Planktonic foraminifera pdf

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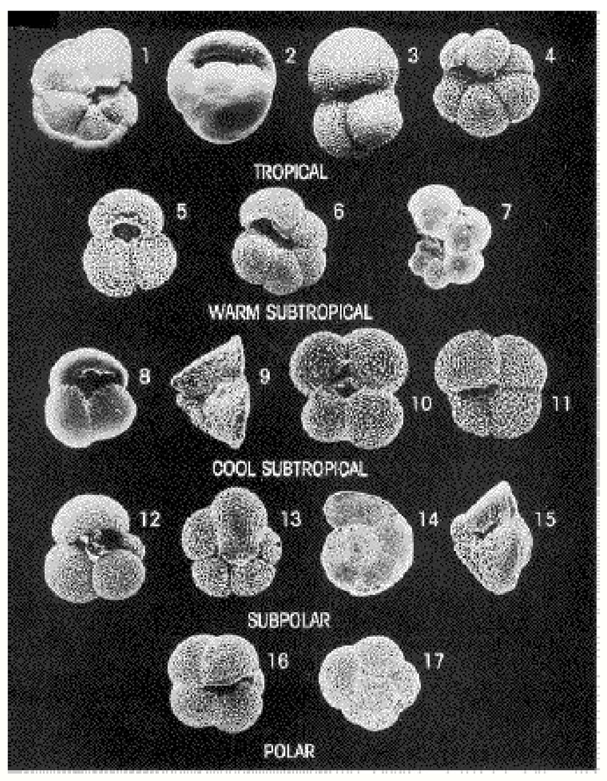

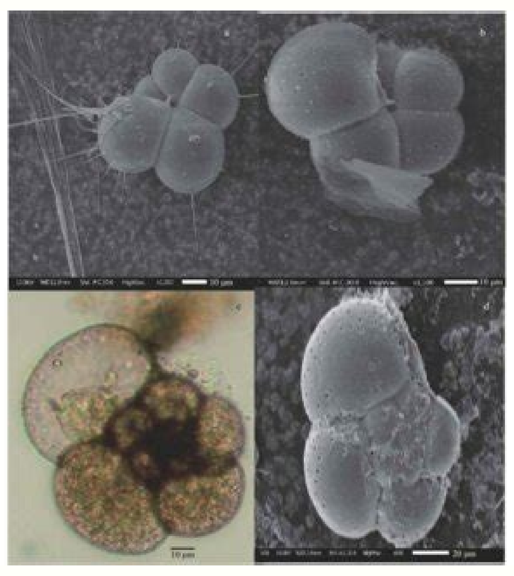

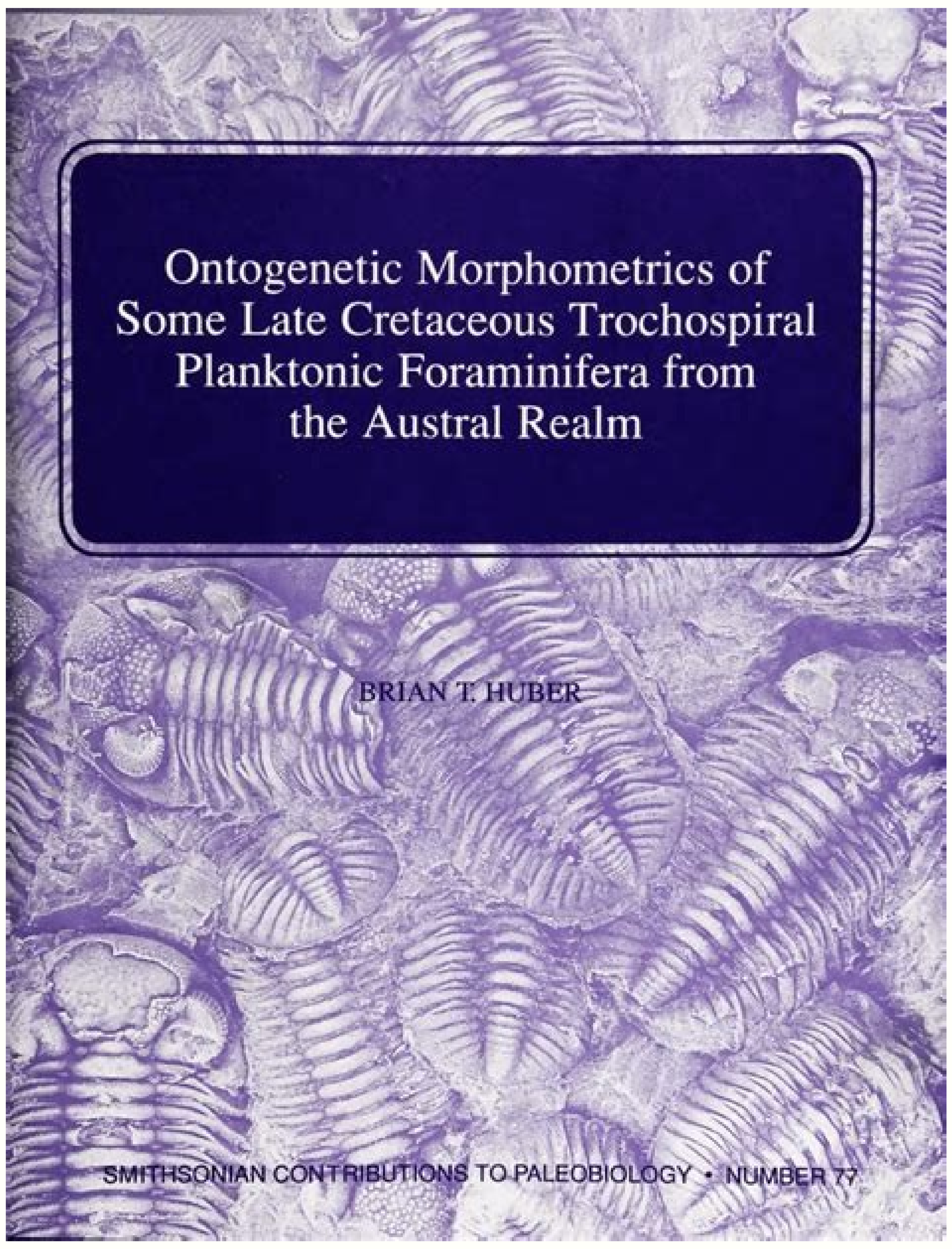

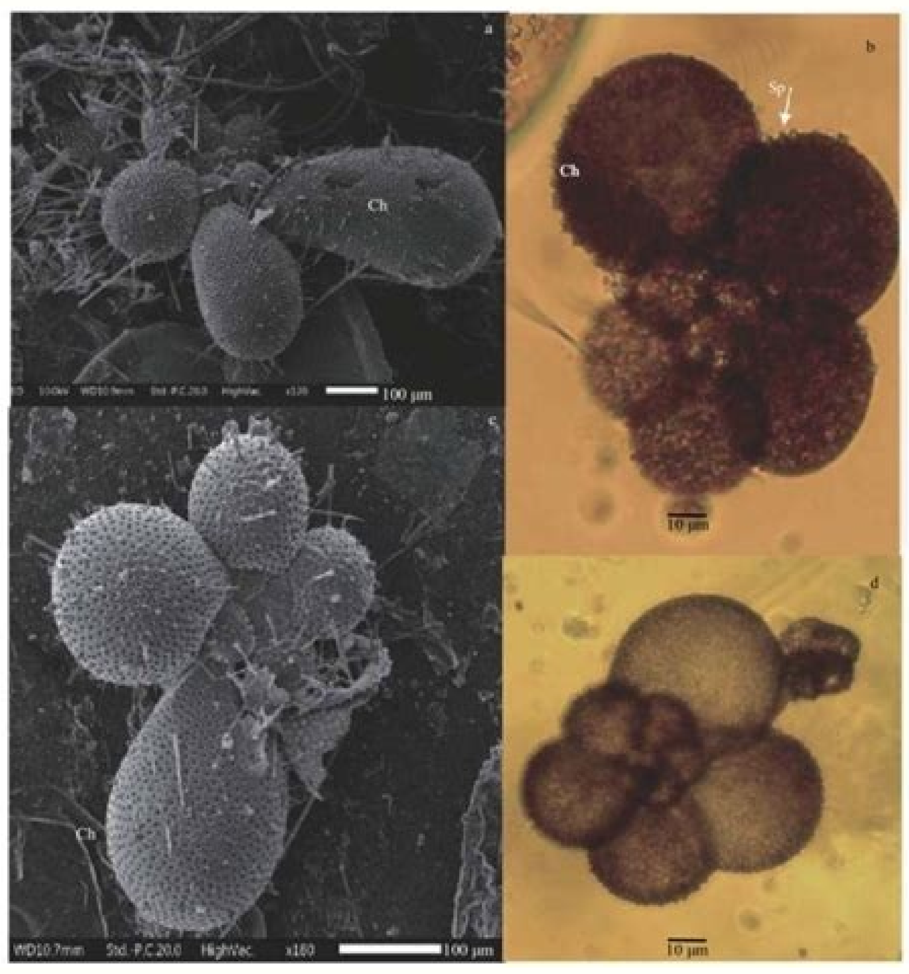

 Page 59 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 4 Effects of Ocean Acidification on Marine Ecosystems Ecosystems are defined by a complex suite of interactions among organisms and also between organisms and their physical environment; a disturbance to any part may lead to cascading effects throughout the system. Ocean acidification has the potential to disturb marine ecosystems through a variety of pathways. Differential sensitivities will result in ecological winners and losers, as well as temporal and spatial shifts in interactions between species (e.g., shifts in the timing of zooplankton development relative to food availability; Pörtner and Farell, 2008), leading to changes in predator-prey, competitive, and other food web interactions. There may also be changes in habitat quality and effects on other ecological processes such as nutrient cycling. Many of the physiological changes from ocean acidification are expected to affect key functional groups –species or groups of organisms that play a disproportionately important role in ecosystems. These include expected effects on phytoplankton, which serve as the base of marine food webs, and on ecosystem engineers, which create or modify habitat (e.g., corals, oysters, and seagrasses). Such changes may lead to wholesale shifts in the composition, structure, and function of these systems and ultimately affect the goods and services provided to society (see Chapter 5). While it is important to understand how ocean acidification will change ocean chemistry and the physiology of marine organisms, as reviewed in chapters 2 and 3, what is equally critical is to understand how these effects may scale up to populations, communities, and entire marine ecosystems. Such changes are likely to be difficult to predict, particularly where more than one species or Page 60 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × functional group will be affected by ocean acidification. In general, higher trophic levels, including most finfish, will likely be sensitive to ocean acidification through changes in the quantity or composition of the food available, although there may be direct physiological effects on some fish species at high pCO_2 (see Chapter 3). The difficulty in predicting ecosystem change is compounded by other simultaneous stressors occurring in the oceans now (e.g., pollution, overfishing, and nutrient eutrophication) and in association with climate change. For example, it is projected that surface waters will become warmer, the upper water column will become more stratified, and the supply of nutrients from deep waters and from the atmosphere will change as a result of climate change. Whether these changes, in combination with the effects of ocean acidification, will have synergistic, antagonistic, or additive effects is unknown, but multiple stressors are likely to affect marine ecosystems at multiple scales. Several previous reports have identified marine ecosystems that are most likely to be at risk from ocean acidification (e.g., Raven et al., 2005; Fabry et al., 2008b). This chapter begins by describing what is known and not known about ecosystem effects of ocean acidification for five vulnerable ecosystems: tropical coral reef, open ocean plankton, coastal, deep sea, and high latitude ecosystems. This is not an exhaustive review of all possible ecological effects, but is instead an overview of the ecosystems that have been identified as most vulnerable to acidification. The chapter looks at examples of high-CO_2 periods in the geologic past for possible information on the ecological response to current acidification. It also examines general principles regarding biodiversity, possible thresholds in ecological systems, and managing ecosystems for change. 4.1 TROPICAL CORAL REEFS Some of the most convincing evidence that ocean acidification will affect marine ecosystems comes from warm water coral reefs. Coral reef ecosystems are defined by the large, wave-resistant calcium carbonate structures, or reefs, that are built by reef calcifiers. The structures they build provide food and shelter for a wide variety of marine organisms (Figure 4.1). There are hundreds of reef-building species; the predominant calcifiers on coral reefs are zooxanthellate corals, which produce hard aragonite skeletons, and calcifying macroalgae,1 which produce high-Mg calcite and aragonite. These groups produce the bulk of the calcium carbonate that make up the reef structures, which in turn support the high biodiversity of coral reef ecosystems. Recent analyses illustrate that 1 There are two types of calcifying macroalgae that are important to reef formation in tropical coral reef ecosystems: crustose coralline red algae (coralline algae) from the family Corallinaceae and calcifying green algae (genus Halimeda) Page 61 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × FIGURE 4.1 Some examples of organisms affected by ocean acidification. Red coral (photo courtesy of Jim Barry, MBARI); Sea urchin (photo courtesy of Jim Barry, MBARI); Foramaniferan (photo courtesy of Howard Spero, University of California, Davis); Coral and sea urchins (photo courtesy of Susan Roberts, NRC); Sea grass (photo courtesy of Richard Zimmerman, Old Dominion University); Tropical coral reef and fish (photo courtesy of Susan Roberts, NRC); Coccolithophores (photo courtesy of Mitch Covington, BugWare Inc.); Deep-sea Gorgonian bubblegum coral (photo courtesy of MBARI); and Pteropod (photo courtesy of Russ Hopkroft, University of Alaska, Fairbanks). Page 62 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × reef ecosystems have served as "cradles of evolution" throughout Earth's biological history (Kiessling et al., 2010); that is, more marine species have originated in reef ecosystems than in any other. As a consequence, a decrease in the resilience of coral reefs or loss of coral reef habitat may adversely affect marine biodiversity in the short and long term. These ecosystems also provide a variety of services to humans, including recreation, fisheries, and coastal protection. Ocean acidification poses a variety of risks to coral reef ecosystems. A critical vulnerability is the potential for ocean acidification to affect the reef structure itself. Acidification may decrease reef growth by reducing calcification rates, reproduction, and recruitment. It may also increase the dissolution or erosion of existing reef structures. Finally, acidification may indirectly result in the mortality of reef-builders. The most obvious and best documented effect of ocean acidification is the depression of calcification rates, which will affect skeletal growth of the reef-building organisms. Decreased coral calcification rates are evident on the Great Barrier Reef, where records from massive corals show that calcification rates decreased by about 14% between 1990 and 2005 (De'ath et al., 2009), although the relative roles of increased temperature and ocean acidification could not be determined. Decreased skeletal growth in tropical reef-building corals and coralline algae has been well documented in high CO_2 conditions that result in ocean acidification (see Appendix C for a summary; see also reviews in Doney et al., 2009; Kleypas et al., 2006; Langdon and Atkinson, 2005). In stony corals, most studies indicate a 10-60% reduction in calcification rate for a doubling of preindustrial atmospheric CO_2 concentration. Differences among studies may reflect different species or experimental setups. Calcification rates in stony corals are affected by factors other than seawater carbonate chemistry, including light, nutrients, and particularly temperature. For example, studies on the effects of temperature show that calcification rates in corals peak near some optimal temperature (usually near the average summertime maximum), then decline at higher values (Clausen and Roth, 1975; Jokiel and Coles, 1977). As a result, increasing temperature from global climate change may initially offset the negative effect of acidification on calcification, but will eventually (and in some cases may already) work synergistically with acidification to decrease calcification. Calcification rates in tropical calcifying macroalgae may decrease even more strongly due to increasing CO_2. Several laboratory studies indicate that reef-building crustose coralline algae will calcify more slowly (e.g., 50% reduction; Reynaud et al., 2003; Anthony et al., 2008). Field studies seem to agree with these findings. In one study, coralline algae showed a higher calcification rate that correlated with the natural pH change from the photosynthetic drawdown of CO_2 when the algae grew in proximity to Page 63 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × seagrasses (Semesi et al., 2009b). By comparison, in a study of a temperate benthic community, the abundance of crustose coralline algae decreased rapidly with proximity to a shallow submarine CO_2 vent, suggesting that coralline algae in this system could not survive at low pH (< 7.7) (Hall-Spencer et al., 2008; Martin et al., 2008). Similar to tropical reef corals, calcification rates of reef-building crustose coralline algae are affected more strongly by ocean acidification at elevated temperature (Anthony et al., 2008). There is little evidence that reef-building corals can adapt to decreased calcification under future ocean conditions. Growth of reef structures relies not only on the calcification of adult corals, but also on successful recruitment of reef organisms, which is determined by gamete production, fertilization rates, larval development and settlement, and post-settlement growth.

