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Future biological and ecosystem impacts of ocean acidification and their socioeconomic-policy implications

Carol Turley¹ and Jean-Pierre Gattuso^{2,3}

Anthropogenic carbon dioxide (CO₂) emissions to the atmosphere and subsequent uptake by the ocean are changing seawater chemistry, a process known as ocean acidification. Research indicates that as ocean acidification continues, reflecting increasing CO₂ emissions, it is likely that although some species will be tolerant it will impact many marine organisms and processes, including composition of communities and food webs. Whilst there may be local actions to limit acidification from local sources the root cause of ocean acidification, CO₂ emissions, is a global issue requiring global action through United Nations bodies.

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Introduction

The acidity of the surface ocean has been remarkably stable for the 800 000 years until the 18th century: ocean pH (the total scale is used throughout this paper) varied between 8.2 and 8.3 depending on the glacial–interglacial cycles [1^{*}]. Beginning at the industrial revolution, human activities (combustion of fossil fuel emissions, production of cement and changes in land use) have released increasing amounts of carbon dioxide (CO₂) in the atmosphere. Of the 10 Pg C released in 2010 [2^{*}], only half remained in the atmosphere thanks to two efficient sinks: the land biosphere (2.6 Pg C) and the oceans (2.4 Pg C). As a result, average ocean pH has already decreased to 8.1 and could reach 7.7–7.9 in 2100, depending on the CO₂ emissions considered (see [Box 1](#) for the chemical reactions involved and [Figure 1](#) for future projections).

Furthermore, the volume of water corrosive to calcium carbonate will greatly increase, especially in the polar regions, the deep-sea and some coastal areas (also see [Box 1](#)). There is a high degree of certainty on these changes in the seawater chemistry ([Table 1](#)) [3^{**}].

The situation is not as straightforward for the effects of ocean acidification on biological, ecological and biogeochemical processes. The number of studies looking at these impacts has increased considerably since 2003 [4^{**}]. This review provides a brief summary of the current understanding of the impacts that ongoing ocean acidification might bring to marine systems this century, how this might impact society and the policy options currently available to take action on ocean acidification.

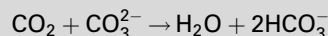
The impacts of ocean acidification on marine systems

Whilst there is a high degree of certainty on future changes in the seawater chemistry based on CO₂ emissions to the atmosphere ([Figure 1](#)) [3^{**}] the impacts of these changes on the marine species physiology and development, foodwebs, biodiversity, biogeochemistry and ecosystems are less clear ([Table 1](#)) [3^{**}]. Over the past 8 years a number of different approaches have been undertaken to reduce this uncertainty. Perturbation experiments were performed in the laboratory and in field mesocosms and observations were made in regions naturally acidified, such as CO₂ vents [e.g. [5^{*},6^{**}]]. Beyond traditional narrative reviews [e.g. [7]], several approaches have been used to synthesize the information: meta-analyses [8,9,10^{**}] and expert surveys [3^{**}].

The precipitation and dissolution of calcium carbonate (CaCO₃) are the processes (see [Box 1](#)) which have been investigated most in the context of ocean acidification, both in the fossil record and in perturbation experiments. Several events in the geological past bear the fingerprint of ocean acidification, global warming, and expanding hypoxia (low oxygen, usually less than 2 mg/L dissolved oxygen) and anoxia (an absence of dissolved oxygen), which led to devastating changes in the abundance, diversity, and evolution of calcifying organisms [11,12^{*}]. Despite the fact that some perturbation experiments reported no effect or a positive effect of ocean acidification on the rate of calcification of a few organisms, meta-analyses reveal an overall significant negative effect [8,10^{**}]. The mean effect is negative and significant on corals, negative but non-significant on calcifying algae, coccolithophores, and molluscs, positive and significant on

Box 1 What is ocean acidification and what are the processes potentially affected?

Anthropogenic ocean acidification refers to changes in the seawater chemistry that are caused by human activities. Once dissolved in seawater, CO₂ is a weak acid that generates a number of changes in seawater chemistry [44,45**]. It increases the concentrations of bicarbonate ions (HCO₃⁻) and dissolved inorganic carbon, and lowers the pH, the concentration of carbonate ions ([CO₃²⁻]):



The concentration of protons ([H⁺]), which is proportional to the ratio [HCO₃⁻]/[CO₃²⁻], increases and pH decreases, hence the increase in acidity. The expression 'ocean acidification' refers to the decrease in pH, but does not imply that the pH of surface-ocean waters will become acidic (below 7) any time soon.

