396, doi:10.1371/journal.pone.0053396, 2012.
- 31 Figure 20.2.
- 32 Figure 20.2.
- 33 W.-J. Cai et al., 'Acidification of subsurface coastal waters enhanced by eutrophication', *Nature Geoscience* 4, 2011, 766–770.
- 34 Orr et al., 'Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms', 6225–245; M. Steinacher et al., 'Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model', *Biogeosciences* 6, 2009, 515–533.
- 35 S.C. Doney et al., 'Ocean Acidification: The Other CO₂ Problem', *Annual Review of Marine Science* 1, 2009, 169–192.
- 36 M. Fine and D. Tchernov, 'Scleractinian coral species survive and recover from decalcification', *Science* 315, 2007, 1811.
- 37 F. Gazeau et al., 'Impact of elevated CO₂ on shellfish calcification', *Geophysical Research Letters* 34, L07603, doi: 10.1029/2006GL028554, 2007.
- 38 Y. Shirayama and H. Thornton, 'Effect of increased atmospheric CO₂ on shallow water marine benthos', *Journal of Geophysical Research* 110, C09S08, doi:10.1029/2004JC002618, 2005.
- 39 H. Kurihara and Y. Shirayama, 'Effects of increased atmospheric CO₂ on sea urchin early development', *Marine Ecology Progress Series* 274, 2004, 161–169.
- 40 V. Tunnicliffe et al., 'Survival of mussels in extremely acidic waters on a submarine volcano', *Nature Geoscience* 2, 2009, 344–348.
- 41 U. Riebesell et al., 'Reduced calcification of marine plankton in response to increased atmospheric CO₂', *Nature* 407, 2000, 364–367; J. Bijma, H.J. Spero, and D.W. Lea, 'Reassessing foraminiferal stable isotope geochemistry: impact of the oceanic carbonate system (experimental results)', in G. Fischer and G. Wefer (ed.) *Use of Proxies in Paleoceanography: Examples from the South Atlantic*, Springer-Verlag, 1999, pp. 489–512; J. Bijma, B. Hönisch and R.E. Zeebe, 'Impact of the ocean carbonate chemistry on living foraminiferal shell weight: comment on "Carbonate ion concentration in glacial-age deep waters of the Caribbean Sea" by W.S. Broecker and E. Clark', *Geochemistry, Geophysics, Geosystems* 3(11), 2002, 1064.
- 42 M.D. Iglesias-Rodríguez et al., 'Phytoplankton calcification in a high CO₂ world', *Science* 320, 2008, 336–339.
- 43 U. Riebesell and P.D. Tortell, 'Effects of ocean acidification on pelagic organisms and ecosystems', in J.-P. Gattuso and L. Hansson (eds.) *Ocean Acidification*, Oxford: Oxford University Press, 2011, pp. 99–121.
- 44 Ibid.
- 45 I. Zondervan, B. Rost and U. Riebesell, 'Effect of CO₂ concentration on the PIC/POC ratio in the coccolithophore *Emiliania huxleyi* grown under light-limiting conditions and different daylengths', *Journal of Experimental Marine Biology and Ecology* 272, 2002, 55–70.
- 46 S. Palacios and R.C. Zimmerman, 'Response of eelgrass *Zostera marina* to CO₂ enrichment: possible impacts of climate change and potential for remediation of coastal habitats', *Marine Ecology Progress Series* 344, 2007, 1–13.
- 47 S.F. Perry and K.M. Gilmour, 'Acid-base balance and CO₂ excretion in fish: Unanswered questions and emerging models', *Respiratory Physiology & Neurology* 154, 2006, 199–215.
- 48 F. Melzner et al., 'Physiological basis for high CO₂ tolerance in marine ectothermic animals: pre-adaptation through lifestyle and ontogeny?', *Biogeoscience* 6, 2009, 2313–2331.
- 49 F. Melzner et al., 'Swimming performance in Atlantic Cod (*Gadus morhua*) following long-term (4–12 months) acclimation to elevated sea water pCO₂', *Aquatic Toxicology* 92, 2009, 30–37.