Theoretically, acidification could affect recruitment success but there is limited evidence of this and no consistent trends. In one study, ocean acidification did not affect either gamete production in one coral species or larval recruitment in another species (Jokiel et al., 2008). Another study also showed no effect on larval settlement, but did show significant decrease in post-settlement growth (> 50%; Albright et al., 2008). In general, there are few data on any of these aspects for reef-building species, making extrapolation to ecosystem effects difficult. Recruitment success may also be decreased through indirect effects on substrate. The presence of microbial biofilms or crustose coralline algae is important in coral recruitment success (Heyward and Negri, 1999; Negri et al., 2001; Webster et al., 2004; Williams et al., 2008). Reduction in the surface cover of newly recruited reef-building crustose coralline algae under future CO_2 conditions (Kuffner et al., 2008) could therefore affect recruitment of coral larvae. While ocean acidification does not appear to cause direct mortality in corals, several studies suggest that the survival of both major calcifying groups will be indirectly affected by ocean acidification, mainly because of its effects on skeletal growth. Several reviews (Kleypas et al., 2006; Kleypas and Langdon, 2006) list multiple ways that reduced skeletal growth may impact coral survival rates, including the ability to withstand hydrodynamic and erosional forces, age of sexual maturity, rate of fragmentation, skeletal light-gathering properties (Enriquez, 2004), and recruitment success. In addition, there is some evidence that ocean acidification has contributed to bleaching, which can ultimately lead to coral mortality (Anthony et al., 2008).2 Competition for space may also 2 Most reef-building zooxanthellate coral species depend on photosynthetic endosymbionts—zooxanthallae—to provide energy. Bleaching refers to the loss of these zooxanthallae due to stress, resulting in a loss of color. While corals can regain their endosymbionts and recover from bleaching events, extended bleaching can also result in coral death (Glynn, 1996). Page 64 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × lead to loss of corals as they become more vulnerable to displacement by other organisms, including those that may benefit from ocean acidification, such as non-calcifying macroalgae. Macroalgae compete with corals by taking up suitable surface area, blocking sunlight, and through the sweeping action of algae in waves and currents that can abrade corals or prevent larval settlement on hard substrates. Conditions that favor macroalgal growth (e.g., high nutrients, elimination of herbivores) and/or slow coral growth (e.g., bleaching, disease, ocean acidification) lower the resilience of coral-dominated systems to disturbance and thus increase the likelihood of a regime shift. The density of several invasive macroalgae increased near natural CO_2 vents in the Mediterranean (Hall-Spencer et al., 2008), but little is known about the response of this or other groups that compete directly with corals for space. In some cases, an increase in non-calcifying primary producers on reefs (seagrasses and macroalgae) may counter the effects of ocean acidification, by drawing down CO_2 directly from the water column during photosynthesis (Palacios and Zimmerman, 2007; Semesi et al., 2009a). While many of these hypothesized effects seem logical, most have not yet been explicitly tested. The overall calcium carbonate budget and reef-building capacity of a reef depend not only on carbonate production rates, but also on dissolution rates and carbonate removal rates due to erosion and sediment transport. Acidification has been shown to increase dissolution rates of coral reefs; in one extreme example, the skeletons of corals placed in seawater with pH of 7.3–7.6 dissolved completely (Fine and Tchernov, 2007). The combination of decreased calcification rates with increased dissolution rates will shift coral reefs from net production/accretion to net dissolution/erosion at some CO_2 threshold (Leclercq et al., 2000; Andersson et al., 2007; Yates and Halley, 2006; Silverman et al., 2009). Several studies indicate that crustose coralline algae will experience accelerated dissolution rates as ocean acidification proceeds and will experience net dissolution as pCO_2 levels approach 700 ppm, expected by the end of the century (Jokiel et al., 2008; Kuffner et al., 2008; Martin and Gattuso, 2009). This directly threatens the existence of this key functional group on coral reefs and in coralline algal-based ecosystems. One projection of reef building estimates that, due to reduced coral cover from bleaching and due to ocean acidification, all coral reefs will be in a state of net dissolution once atmospheric CO_2 concentration reaches 560 ppm (Silverman et al., 2009). The rapid loss of reef structure in the Galápagos following a severe bleaching event provides some evidence for this; the erosion rates of the Galápagos reefs were the highest recorded on any reef, which appears to be due in part to the naturally high CO_2 waters (400-700 ppm) in this region (Manzello et al., 2008). The combination of potential effects of acidification on the ecosystem engineers of coral reefs—decreased calcification, increased dissolution, Page 65 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × changes in recruitment and survivorship—will ultimately lead to changes in the reef structure. The function of calcium carbonate in reef ecosystems is widely recognized as important, but few studies have addressed what will happen as reef-building slows down. The dramatic loss of coral cover on many reefs has already resulted in “reef flattening” (a reduction in architectural complexity) that reduces the diversity of habitats and thus lowers the ability of the reef to support biodiversity (Alvarez-Filip et al., 2009). Ocean acidification is likely to exacerbate reef flattening. Loss of architectural complexity on reefs has been associated with changes in fish communities (Gratwicke and Speight, 2005; Pratchett et al., 2008), including the overall decline on Caribbean reefs (Paddack et al., 2009). Densities of important commercial species such as lobster have been linked to habitat complexity (Wynne and Côté, 2007), as well as recruitment of larval fish (Feary et al., 2007; Graham et al., 2007). Loss of structural complexity may also affect the recruitment of corals and other invertebrates, but this has not been examined. Finally, if reef structures suffer net erosion, then they lose their breakwater role, leaving coastlines and quiet-water habitats like mangroves more exposed to storm waves. The projected changes on reef structure are thus likely to have major consequences throughout tropical coral reef ecosystems. 4.2 OPEN OCEAN PLANKTONIC ECOSYSTEMS The open ocean is not a uniform ecosystem; the components vary greatly by location. In open ocean systems, microscopic photosynthetic organisms—phytoplankton—which grow in the sunlit surface waters, serve as the base of diverse and complex food webs including zooplankton and larger free-swimming animals such as fish and marine mammals. Phytoplankton and bacteria also play an important role in cycling nutrients in open ocean ecosystems. Ocean acidification has been found to affect several key processes in open ocean planktonic ecosystems, including calcification, photosynthesis, and nitrogen-fixation. These changes affect the community composition of phytoplankton and zooplankton at the base of open ocean pelagic food webs; effects on these key functional groups may have cascading effects throughout the ecosystem. There may also be changes to the cycles of organic and inorganic carbon, oxygen, nutrients, and trace elements in the sea. In addition, the exchange of carbon dioxide and other climatically relevant trace gas species with the atmosphere may be modified, thus inducing feedbacks on the climate system. The effect of acidification on calcification rates has been a major area of study because a number of the phytoplankton and zooplankton near the base of the food chain are calcifiers. Of the three major groups of Page 66 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × planktonic calcifiers—coccolithophores, foraminifera, and pteropods (a planktonic snail) (Figure 4.1)—coccolithophores have been studied most widely. While