Changes in pH can have a wide range of effects because it plays a key role in many physiological processes such as ion transport, enzyme activity, and protein function [4**]. Other direct effects of ocean acidification could occur when one or several reactant(s) in a physiological process is a carbon species, such as photosynthesis and the precipitation and dissolution of calcium carbonate [4**].

The decrease in carbonate ions increases the rate of dissolution of CaCO₃ minerals in the ocean. The saturation state (Ω) is the degree of CaCO₃ saturation in seawater:

$$\Omega = [\text{Ca}^{2+}][\text{CO}_3^{2-}]/K_{\text{sp}}$$

where [Ca²⁺] and [CO₃²⁻] are the *in situ* calcium and carbonate ion concentrations, respectively, and K_{sp} is the solubility product for CaCO₃ (concentrations when at equilibrium, neither dissolving nor forming). Values of K_{sp} depend on the crystalline form of CaCO₃; they also vary with temperature and pressure, with CaCO₃ being unusual in that it is more soluble in cold water than warm water [28].

Environments with high saturation states are potentially more suitable for calcifying organisms (plants and animals that produce shells, plates and skeletons of CaCO₃), since high Ω values reduce the energy required for calcification, involving active intracellular regulation of Ca²⁺, H⁺ and inorganic carbon, and also help maintain the integrity of mineral CaCO₃ after its formation. Currently, Ω is >1 for the vast majority of the surface ocean, that is, seawater is supersaturated with respect to CaCO₃ [28].

However, most of the deep ocean is unsaturated, Ω < 1, due to changes in temperature, pressure and the accumulation of biologically produced CO₂; it is therefore corrosive to unprotected CaCO₃ structures, and calcareous (micro-)fossils are absent from sediments below the level at which the rate of CaCO₃ dissolution exceeds the rate of its supply [28,30**].

The three main mineral forms of CaCO₃, in order of least to most soluble, are calcite, aragonite and magnesium-calcite; their differences in K_{sp} result in each form having different saturation state profiles and saturation horizons, with the aragonite saturation horizon (ASH) shallower than the calcite saturation horizon (CSH). Ω varies with latitude (mostly due to temperature effects), with lowest surface Ω_{aragonite} in the Arctic and Southern Oceans currently mostly below 1.5, although with large spatial and seasonal variability. The ASH depth in the North Pacific is ≤600 m but in the North Atlantic can be >2000 m, this difference is due to global circulation patterns affecting CO₂ values at depth. Increasing atmospheric CO₂ will cause Ω to decrease, and the ASH and CSH levels to move towards the sea surface, as has already occurred in the past 200 years. Most of the Arctic is projected to be undersaturated with respect to aragonite and calcite by around 2030 and 2080 respectively, with equivalent values for the Southern Ocean being around 2060 and 2100 [28,46].

crustaceans, and positive but non-significant on echinoderms [10**]. Some organisms may therefore have the capacity to upregulate their metabolism and calcification to compensate for lower availability of carbonate ions (CO₃²⁻; Box 1), key building blocks for calcifiers. However, this would have energetic costs that would divert energy from other essential processes, and thus would not be sustainable in the long term [see, e.g. [13*]]. Full or partial compensation may be possible in certain organisms if the additional energy demand required to calcify under elevated CO₂ can be supplied as food, nutrients, and/or light (for those organisms dependent on photosynthesis). Calcifying organisms are more susceptible overall to ocean acidification than non-calcifying organisms also for processes other than calcification [10**].