- 50 H.-O. Pörtner et al., 'Effects of ocean acidification on nektonic organisms', in J.-P. Gattuso and L. Hansson (eds.) *Ocean Acidification*, Oxford: Oxford University Press, 2011, pp. 154–175.
- 51 P.L. Munday, N.E. Crawley and G.E. Nilsson, 'Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes', *Marine Ecology Progress Series* 388, 2009, 235–242.
- 52 J.L. Armstrong et al., 'Distribution, size, and interannual, seasonal and diel? food habits of northern Gulf of Alaska juvenile pink salmon, *Oncorhynchus gorbuscha*', *Deep-Sea Research Part II: Topical Studies in Oceanography* 52, 2005, 247–265.

- 53 Riebesell and Tortell, 'Effects of ocean acidification on pelagic organisms and ecosystems', pp. 99–121.
- 54 J.T. Wootton, C.A. Pfister and J.D. Forester, 'Dynamical patterns and ecological impacts of changing ocean pH in a high-resolution multiyear dataset', *Proceedings of the National Academy of Sciences* 105, 2008, 18848–18853.
- 55 J.P. Kennett and L.D. Stott, 'Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene', *Nature* 353, 1991, 225–229.
- 56 R.E. Zeebe, 'History of Seawater Carbonate Chemistry, Atmospheric CO₂, and Ocean Acidification', *Annual Review of Earth and Planetary Sciences* 40, 2012, 141–165.
- 57 *Ibid.*
- 58 Herr, Isensee and Turley, 'Ocean acidification: Overview', p. 8.
- 59 C. Gonzalez, 'An Alternative Approach for Addressing CO₂-Driven Ocean Acidification' *Sustainable Development Law & Policy* 12, 2011, 45, 69.
- 60 D. Bialek and J. Ariel, 'Ocean Acidification: International Legal Avenues under the UN Convention on the Law of the Sea' in M.B. Gerrard and G.E. Vannier (eds.) *Threatened Island Nations: Legal Implications of Rising Seas and a Changing Climate*, Cambridge: Cambridge University Press, 2013, pp. 473–529.
- 61 D.R. Rothwell and T. Stephens, *The International Law of the Sea*, Oxford and Portland, Oregon: Hart Publishing, 2010, pp. 439–460.
- 62 ITLOS, Rules of the Tribunal, Art. 138. The provision states that the Tribunal may give an advisory opinion on a legal question if an international agreement related to the purpose of the Convention specifically provides for the submission to the Tribunal of a request for such an opinion.
- 63 *Responsibilities and obligations of States sponsoring persons and entities with respect to activities in the Area, Advisory Opinion*, 1 February 2011, ITLOS Reports 2011, p. 10. Case No. 17, available <<http://www/itlos.org>> (accessed 4 September 2014).
- 64 Bialek and Ariel, 'Ocean Acidification', pp. 510–516; M. Burkett, 'Legal Rights and Remedies', in M.B. Gerrard and K. Fisher Kuh (eds.) *The Law of Adaptation to Climate Change: U.S. and International Aspects*, Chicago: American Bar Association, 2012, pp. 815–846.
- 65 Bialek and Ariel, 'Ocean Acidification', pp. 524–527.
- 66 Simons and Stephens, 'Addressing the other CO₂ Problem', pp. 1–19.
- 67 UNFCCC, Art. 1(3).
- 68 Simons and Stephens, 'Addressing the other CO₂ Problem', p. 7.
- 69 On the difficulty of interpretation with both scientific and normative considerations, see Intergovernmental Panel on Climate Change (IPCC) Working Group III, *Climate Change 2014: Mitigation of Climate Change* (2014), chapter 1, p. 18, available <<http://www.ipcc.ch>> (accessed 12 September 2014).
- 70 UNFCCC, Art. 2.
- 71 R. Baird, M. Simons and T. Stephens, 'Ocean Acidification: A Litmus Test for International Law', *Carbon and Climate Law Review* 3 (2009) 459–471.
- 72 Article 3(1) of the Protocol establishes an overall commitment to reduce GHG emissions by at least 5 per cent below 1990 levels in the commitment period 2008–2012, while Annex B of the Protocol sets out quantified emission limitation or reduction commitments for individual countries.