experiments using monospecific cultures of Coccolithophores revealed considerable species- and strain-specific differences in CO_2 responses (Rost et al., 2008; Langer et al., 2009), a consistent trend of decreasing calcification with increasing CO_2 has been seen in shipboard and mesocosm studies using mixed assemblages (Ridgwell et al., 2009). Studies on planktonic foraminifera and pteropods also indicate reduced calcification and increased calcium carbonate dissolution at elevated CO_2 (see Fabry et al., 2008b for review; Moy et al., 2009; see also section 4.5). It is presently unknown to what extent these responses affect the competitive abilities, susceptibility to viral attack, predator-prey interactions, or the fitness of calcifying plankton. Reduced rates of calcification, along with the shoaling of the saturation horizons for calcium carbonate minerals to shallower depths will also affect the marine calcium carbonate cycle (see Chapter 2) through decreased $CaCO_3$ burial in sediments, additional carbon storage from increased production of extracellular organic carbon by phytoplankton (see below), and by the accelerated bacterial decomposition of organic matter at higher temperature. Ocean acidification can also affect processes related to photosynthetic activity, including increased rates of phytoplankton growth, primary production, and release of extracellular organic matter, as well as shifts in cellular carbon to nitrogen to phosphorus (C:N:P) ratios (e.g., Riebesell et al., 2007; Bellerby et al., 2007; Fu et al., 2007; Hutchins et al., 2009; see also Chapter 3). A shift in the ratio towards higher C:N and C:P at elevated pCO_2 was observed during a mesocosm study with a natural plankton community (Riebesell et al., 2007). Changes in the C:N and C:P ratios alter the nutritional value of phytoplankton and may adversely affect growth and reproduction of their consumers (e.g., as seen in copepods and daphnids; Sterner and Elser, 2002). A change in the composition of the biomass is one of the few mechanisms by which biology can alter ocean carbon storage (Boyd and Doney, 2003; Riebesell et al., 2009). If phytoplankton growing at high CO_2 produce and export biomass with a higher C:N ratio, it would make the ocean biological pump more efficient in exporting carbon to depth. In a mesocosm experiment, the net effect of this phenomenon was estimated to increase the carbon consumption by 27% in response to a doubling in present day CO_2 (Riebesell et al., 2007). The evidence from experiments on natural plankton communities is equivocal, with examples of both increasing and decreasing C:N ratios (Hutchins et al., 2009). In a model study, the hypothesized effect of enhanced organic carbon export due to elevated C:N ratio resulted in a moderate increase in oceanic CO_2 uptake (a cumulative value of 35 Pg C by 2100) and a fifty percent increase in Page 67 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × the extent of subsurface low-oxygen zones in the tropical ocean (Oschlies et al., 2008). In addition, increased production of extracellular organic matter under high CO_2 levels (Engel, 2002) may enhance the formation of particle aggregates (Engel et al., 2004; Schartau et al., 2008) and thereby increase the vertical flux of organic matter (Riebesell et al., 2007; Arrigo, 2007), which may also affect nutrient availability for phytoplankton in surface waters. Ocean acidification has the potential to alter the marine nitrogen cycle which controls much of primary production in the sea. Laboratory experiments with the nitrogen-fixing cyanobacterium Trichodesmium revealed an increase in both carbon and nitrogen fixation with increasing pCO_2 (Barcelos e Ramos et al., 2007; Hutchins et al., 2007; Levitan et al., 2007; Kranz et al., 2009). Since Trichodesmium is a dominant species in large parts of the nutrient-poor tropical and subtropical oceans, this response has the potential to increase the reservoir of bioavailable nitrogen in the surface layer of these areas. These areas of the ocean are predominantly nitrogen-limited; therefore, an increase in nitrogen fixation would provide additional new nitrogen in low-nutrient subtropical regions and would lead to increased primary production and carbon fixation. The actual increase in nitrogen fixation, however, could be limited by phosphorus or iron supplies. A strong positive relationship between nitrogen fixation and rising CO_2 has also been observed for cultured Crocosphaera, a nitrogen-fixing unicellular cyanobacterium, under iron-replete conditions but not under iron limited conditions (Fu et al., 2008), but another nitrogen-fixing cyanobacterium, Nodularia spumigena, showed the opposite response (i.e., reduced growth rate and nitrogen fixation rate at elevated CO_2; Czerny et al., 2009). These effects on calcification, photosynthesis, nitrogen fixation, and other processes will likely lead to shifts in the planktonic community as some species fare better than others under acidification. However, no consistent responses have been obtained in experiments concerning the effect of ocean acidification on plankton community composition. In one experiment with a phytoplankton community dominated by microflagellates, cryptomonads, and diatoms, only the diatom Skeletonema costatum responded to elevated CO_2 by increased growth rate (Kim et al., 2006). A similar shift in phytoplankton species composition from Phaeocystis to diatom dominance occurred in another shipboard incubation experiment (Tortell et al., 2002). In contrast, a remarkable resilience of the enclosed plankton communities to seawater acidification was observed in a series of mesocosm CO_2 enrichment experiments: no significant differences between CO_2 treatments were observed for phytoplankton composition and cell cycle, inorganic nutrient utilization and nutrient turnover, bacterial abundance and diversity, microzooplankton grazing and copepod feeding and egg production (Riebesell Page 68 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × et al., 2008). While shifts in planktonic community composition could theoretically affect higher trophic levels, no experimental results exist to confirm these predictions. Another important consideration is the possible interactive effects of climate change and acidification such as the warming of surface waters and reduced nutrient availability. Similarly, ocean microbes produce and destroy a number of trace gases that are important for atmospheric chemistry and climate besides CO_2 and O_2. For example, nitrous oxide (N_2O), a powerful greenhouse gas, is a by-product of both nitrification and denitrification and its marine production might thus be affected by acidification. Another important trace gas produced in the oceans is dimethylsulfide (DMS), which serves as a precursor for atmospheric sulfate aerosols that nucleate cloud droplets and cool surface temperatures. Mesocosm experiments at elevated CO_2 (Vogt et al., 2008; Wingenter et al., 2007; Hopkins et al., 2010) have shown both positive and negative responses in dissolved DMS responses with both small decreases. In this way, changes in the microbial community composition and activity triggered by ocean acidification may act as a feedback on climate change. 