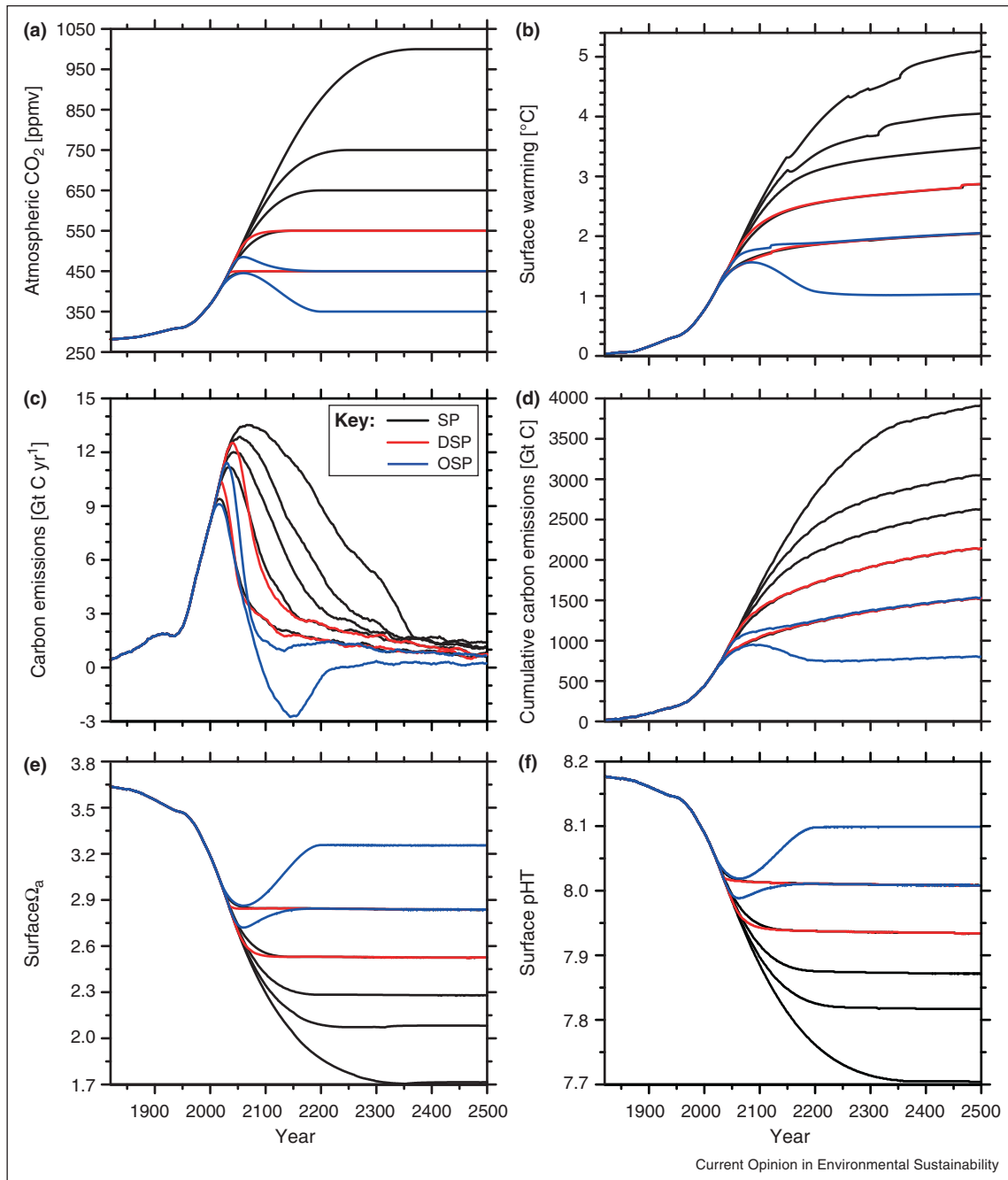
Marine primary producers encompass phylogenetically very diverse groups, from prokaryotes to angiosperms, differing widely in their photosynthetic apparatus and use of dissolved inorganic carbon for photosynthesis. The species that possess effective carbon concentrating mechanisms are likely to be less sensitive to increased CO₂

levels than those lacking it. Stimulating effects of elevated CO₂ on photosynthesis and carbon fixation have been observed in a variety of phytoplankton taxa, including diatoms, coccolithophores, cyanobacteria, and dinoflagellates [14]. Modest increases of 10–30% in photosynthetic carbon fixation in response to elevated CO₂ were also observed in bioassay studies with oceanic plankton assemblages and in mesocosm experiments with coastal plankton communities. Seagrasses are also likely to benefit from the future increases in CO₂ [e.g. [15]].