- 73 T. Stephens, 'Warming Waters and Souring Seas: Climate Change and Ocean Acidification', in D.R. Rothwell, K.N. Scott, A.G. Oude-Elferink and T. Stephens (eds.) *The Oxford Handbook of the Law of the Sea*, Oxford: Oxford University Press, forthcoming 2015, chapter 34.
- 74 IPCC Working Group III *Mitigation of Climate Change*, chapter 13, p. 34.
- 75 UNFCCC, 'Status of Ratification of the Kyoto Protocol', available <<http://unfccc.int>> (accessed 5 September 2014).
- 76 IPCC Working Group I, 'Summary for Policymakers', in T.F. Stoker et al. (eds.) *Climate Change 2013: The Physical Science Basis*, Cambridge: Cambridge University Press, 2013, p. 11.
- 77 *Ibid.* p. 12.
- 78 IPCC Working Group II, 'Summary for Policymakers', in C.B. Field et al. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, Cambridge: Cambridge University Press, 2014, p. 17.
- 79 *Ibid.*, p. 30.
- 80 IPCC Working Group III, *Mitigation of Climate Change*, p. 13.
- 81 E.R. Harrould-Kolieb and D. Herr, 'Ocean acidification and climate change: synergies and challenges of addressing both under the UNFCCC', *Climate Policy* 12, 2012, 378–389.
- 82 Galland, Harrould-Kolieb and Herr, 'The ocean and climate change policy', pp. 764–771.

- 83 The Cancun Agreements: Outcome of the Work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention, Decision 1/CP.16 (2010).
- 84 Decision 1/CP.17, Establishment of an Ad Hoc Working Group on the Durban Platform for Enhanced Action (2011).
- 85 Galland, Harrould-Kolieb and Herr, 'Ocean and climate change policy', p. 766.
- 86 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and other Matter, 7 November 1996, 36 I.L.M. 1 (1997).
- 87 IMO, *MARPOL Consolidated Edition 2011*, London: IMO, 2011.
- 88 UNEP (OCA)/LBA/IG.2/7 (5 December 1995).
- 89 D.L. VanderZwaag and A. Daniel, 'International Law and Ocean Dumping: Steering a Precautionary Course Aboard the 1996 Protocol, but Still an Unfinished Voyage', in A. Chircop, T.L. McDorman and S.J. Rolston (eds.) *The Future of Ocean Regime Building: Essays in Tribute to Douglas M. Johnston*, Leiden: Martinus Nijhoff, 2009, 515–550; A. Sielen, 'The New International Rules on Ocean Dumping: Promise and Performance', *Georgetown International Environmental Law Review* 21, 2009, 295–336.
- 90 Amendments, adopted in November 2006, include sub-seabed sequestration of CO₂ as one of the permitted disposals allowed under Annex 1 to the Protocol. IMO, 'New international rules allow storage of CO₂ under the seabed' (2007), <<http://www.imo.org>> accessed 4 September 2014.
- 91 Annex 2 of the Protocol sets out detailed waste assessment requirements that must be weighed before ocean dumping permits may be granted and this includes consideration of waste management options and assessment of potential environmental effects.
- 92 2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-Seabed Geological Formations, LC 34/15, annex 8, 2 November 2012.
- 93 Under Annex 1 of the Protocol only seabed sequestration is allowed.
- 94 For example, fertilizing the ocean with iron facilitates the uptake of CO₂ which may increase ocean acidity. D.L. VanderZwaag, 'Ocean Dumping and Fertilization in the Antarctic: Tangled Legal Currents, Sea of Challenges', in P.A. Berkman, M.A. Lang, D.W.H. Walton and O.R. Young (eds.) *Science-Diplomacy: Antarctica, Science, and the Governance of International Spaces*, Washington DC: Smithsonian Institution Scholarly Press, 2011, pp. 245–252.
- 95 IMO, *Report of the Thirty-fifth Consultative Meeting and the Eighth Meeting of Contracting Parties*, LC 35/15 Annex 4, 21 October 2013. For a review of the amendments see P. Verlaan, 'New Regulation of Marine Geo-engineering and Ocean Fertilization', *The International Journal of Marine and Coastal Law* 28, 2013, 729–736.