4.3 COASTAL ECOSYSTEMS Coastal ocean ecosystems include a variety of benthic habitat types, including seagrass beds, kelp forests, tidal wetlands, mangroves, and others. They represent some of the most productive marine ecosystems that support numerous finfish and shellfish fisheries, both managed and cultured. Humans rely on coastal ecosystems for commerce, recreation, protection from storm surges, and a suite of other services; however, there is also a great deal of anthropogenic impact on coastal habitats. This section does not attempt to review all of the possible impacts of acidification on the various types of coastal ecosystems. Rather it highlights some general concerns, particularly for important coastal species and functions such as commercially-important fishery species and ecosystem engineers. Ocean acidification may affect coastal ecosystems in a variety of ways. It can directly impact the growth and survival of coastal organisms, particularly in sensitive reproductive and early developmental stages. It can also affect growth and survival indirectly by altering food web dynamics and nutrient cycling. It is also likely to affect important coastal ecosystem engineers that create habitat. A major focus of recent studies has been on the potential effects of ocean acidification on the early life history of various species. For many coastal benthic calcifiers, including commercially-important species, reproduction and early development appear to be particularly sensitive to acidification (Kurihara, 2008). Reduced growth and calcification rates, and in Page 69 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × some cases even shell dissolution and mortality, have been reported for larval and juvenile stages in a number of bivalve species: the bay scallop Argopecten irradians (Talmage and Gobler, 2009), the hard clam Mercenaria mercenaria (exposed to sediments that were undersaturated with respect to aragonite; Green et al., 2004, 2009), the soft-shell clam Mya arenaria (Salisbury et al., 2008), the Mediterranean mussel Mytilus galloprovincialis (Kurihara et al., 2008a), the Sydney rock oyster Saccostrea glomerata (Watson et al., 2009), the Pacific oyster Crassostrea gigas (Kurihara et al., 2007), and the Eastern oyster Crassostrea virginica (Miller et al., 2009). Interestingly, Miller et al. (2009) did not see similar effects on the Suminoe oyster, Crassostrea ariakensis, indicating a species-specific response that could lead to shifts in community composition. Hence, these comparative studies did find that some species were more tolerant of high CO_2 conditions. Negative effects of acidification have also been seen in the early development of non-bivalve species such as the European lobster Homarus gammarus (Arnold et al., 2009), the Pacific shrimp Palaemon pacificus (Kurihara, 2008), and the sea urchin Echinometra mathaei (Kurihara and Shirayama, 2004). In contrast, juveniles of American lobster (H. gammarus) and the blue crab (Callinectes sapidus) showed elevated rates of calcification at very high pCO_2 levels (Ries et al., 2009). Many studies have also shown negative effects on adult growth and survivorship of these and other coastal benthic species (e.g., Gazeau et al., 2007; Kurihara et al., 2008b; Ries et al. 2009). There were mixed responses—increasing, decreasing, parabolic, and no change in calcification rates—to decreasing saturation state in the eighteen benthic coastal species studied by Ries et al. (2009). It is not known whether positive or negative changes in calcification in these organisms would affect their lifelong productivity, growth, and fitness. Impacts on many other species not yet studied are likely. Indirectly, acidification may affect the productivity and composition of some coastal ecosystems by affecting the key species at the base of coastal food webs. As noted previously, several calcifying planktonic species are sensitive to seawater pH and carbonate chemistry changes and can be important prey species in coastal ecosystems (e.g., pteropods may be important prey in salmon diets, Armstrong et al., 2008). In addition, the planktonic larvae of many species are also prey items and, as previously discussed, may be negatively affected by acidification. Therefore, coastal organisms that are not directly susceptible to the effects of acidification may indirectly be affected through trophic interactions. Many coastal habitats depend on ecosystem engineers to build and maintain structures that provide critical habitat for other organisms, including oyster reefs, kelp forests, and seagrass beds. Oysters have already been discussed as species that will likely be negatively affected Page 70 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × by acidification. On the other hand, research has shown increased growth of seagrass (Figure 4.1) with increased CO_2 (Zimmerman et al., 1997). It is probable that an increase in total seagrass area will lead to more favorable habitat and conditions for associated invertebrate and fish species (Guinotte and Fabry, 2009). Coastal ecosystems exhibit naturally high variability in pH and seawater chemistry due to biological activity, freshwater input, upwelling, atmospheric deposition, and other factors. They are also subject to a diversity of stresses caused by human activities, such as organic matter and nutrient inputs, pollution by toxic organic compounds and metals, acid rain, sea level rise and other climate change effects, and overfishing. The effects of ocean acidification on coastal ecosystems may be small relative to the effects of these natural and human-induced stresses. But in some instances, acidification may act synergistically with other factors (Figure 4.2). For example, coastal upwelling is a natural phenomenon that brings deep water to the surface; this water is often undersaturated with respect to calcium carbonate. However, further acidification of these upwelled waters by anthropogenic CO_2 uptake may be increasing the intensity and areal extent of these “corrosive” events (Feely et al., 2008). Increased temperature due to climate change is another stressor that is likely to interact with acidification; for example, temperature has been shown to act synergistically with acidification in the development of the Sydney rock oyster (Parker et al., 2009). Another likely interaction is that of increased nutrients and acidification. For example, in kelp forests, it is predicted that local nutrient pollution and increased CO_2 will enhance the growth of filamentous algae species while simultaneously decreasing calcifying macroalgae that serve as the understory of kelp forests, thus allowing for a shift from kelp forests to filamentous turf mats (Russell et al., 2009). Another example of a potential synergism is the interaction between acidification and low oxygen (i.e., hypoxic) or no oxygen (i.e., anoxic) “dead zones.” The decomposition of organic matter near the bottom in shallow coastal waters increases the ambient CO_2 concentration and decreases the oxygen concentration and pH. This natural phenomenon can be exacerbated by anthropogenic inputs of organic waste and algal nutrients, resulting in dead zones. But in regions that are only hypoxic, the low oxygen and the high CO_2 tend to act in concert to make respiration difficult for a number of aerobic organisms. It is possible that a further increase in CO_2 caused directly or indirectly by acidification could increase the intensity or spatial extent of the hypoxic and anoxic events. Examples of ecosystems where this could occur is along many highly productive coastal upwelling zones around the world, such as the eastern Pacific, the Arabian Sea, and along northern and southern west Africa. Page 71 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × FIGURE 4.2 Specific combinations of environmental factors affect animal performance in ways that can narrow the range of performance for any given factor. These windows of performance (modified from Pörtner and Farrell, 2008) for organisms can be measured along environmental gradients such as temperature. In the example illustrated in the graph, an organism may have a relatively broad temperature tolerance (green line, from low to high), but this tolerance may only be observed under oxygenated conditions and normal seawater pH. Both low oxygen (hypoxia) and lower pH/high CO_2 conditions could not only reduce the overall organismal performance, but also could narrow the temperature range under which this organism could survive. Hence, for some organisms, ocean acidification would restrict the habitable range of temperature and reduce the performance range (the metabolic scope which represents the maximium minus the minimum metabolic rate). There, as previously discussed, the natural cycle in acid-base chemistry resulting from seasonal upwelling is amplified by penetration of anthropogenic CO_2 into the upwelled water. The ambient flora and fauna, particularly benthic organisms, may well be affected by annual exposure to acidic and, in some cases, corrosive hypoxic water. Depending on the differential tolerances of organisms to changes imposed by acidification, there are likely to be shifts in community composition or productivity of the various ecosystems. However, existing Page 72 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × research in coastal ecosystems, as is the case with other ecosystems, has been focused on individual organisms, not on the population, community, or ecosystem levels. Consequently, it is unknown whether populations sensitive to changes in ocean chemistry will be able to adapt through behavioral or physiological changes. For example, populations with individuals possessing genetic variations that tolerate the expected changes in ocean chemistry may result in higher survival or reproductive success because of more-rapid-than-expected adaptation to the new conditions. It is not known whether coastal ecosystems that do not currently experience natural hypoxic and low pH events are less susceptible to incremental shifts in regional ocean chemistry due to ocean acidification. Areas along the U.S. eastern seaboard, the Gulf of Maine, and others have weaker oxygen minimum zones and higher pH waters along coastal zones. Organisms inhabiting these ecosystems may tolerate larger shifts in ocean chemistry caused by ocean acidification than those in ecosystems overlying more hypoxic upwelling waters, but this hypothesis requires study. Hypoxic dead zones caused by anthropogenic sources have been observed in most urbanized coastlines of the world, regardless of regional oceanography. These events, also accompanied by low pH, may indicate that most coastal ecosystems are sensitive to extreme eutrophication events. 