These differences are likely to alter competitive relationships among phytoplankton groups and result in shifts in species composition as the oceanic CO₂ concentration continues to rise. The level of confidence of this stimulating effect is medium and its magnitude must be better constrained, especially at community level under *in situ* conditions (Table 1).

Nitrogen fixation, the production of ammonium readily available to the biota from atmospheric nitrogen gas, is a key process because primary production is limited by the

Figure 1



Atmospheric CO₂ stabilization pathways (A), used in the Bern2.5CC model to estimate future global mean surface air temperature change (B); annual and cumulative carbon emissions (C) and (D); global mean surface ocean saturation for aragonite (E), see Box 1 for explanation of aragonite saturation; and global mean surface pH (F). Dotted lines labelled OSP (Overshoot Stabilization Profile) show pathways requiring negative CO₂ emissions (i.e. CDR geoengineering) to achieve atmospheric CO₂ stabilization at 350 and 450 ppm; dashed lines labelled DSP (Delayed Stabilization Profile) show delayed approach to emissions reductions to achieve stabilization at 450 and 550 ppm.

From Joos *et al.* [46]; reproduced by permission of Oxford University Press. p. 286, Fig. 14.10 from 'Ocean Acidification' edited by Gattuso and Hansson [4**].

availability of nitrogen in large areas of the global ocean. It is primarily carried out by a small group of cyanobacteria and is stimulated by elevated CO₂ in a two key species but information is still very scarce. The level of confi-

dence (Table 1) that ocean acidification will stimulate nitrogen fixation is medium because, considering the small number of species tested so far and the potential phylogenetic and metabolic diversity of nitrogen fixers,

Table 1

Summary of the knowns and unknown. The recommendations of Mastrandrea *et al.* [47] were used for the levels of evidence ('limited', 'medium', or 'robust'), agreement among the expert coauthors ('low', 'medium', or 'high') and confidence ('very low', 'low', 'medium', 'high', and 'very high'). Question marks indicate that the effect is unknown. From Gattuso *et al.* [3]**

Statement	Level of evidence	Level of agreement	Level of confidence
Chemical aspects			
Ocean acidification occurred in the past	Robust	High	Very high
Ocean acidification is in progress	Robust	High	Very high
Ocean acidification will continue at a rate never encountered in the past 55 Myr	Robust	High	Very high
Future ocean acidification depends on emission pathways	Robust	High	Very high
The legacy of historical fossil fuel emissions on ocean acidification will be felt for centuries	Robust	High	Very high
Biological and biogeochemical responses			
Ocean acidification will adversely affect calcification	Medium	High	High
Ocean acidification will stimulate primary production	Medium	High	High
Ocean acidification will stimulate nitrogen fixation	Medium	High	Medium
Some species or strains are tolerant	Robust	High	Very high
Some taxonomic groups will be able to adapt	Low	Medium	?
Ocean acidification will change the composition of communities	Robust	Medium	High
Ocean acidification will impact food webs and higher trophic levels	Limited	High	?
Ocean acidification will have biogeochemical consequences at the global scale	Medium	High	Medium
Policy and socio-economic aspects			
There will be socio-economic consequences	Limited	Medium	?
An ocean acidification threshold that must not be exceeded can be defined	Limited	High	?

and the little information available on the synergistic effects of CO₂, light, and iron, it is too early to assess the global significance of a stimulating effect of rising CO₂ on oceanic nitrogen fixation.

Until recently, it was widely thought that ocean acidification would have little effect on high-level organisms because they have efficient mechanisms to maintain their internal pH relatively constant [16•]. It was shown recently, however, that the larval stages of some species may not be able to maintain their acid-base balance. For example, exposure of cod larvae to elevated CO₂ (1800–4200 μatm; pCO₂ is 1200–2300 μatm in their natural habitat) results in severe to lethal tissue damage in many internal organs [17•]. The avoidance of acidosis also interferes with neurotransmitter function in fish [18], thereby affecting behaviour and causing dramatic shifts in sensory preferences such attraction to odours they normally avoid, including ones from predators [19].

There remain numerous unknowns on the impact of ocean acidification on marine organisms and ecosystems [3**]. Among the key ones are the interactive effects of ocean acidification and other stressors such as warming and deoxygenation (oxygen loss). These three stressors share the same origin, anthropogenic CO₂ emissions, and therefore occur concurrently. They could have synergistic effects, amplifying or dampening their impact. For example, it is well established that ocean acidification decreases the thermal window of some marine organisms, thereby decreasing their metabolic performance [16•]. It is critical to better understand the response of marine

organisms and ecosystems to multiple stressors to inform policy makers.