- 96 Paragraph 1.3 of a new Annex 4 to the Protocol. *Ibid.*
- 97 For example, key considerations include whether the proposed activity is subject to scientific peer review and whether there is any financial and/or economic gain arising directly from the experiment or its outcomes. *Ibid.*, Annex 5, para. 8.
- 98 *Ibid.*, Article 6bis.
- 99 IMO, *Third IMO GHG Study 2014*, MEPC 67/INF.3 (25 July 2014), p. 13.
- 100 *Ibid.*, pp. 17–18.
- 101 Marine Environment Protection Committee (MEPC), *Report of the Marine Environment Protection Committee on Its Sixty-Second Session*, MEPC 62/24/ Add. 1, (26 July 2011) Annex 19.
- 102 *Ibid.*, Regulation 21.
- 103 *Ibid.*, Regulation 22.
- 104 D.L. VanderZwaag, 'The IMO and Arctic Marine Environmental Protection: Tangled Currents, Sea of Challenges' in O.R. Young, J.D. Kim and Y.H. Kim (eds.) *The Arctic in World Affairs: A North Pacific Dialogue on Arctic Marine Issues, 2012 North Pacific Arctic Conference Proceedings*, Seoul, Korea: Korea Maritime Institute and Honolulu, Hawaii at East West Center, 2012, pp. 99–128, pp. 113–114.
- 105 MEPC, *Report of the Marine Environment Protection Committee on Its Sixty-Fifth Session*, MEPC 65/22 (24 May 2013), para. 5.1.
- 106 GPA, para. 19 and 31.
- 107 UNEP, *Report of the third session of the Intergovernmental Review Meeting on the Implementation of the Global Programme of Action for the Protection of the Marine Environment from land-based Activities*, UNEP/GPA/16R.3/6 (26 January 2012), Annex, Manila Declaration, para. 5.
- 108 GPA, 'Global Wastewater Initiative', available <<http://www.gpa.unep.org/index.php/global-wastewater-initiative>> (accessed 11 September 2014 and GPA, 'Global Partnership on Nutrient

- Management', available <<http://www.gpa.unep.org/index.php/global-partnership-on-nutrient-management>> (accessed 11 September 2014).
- 109 D.L.VanderZwaag and A. Powers, 'The Protection of the Marine Environment from Land-Based Pollution and Activities: Gauging the Tides of Global and Regional Governance', *The International Journal of Marine and Coastal Law* 23, 2008, 423–452, 439–440.
- 110 *Ibid.*, 438.
- 111 For a further review of the Convention's roles, see Herr, Isensee and Turley, 'Ocean Acidification: Overview', pp. 9–10.
- 112 Secretariat of the CBD, *Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*, CBD Technical Services No. 46, Montreal, 2009.
- 113 Secretariat of the CBD, *An Undated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*, CBD Technical Series No. 75, Montreal 2014.
- 114 COP 10 decision X/2, 'Strategic Plan for Biodiversity 2011–2020' (2010).
- 115 *Ibid.*, Annex, para. 13.
- 116 *Ibid.*
- 117 *Ibid.*
- 118 COP 10 decision X/33, 'Biodiversity and Climate Change' (2010), para. 8(A).
- 119 Secretariat of the CBD, *Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters*, CBD Technical Series No. 66, Montreal, 2010.
- 120 CBD Secretariat, *Interim Update of Information on the Potential Impacts of Climate Geoengineering on Biodiversity and the Regulatory Framework Relevant to the Convention on Biological Diversity*, UNEP/CBD/SBSTTA/18/INF5 (22 May 2014).
- 121 COP decision IX/16 'Biodiversity and Climate Change', (2008) part C, para. 4.
- 122 COP 11 decision XI/20 'Climate – related geoengineering', (2012) para. 8.
- 123 *Ibid.*, para. 4.
- 124 A/RES/68/70, 'Oceans and the law of the sea' (adopted on 9 December 2013), para. 153.
- 125 *Ibid.*, para. 156.
- 126 A/RES/68/71, 'Sustainable fisheries including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and related Instruments' (adopted on 9 December 2013).
- 127 *Ibid.*, para. 5.
- 128 *Ibid.*, para. 157.