4.4 DEEP SEA, INCLUDING COLD-WATER CORALS Acidification of the deep ocean will occur more slowly than in surface seawater. But its ecological effects may nonetheless be severe because of the assumed greater sensitivity of the deep biota. Deep-sea organisms live in a cold, dark environment with low nutrient inputs and reduced reliance on visual interactions between predator and prey. These organisms generally grow slowly and have lower metabolic rates than comparable taxa living in warmer surface waters (Seibel and Walsh, 2001, 2003; Goffredi and Childress, 2001; Seibel et al., 1997; Gage and Tyler, 1991; Pörtner et al., 2004). In animals, slow metabolism typically corresponds to a low capacity for gas exchange (i.e., oxygen transport and CO_2 release) and reduced enzyme function, including those linked to acid-base regulation (Seibel and Drazen, 2007; Melzner et al., 2009). For example, a logarithmic decrease in passive pH buffering ability with depth has been measured in highly active pelagic predatory cephalopods (Seibel and Walsh, 2003), indicating increasing vulnerability to acid-base disturbance with depth. The environmental stability of the deep sea over long time scales is also postulated to have reduced the tolerance of deep-sea species to environmental extremes through the loss of more tolerant genotypes (Dahlhoff, 2004), thereby decreasing the potential for adaptation to future ocean acidification. Page 73 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Experimental studies with deep-sea organisms are obviously difficult and very few provide direct information on their sensitivity to acidification. In experiments performed on the abyssal floor off central California, low rates of survival of deep benthic organisms were observed after exposure to a modest decrease in pH (-0.2 units) near pools of liquid CO_2 (Barry et al., 2003, 2005; Thistle et al., 2005; Fleeger et al., 2006). In contrast, deep-sea fish and cephalopods survived month-long exposure to mildly acidic waters during these experiments (Barry and Drazen, 2007), although related physiological studies indicate that respiratory stress (impaired oxygen transport) is likely for deep-living cephalopods exposed to low pH waters (Seibel and Walsh, 2003). In other experiments, deep sea crabs were much less able to recover from short-term exposure to very high CO_2 than shallow dwelling crabs and this effect was amplified at low oxygen concentrations (Pane and Barry, 2007). Some likely consequences of future ocean acidification in deep-sea waters can be inferred from organisms inhabiting hydrothermal vent and cold seep environments, which often (but not always) have low pH levels. Echinoderms and some other calcifying taxa are generally absent from hydrothermal vents (Grassle, 1986) and cold seeps (Sibuet and Olu, 1998), presumably as a result of the low ambient pH or other stressful environmental factors. For example, high concentrations of toxic metals (e.g., cadmium, silver, strontium, barium, and others) in vent effluent at some sites (Van Dover, 2000) may limit distribution of some fauna. Other vent and seep taxa thrive, in spite of high CO_2 levels, and in some cases exploit the energy-rich conditions in these environments to sustain anomalously high rates of growth (Barry et al., 2007; Urcuyo et al., 2007). Adaptations promoting success for some animals at vent and seep habitats are likely to have evolved over long periods; it remains unknown whether more typical deep-sea animals are capable of adapting to future changes in deep ocean chemistry caused by acidification. A unique habitat type in the deep sea that deserves particular attention is cold-water coral communities. Cold-water corals, also known as deep-water or deep-sea corals, form ecosystems that are in some ways the deep-water counterparts of tropical coral reefs. Cold-water coral reefs (or bioherms) are also founded on the accumulation of calcium carbonate, providing the structural framework for these biodiverse ecosystems that serve as habitat for a range of organisms, including commercially important fish species (Freiwald et al., 2004; Roberts et al., 2006). The primary reef-building species are stony corals that lack zooxanthellae, the symbiotic algae common in shallow, tropical species. Cold-water coral ecosystems occur globally in darker, colder waters than their tropical counterparts, from depths as shallow as 40 m to greater than 1,000 m (Freiwald, 2002; Freiwald et al., 2004). Page 74 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × As with tropical coral reefs, the main concern for cold-water corals with respect to ocean acidification is the effect on calcification rates for key reef-builders. The geographic distribution of cold-water coral communities suggests that they are limited to waters supersaturated with respect to their predominant skeletal mineralogy aragonite (Guinotte et al., 2006). With expected shoaling of the aragonite saturation horizon, many of these communities may become exposed to waters corrosive to coral skeletons. However, it is unclear whether it is the species or the structures they construct (or both) that are limited by the saturation horizon. Calcification rates in the cold-water species Lophelia pertusa were reduced by an average of 30 and 56% when pH was lowered by 0.15 and 0.3 units relative to ambient conditions, respectively (Maier et al., 2009), but despite this response, calcification rates in this species did not stop completely even in aragonite-undersaturated conditions. It must be noted that this is the only study on the response of a cold-water coral species to ocean acidification. Deep-sea coral communities are also abundant and ecologically significant on thousands of seamounts throughout the world ocean that could be affected by ocean acidification. Seamounts—undersea mountains that rise from the abyssal plain but do not breach the surface—number about 100,000 worldwide (Figure 4.3). The coral- and sponge-dominated assemblages found near the peaks of seamounts depend nutritionally on suspended organic debris sinking from sunlit surface waters and form important habitat for deep-sea fisheries, including orange roughy, alfonsino, roundnose grenadier and Patagonian toothfish (Clark et al., 2006). Corals that dominate seamount assemblages include stony corals (scleractinians), black corals (Antipatharians), and octocorallians, including sea fans (gorgonians). Waters around seamounts and throughout the deep-sea are naturally more acidic than those found in shallower depths because of the accumulation of carbon dioxide from the respiration of deep-sea organisms. This effect is greatest in areas such as the Northeast Pacific Ocean. Mixing of anthropogenic carbon dioxide into the deep-sea will make these waters even more acidic. Aragonitic corals are much less abundant in the more acidic waters of the Pacific Basin (Roberts et al., 2006), and most species appear to be limited in distribution by the depth of the existing saturation horizon for aragonite, as shown by the strong reduction in the abundance and diversity of scleractinians below this boundary (Guinotte et al., 2006; Cairns, 2007). For seamounts with summits that are more than a few hundred meters below the surface, especially in the Pacific basin where waters are corrosive or nearly so to