The risk of ocean acidification to society and avenues for international policy

What the ocean provides society

The ocean provides enormous, often forgotten, diverse resources. It provides ~96% of the living space on Earth, providing diverse habitats for 80% of the planet's organisms. It produces ~50% of the oxygen (O₂) in the atmosphere, fixes ~50% of global primary production and ~80% of world trade is carried across it. The ocean is also an important recycler of waste and an enormous store of carbon, substantially greater than on land or in the atmosphere. It plays a key role in the global carbon cycle, especially climate change through the regulation of the amount of CO₂ in the atmosphere. Currently, the ocean has taken up ~30% of anthropogenic CO₂ emissions and ~90% of the heat generated by warming of the Earth system over recent decades [20].

Many of these invaluable roles are literally priceless and are performed by a series of biogeochemical processes regulated by marine organisms as well as the important physical processes of ocean mixing, tides, currents, and air–sea exchange.

The ocean also provides food and livelihoods for millions and its coastal ecosystems, such as coral reefs, mangroves, salt marshes, seagrass and kelp beds, protects shorelines and also stores carbon [21]. The substantial alteration in basic ocean chemistry associated with future ocean

acidification is likely to have wide implications for life in the ocean with socio-economic consequences, including food security [22*].

Tropical coral reef ecosystems, for example, provide food, income, and coastal protection for around 500 million people throughout tropical coastal areas of the world [23]. They have an estimated annual value of US\$30 billion with the protective function of reefs to shorelines valued at US\$9 billion per annum [24]. The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated to be US\$500 to 870 billion depending on the level of CO₂ emissions scenarios [25].

Polar, subpolar, and deep-sea ecosystems and shallow productive seas including those associated with upwelling of CO₂-rich seawater are also at risk as ocean acidification will be most severe there and will start occurring within a decade or two [Box 1, [26–29,30**]]. As many of these ‘hot spots’ support considerable fin and shell fisheries there may be a risk to food security [31,32*]. In 2004 global fish production was valued at US\$150 billion per annum [33], providing 16% of annual protein consumption for around 3 billion people worldwide [34], the primary protein source for about 1 billion people and employment for 38 million people, 95% of whom live in developing countries. Ocean acidification is not the only climate related threat to the oceans, with ocean warming and oxygen loss also of great concern. World fisheries already face multiple challenges [35] but some are now further subject to the combined global scale stressors of ocean acidification, warming and deoxygenation [22*,32*,36,37*].

Avenues available for international policy action on ocean acidification

Opportunities to raise awareness and highlight options on ocean acidification are via the United Nations (UN) (Figure 2). These include the United Nations Framework Convention for Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), the Intergovernmental Oceanographic Commission (IOC), the United Nations Environment Programme (UNEP) Governing Council, and the UN Commission on Sustainable Development. The UN General Assembly is charged with undertaking an annual review and evaluation of the implementation of the UN Convention on the Law of the Sea and other developments relating to ocean affairs and legislation, including in relation to the ocean and climate change.

Ocean acidification was first recognized by the Intergovernmental Panel on Climate Change (IPCC) in its 4th Assessment Report as a risk caused by increasing CO₂ emissions [38] and its assessment in this area will be even more substantial in its 5th Assessment Report due in 2013–2014. CBD has also considered the issue with respect to its impacts on marine biodiversity and will