- 129 UNGA, *Report on the Work of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea at its fourteenth meeting*, A/68/159 (17 July 2013).
- 130 *Ibid.*, para. 15.
- 131 *Ibid.*
- 132 *Ibid.*, para. 16.
- 133 *Ibid.*
- 134 A/RES/66/288, 'The future we want' (adopted on 27 July 2012), para. 166.
- 135 Open Working Group on Sustainable Development Goals, *Outcome Document* (2014), goal # 14, available <<http://www.sustainabledevelopment.un.org>> (accessed 7 September 2014).
- 136 *Ibid.*, target 14.3.
- 137 See González, 'An Alternative Approach for Addressing CO₂-Driven Ocean Acidification' (suggesting an ocean acidification instrument under the UN Convention on the Law of the Sea) and R.E. Kim, 'Is a New Multilateral Agreement on Ocean Acidification Necessary?', *Review of European Community & International Environmental Law* 21, 2012, 243–258.
- 138 Simons and Stephens, 'Addressing the other CO₂ Problem', p. 19.
- 139 Stephens, 'Ocean Acidification.'
- 140 Harould-Kolieb and Kerr, 'Ocean acidification and climate change', p. 383; Stephens, 'Warming Waters and Souring Seas.'
- 141 For a suggestion to establish an ocean acidification target based on the global mean saturation state of aragonite, a form of calcium carbonate that becomes more soluble as the acidity of seawater rises, see J. Rockström et al. 'A safe operating space for humanity', *Nature* 46, 24 September 2009, 472–475. A saturation state of 2.75 is proposed compared to a current status of 2.90 and a pre-industrial value of 3.44. *Ibid.*, p. 473.

- 142 D.E.J. Currie and K. Wowk, 'Climate Change and CO₂ in the Oceans and Global Oceans Governance', *Carbon & Climate Law Review* 4, 2009, 387–404, 403.
- 143 C. Nellemann et al. (eds.), *Blue Carbon: A Rapid Response Assessment*, UNEP, GRID-Arendal, 2009, p. 8.
- 144 Stephens, 'Warming Waters and Souring Seas.'
- 145 COP 10 decision X/29 (2010) on marine and coastal diversity already raised serious concerns over increasing ocean acidification (para. 64) and called on Parties to incorporate emerging knowledge into national biodiversity strategies and action plans and into national and local marine / coastal management plans (para. 67).
- 146 R. Kundis Craig, 'Marine Biodiversity, Climate Change, and Governance of the Oceans', *Diversity* 4, 2012, 224–238 and IGBP, IOC, SCOR, *Ocean Acidification Summary for Policymakers – Third Symposium on the Oceans in a High-CO₂ World*, Stockholm, Sweden: International Geosphere-Biosphere Programme, 2013.
- 147 For arguments in favour of a new global agreement, see D. Hassan, *Protecting the Marine Environment from Land-Based Sources of Pollution: Towards Effective International Cooperation*, Burlington, VT, Ashgate Publishing Company, 2006.
- 148 For example, buffering the global ocean with limestone looms as a possibility, although the huge amounts required represent a major constraint. See, *20 Facts about Ocean Acidification* (November 2013), available <<http://www.whoi.edu/filesaver.do?id=165564&pt=2tp=150429>> (accessed 11 September 2014).
- 149 On the difficulties RFMOs have faced in managing fisheries in a sustainable manner even without the complications of climate change and ocean acidification, see D.A. Russell and D.L. VanderZwaag, *Recasting Transboundary Fisheries Management Arrangements in Light of Sustainability Principles: Canadian and International Perspectives*, Leiden, Martinus Nijhoff, 2010.
- 150 T. Stephens and D.L. VanderZwaag, 'Polar oceans governance: shifting seascapes, hazy horizons', in T. Stephens and D.L. VanderZwaag (eds.), *Polar Oceans Governance in an Era of Environmental Change*, Cheltenham, UK; Edward Elgar, 2014, pp. 1–17.
- 151 For a review of the numerous adaptation implications of climate change and ocean acidification in the United States, see P. Parenteau, "Species and Ecosystem Impacts", in Gerrard and Fisher Kuh, *The Law of Adaptation*, pp. 307–349.