aragonite, the most common corals are calcitic, including the gorgonians, which often dominate as habitat-forming species. For example, the bubblegum coral (Paragorgia sp.; Figure 4.1) is a common coral found worldwide Page 75 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × FIGURE 4.3 Global dataset of more than 30,000 potential seamounts (Kitchingman and Lai, 2004; www.seaaroundus.org). Estimates of the total number of seamounts in the world ocean varies greatly depending upon the resolution of bathymetric data available and analytic methods used. The abundances of deep-sea corals on seamounts are correlated closely with the aragonite and calcite saturation horizons (Guinotte et al., 2006). on seamounts, and can reach at least 3 m in height (Mortensen and Buhl-Mortensen, 2005). Like aragonitic corals, gorgonians and other calcitic corals are likely to be affected by changes in calcite saturation with depth, though protective coverings and tissues may provide some protection from carbonate dissolution. Seamount coral communities are highly vulnerable to anthropogenic disturbances. Growth rates of deep-sea corals are known to be low, with longevity estimates ranging from at least decades to centuries (e.g., Andrews et al., 2002; Clark et al., 2006), with at least some species living more than 1,000 years. Longevity estimates of some corals from ~500 m depth off the Hawaiian Islands were estimated at 2,742 y (Gerardia sp.) and 4,265 years (Leiopathes sp.) (Roark et al., 2009). The slow growth and long recovery time of seamount coral communities put them at greater risk for damage from human activities, including ocean acidification. Considering the expected rapid shoaling of the calcite and aragonite saturation horizons with future ocean acidification and the observed relationship between coral distributions and existing saturation horizons, deep-sea coral communities on seamounts or bioherms are likely to be impacted. Page 76 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 4.5 HIGH LATITUDES High latitude waters of the Arctic and Southern oceans are very productive and support diverse pelagic and benthic communities. Some of the richest and most heavily exploited fishing areas in the world are located in high latitude waters, including the northern Bering, Chukchi, and Barents Seas in the Arctic and a krill fishery in the Southern Ocean (Dayton et al., 1994). About half of the U.S. domestic fish catch by biomass tonnage is landed in Alaska (Fisheries Economics of the U.S., 20083). Many protected and endangered marine mammals and seabirds also roam high latitude waters. High biodiversity cold-water coral habitats can be found in the high latitudes, including the “coral gardens” off the Aleutian Islands (discussed in further detail in section 4.4). Yet high latitude organisms are not as well studied as those in lower latitudes and the effects of ocean acidification on polar and subpolar marine life and ecosystems are largely unknown. Like many other ecosystems, the most likely threat that acidification poses in the high latitudes is to planktonic calcifiers. In the subarctic Pacific, pteropods can be important prey of juvenile pink salmon, accounting in some years for >60% by weight of their diet (Armstrong et al., 2005). When exposed to the level of aragonite undersaturation expected to occur by the year 2100 (see Figure 2.10), thecosomatous pteropods showed visual evidence of reduced calcification (Comeau et al., 2009; Orr et al., 2005). If thecosomatous pteropods cannot adapt to living continuously in seawater that is undersaturated with respect to aragonite, their ranges will contract to shallower depths and lower latitudes that have higher carbonate ion concentrations. The possible exclusion of pteropods from high latitude regions would impact the downward organic carbon flux associated with pteropod fecal pellets (Thibault et al., 1999; Collier et al., 2000) and remove a major source of calcium carbonate in such regions (e.g., Bathmann et al., 1991; Honjo et al., 2000; Gardner et al., 2000; Accornero et al., 2003; Tsurumi et al., 2005). Similarly, if foraminifera densities decrease in some high latitude areas where they are currently abundant (e.g., subarctic Pacific), calcium carbonate export to the ocean interior will be reduced, which would in turn decrease the potential of foraminiferal tests to act as ballast in the transport of organic carbon to the deep sea (Schiebel, 2002; Moy et al., 2009). As in other regions, ocean acidification could also alter the species composition of primary producers and rates of photosynthesis through pH-dependent speciation of nutrients and metals (Zeebe and Wolf-Gladrow, 2001; Byrne et al., 1988; Shi et al., 2009; Millero et al., 2009). 3 Page 77 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Polar benthic communities may also be affected by acidification. Although there are major differences in the modern biota and structure of benthic communities in the Arctic and Southern Ocean that reflect the distinct topography and evolutionary history of the polar habitats, there may be similar vulnerabilities in the two systems. Polar invertebrates tend to have low metabolic rates and slow growth rates. In addition, high latitude benthic (and some planktonic) invertebrates can have long generation times compared to warmer water taxa, providing them fewer opportunities to evolve effective adaptations to cope with seawater that will be progressively depleted in carbonate ion concentration and corrosive to calcium carbonate minerals in the coming decades (Orr et al., 2005; Bates et al., 2009; Olafsson et al., 2009). Calcifying macroalgae and marine invertebrates, including cold-water corals, sea urchins, and molluscs, make up significant components of the rich benthic communities in high latitudes, and these are thought to be at risk with increasing ocean acidification. The aragonite saturation state of seawater provides a clear geochemical threshold when seawater becomes undersaturated with respect to aragonite. While many studies indicate that calcification correlates with the calcium carbonate saturation state of seawater, biological thresholds of the calcification response to ocean acidity may be species-specific. Such differential responses of species to rising ocean acidity may result in competitive advantages that could drive the reorganization of planktonic and benthic ecosystems, thereby affecting food webs, fisheries, and many ecological processes. The high latitudes will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of anthropogenic-induced acidification (Figure 2.10). Thus, these ecosystems are natural laboratories in which to test many hypotheses on the impacts of ocean acidification and other stressors, particularly those induced by global warming. Many polar and subpolar ecosystems are undergoing rapid change owing to global warming. The reduction in sea ice, freshening of seawater, and increasing ocean and air temperatures are forcing major ecological shifts in polar regions of both hemispheres. The western shelf of the Antarctic Peninsula is the fastest warming region on earth, with rates of temperature increase nearly five times the global average rate over the past century (Ducklow et al., 2007). Warming sea temperatures may allow shell-crushing crabs to invade the shelf benthos surrounding Antarctica, with significant consequences for benthic organisms that have evolved in the absence of such predators (Aronson et al., 2007). Since the Eocene, cold temperatures have prevented crabs from invading Antarctic shelves; however, king crabs are moving up the western Antarctic continental slope (Thatje et al., 2005) and should they arrive on the continental shelves, the Page 78 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × weakly calcified shells of Antarctic echinoderms and molluscs—further stressed by acidification—would provide little defense from these predators. A change from arctic to subarctic conditions is underway in the northern Bering Sea, and poleward displacement of marine mammals has coincided with a reduction in benthic prey, an increase in pelagic fish, and reduced sea ice (Grebmeier et al., 2006). Again, acidification impacts on prey species could further exacerbate food web changes caused by changing climate conditions. In both hemispheres, the observed regional changes are expected to affect broader areas of the Arctic and Southern Oceans, respectively, in future decades. In addition to warming temperatures, retreat of sea ice and increasing species invasions, high latitude regions, particularly in the north, are subject to heavy fishing pressure which is an additional stressor for these ecosystems. 