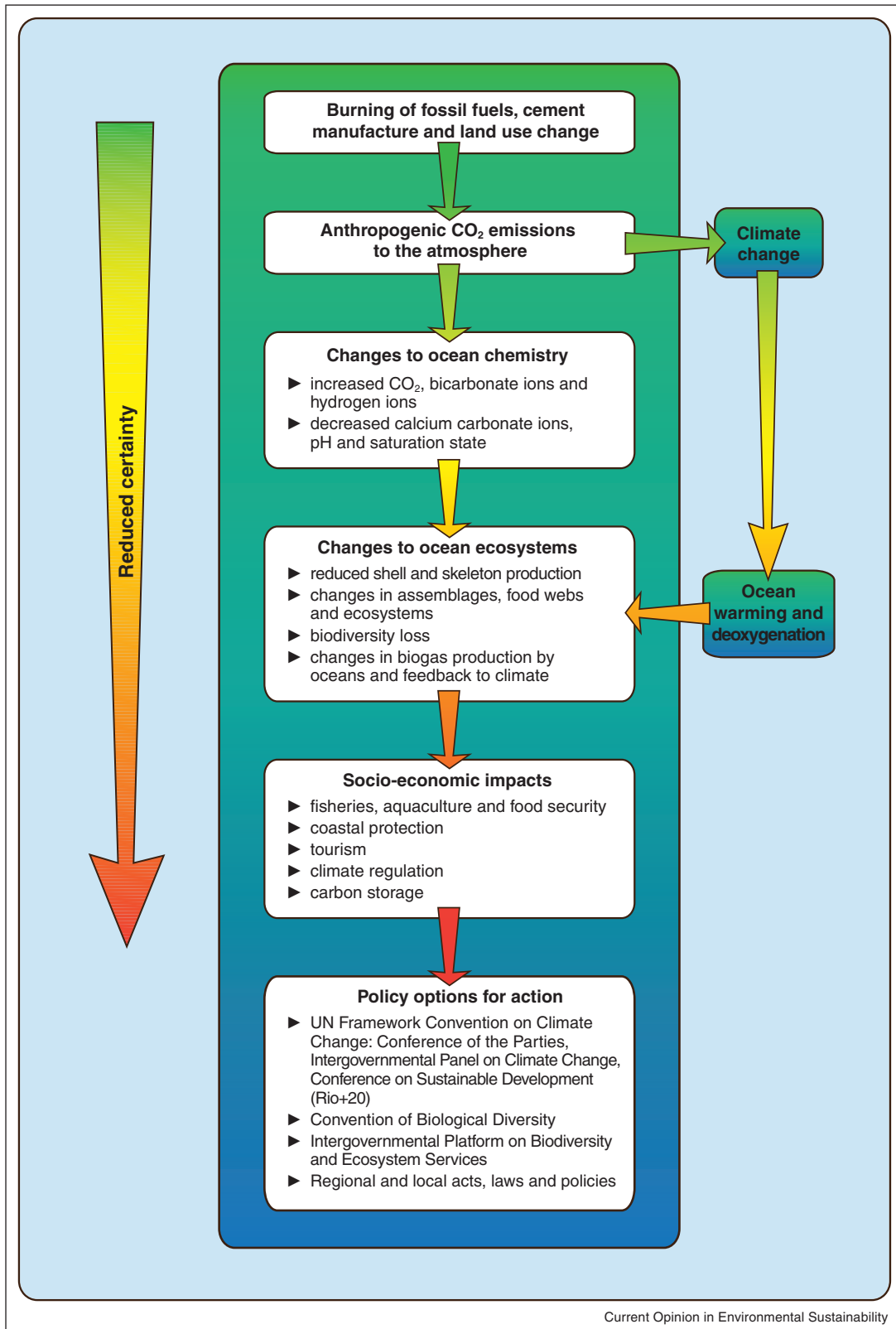
report in 2012. The Commission on Sustainable Development will consider the issues of oceans and seas and Small Island Developing States in 2014 and 2015. A further UN aim is to carry out an assessment for ecosystem services through the creation of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). IPBES, like the IPCC, will not recommend specific policies, rather it will conduct periodic biodiversity and ecosystem services assessments on global, regional and subregional scales.

Ocean acidification is relevant to all these intergovernmental bodies and they each offer opportunities to inform policy-makers of this threat to the largest ecosystem on the planet. However, as the only policy option for mitigating ocean acidification on a global scale is to reduce fossil fuel CO₂ emissions to the atmosphere it is important that policy-makers consider impacts of CO₂ on the ocean as well as on climate change. It is for this reason that the UNFCCC Conference of the Parties (COP) climate change discussions currently offer the best chance for the mitigation of ocean acidification particularly as ocean acidification and climate change together give a compelling rationale for CO₂ emissions reduction. However, the ocean has not figured on the agenda of the UNFCCC until very recently despite substantial activities by numerous stakeholders in bringing this to the attention of policy-makers [summarized in [39]]. At the UNFCCC COP17, Durban in late 2011, there were a number of side-events on the ocean, one of which was a collaboration between a number of national and international research programmes and organizations which brought their concerns of the risk of ocean acidification, warming and oxygen loss to the delegates and other participants in the policy document “Hot, Sour and Breathless: Ocean Under Stress” [40].

The UN Conference on Sustainable Development (Rio+20) in 20–22 June 2012 in Rio de Janeiro, Brazil offers a further opportunity. There are encouraging signals of consideration of ocean acidification by its inclusion in the zero-draft declaration for Rio+20 released on 10 January 2012 by the UN and the organization of a number of side events on ocean acidification during the lead up to and at the Rio summit.

IOC/UNESCO and other UN agencies launched “A Blueprint for Ocean and Coastal Sustainability” [41] a proposal to implement a number of urgent actions to mitigate and adapt to ocean acidification which have since been tabled for consideration by UN delegates negotiating the outcome document at the Rio+20. One of these actions is to launch a global inter-disciplinary program on ocean acidification risk assessment, which would assist countries in formulating mitigation responses and to identify regions most at risk of impact from ocean acidification as it progresses. In addition, a call has been made

Figure 2



Showing the direct cause of ocean acidification, the impacts on ocean chemistry, ecosystems and socio-economics and the interaction with climate change through ocean warming and oxygen loss. Note the decreasing certainty from chemistry, through life and social science. The policy options for mitigating ocean acidification are also shown.

to the UNFCCC negotiations to include atmospheric CO₂ impacts on ocean chemistry and ecosystems in their deliberations.

The Global Ocean Forum has also been active at recent UNFCCC COPs and the lead up to Rio+20, holding Oceans Day side-events at each conference. The forum gives a platform to scientists, policy makers and other stakeholders from a wide range of concerned organizations, coastal nations and islands. The forum submitted “Oceans at Rio+20: How well are we doing on the major ocean commitments from the 1992 Earth Summit and the 2002 World Summit on sustainable development?” [42] to the compilation documents for Rio+20 and contains specific recommendations on achieving a strong oceans outcome.

Avenues available for regional and local policy action on ocean acidification

There are a number of local drivers that may contribute to the acidification of coastal waters [43]. Some of these drivers, such as fertilizers and emissions of nitrogen oxides and sulfur oxides, are weak acids that directly lower the pH of the coastal ocean. Others such as erosion and point-source nutrient pollution act indirectly by increasing the productivity in coastal waters, which ultimately results in higher CO₂ concentrations as phytoplankton are broken down by bacteria.

There are multiple options for regional, state, and local jurisdictions to begin to address these local drivers. Various national Clean Water Acts or equivalents, local land use, coastal zone management and local coastal development plans, laws and policies (Figure 2) can direct agencies to ensure that discharge and runoff of pollutants, urban sprawl, coastal erosion and water quality are monitored, limited and consistent with sustainable function of aquatic ecosystems. Similarly, Clean Air Acts and equivalents can be enforced to reduce the amount of short-lived atmospheric pollutants that are deposited in coastal waters close to the site of emission. However, upwelled waters are one of the few local drivers that do require action on a larger scale. It should be noted however, that regional and local actions are not an alternative to the implementation of a global solution; rather it may buy time until this occurs.

Conclusions

Ocean acidification is happening now at a speed not experienced by planet Earth for ~60 million years, is caused by anthropogenic CO₂ emissions and will continue as emissions continue. If unabated it will change the chemistry of the oceans for 10 000 years and many marine organisms, ecosystem and biogeochemical processes are likely to be affected (Figure 2). At the same time the ocean is warming and losing oxygen. Research capacity needs to grow globally, including in vulnerable countries,

in order to understand the impacts of these three connected stressors on ecosystems and feedbacks to climate change. Research will increasingly need to follow a multidisciplinary approach across the physical, life, chemical, Earth, social and economic sciences. Such research and capacity building will need international coordination to be most effective.

These studies will need to be policy relevant, with a rapid exchange of knowledge between researchers and policy-makers. It is also essential that the role of the ocean in sustaining life on Earth and the threat it is under from ocean acidification, warming and deoxygenation are urgently recognized in the UN process to prevent irreversible change in ocean physics, chemistry and biology and the goods and services it provides all inhabitants of planet Earth.

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