4.6 LESSONS FROM THE GEOLOGIC PAST Evidence from the geologic record indicates that the Earth previously experienced periods of high atmospheric CO_2 which also changed ocean chemistry. Studies of past ocean chemistry and coincident changes in marine ecosystems may provide insight into the potential impacts of ocean acidification today and in the future. Approximately 55 million years ago, a large release of carbon into the oceans changed the Earth’s climate and ocean chemistry, an event called the Paleocene-Eocene thermal maximum (PETM). Atmospheric CO_2 and global temperature spiked upward and then slowly recovered over a period of more than 100,000 years (Kennett and Stott, 1991; Pagani et al., 2006; Zachos et al., 2001). The evidence from the isotopic compositions of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) in $CaCO_3$ in deep ocean sediments indicate that the release of carbon was relatively rapid (~10,000 years) though the exact duration of the release event is not well constrained by the sedimentary data. The $\delta^{13}C$ of surface-dwelling plankton appeared to change instantaneously, while benthic foraminifera recorded transitional $\delta^{13}C$ values, as if the atmospheric CO_2 changed on a time scale shorter than the circulation time of the ocean (Thomas et al., 2002), which today takes about 1,000 years. However, a longer CO_2 release time of 10,000 years is suggested by the sedimentary time scale based on orbital variations (Lourens et al., 2005). The oxygen isotopic composition of the $CaCO_3$ indicates that intermediate-depth ocean, and presumably the Earth’s surface, warmed in concert with the carbon release. Both temperature and CO_2 gradually returned to their initial, steady values (Lourens et al., 2005). The recovery to initial conditions of carbon and oxygen occurred on a time scale, over 100,000 years, comparable to the silicate weathering thermostat mechanism for regulating atmospheric CO_2 (Berner and Page 79 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Kothavala, 2001), a further indication that CO_2 played a role in the spike in global temperature. Deep sea sediments from the PETM show extensive dissolution of $CaCO_3$ (Zachos et al., 2005), consistent with an elevation in atmospheric CO_2. Somewhat puzzlingly, the extent of $CaCO_3$ dissolution differs greatly between the Atlantic and Pacific basins during that time (Zeebe and Zachos, 2007), possibly the result of regional anoxia events that would reduce mixing of surface sediments. Nonetheless, a number of factors limit the utility of the PETM as an analog for the detailed effects of acidification on the biota and carbon cycle of the ocean. First, the amount of carbon released is not well constrained because the exact source is unknown, and the magnitude of carbon isotope excursions in different carbon isotopic records vary by roughly a factor or two, with larger excursions typically found in soil carbon records than in deep sea sediments. Second, the magnitude of the ocean pH excursion is also unclear because it is dependent on whether the CO_2 release was faster or slower than the $CaCO_3$ neutralization time scale. The PETM was marked by the extinction of $CaCO_3$-producing foraminifera that live on the sea floor, perhaps in response to acidification or alternatively as a result of anoxia in the deep sea. There was not a comparable extinction in shallow-water species such as mollusks, but the occurrence of weakly calcified planktonic foraminifera may indicate changes in carbonate ion concentration in surface waters. A decrease in productivity or diversity, which would be relevant to humankind in the future, is difficult to gauge from the fossil record. The impact of a comet or asteroid at the boundary between the Cretaceous and the Tertiary periods (also known as the K/T boundary), which occurred 65 million years ago and is responsible for the extinction of the dinosaurs, may have also perturbed the pH of the ocean. In this event, the impact fireball caused the oxidation of atmospheric nitrogen to nitric acid (D’Hondt and Keller, 1991) and produced sulfuric acid from the calcium sulfate enriched carbonate structures at the point of impact (D’Hondt et al., 1994). The atmospheric deposition of nitric and sulfuric acids likely only affected the pH of surface waters which would have recovered ambient pH relatively quickly as they mixed with deeper water. The impact also released large quantities of dust and aerosols that would have darkened the skies and cooled Earth’s atmosphere. As in the PETM, calcifying organisms suffered greater extinction rates than organisms that do not produce $CaCO_3$, but the ecological responses that can be reconstructed could have been the result of the collapse of photosynthesis from the darkened skies, or disruption of other geochemical factors, in addition to or instead of changes in ocean pH. The largest extinction event in Earth’s history took place 251 million Page 80 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × years ago at the boundary between the Permian and Triassic periods (Knoll et al., 1996). The cause of this event is speculative; possibilities include the impact of a large object (such as a meteor), extensive volcanism, ocean anoxia, or release of methane from methane hydrates. Analysis of the correlations between extinction patterns and physiology suggest that elevated CO_2 levels might have played a role, but the duration over which this extinction occurred is unknown. These three geological events give general support to current concerns about ocean acidification, particularly related to the possibility that calcifying organisms may decrease or even disappear as a result of increasing CO_2. However, the severity of the perturbations and their durations are not known with enough accuracy to determine their similarity to conditions resulting from anthropogenic CO_2 emissions. As a consequence, responses of marine ecosystems to the ongoing increase in CO_2 may not be analogous to the changes in biological diversity associated with events in the deep past. Further development of proxy measurements, such as the use of boron isotopes to estimate ocean pH changes, could provide additional information on the rate and extent of changes in ocean CO_2 and pH during these past climatic events. 4.7 BIODIVERSITY, THRESHOLDS, AND MANAGING FOR CHANGE Regardless of the ecosystem, there is a concern that ocean acidification, along with other stressors, will reduce the biodiversity (i.e., species richness) of marine ecosystems through species extinctions, with potentially important consequences. Changes in species’ abundances, either directly due to the tolerance or intolerance of species to ocean acidification, or indirectly through changes in competitive interactions and trophic linkages, are very likely in the future. Depending on the sensitivities of species, ocean acidification may result in extinctions that reduce the biodiversity of marine communities. Very little information is available on the effects of ocean acidification on biodiversity, but studies in areas where the water is naturally high in CO_2 may provide some indication of the types of changes that could occur with global ocean acidification. For example, studies of species composition in the vicinity of CO_2-rich volcanic vents in the Mediterranean Sea suggest that acidification will reduce the biodiversity of shallow, marine benthic communities (Hall-Spencer et al., 2008). High biodiversity in marine ecosystems is generally considered to enhance the stability of ecosystems through “functional redundancy” or “species complementarity.” In other words, when biodiversity is high, there are many species serving similar ecological roles. Reduced ecosystem biodiversity due to Page 81 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × the loss of species increases the dependence of the ecosystem on the services (e.g., prey or predatory rates) provided by the remaining similar species. If key trophic linkages are lost (e.g., an intermediate consumer guild is reduced severely), food web integrity may be compromised, energy flow may be impaired, and significant changes in ecosystem structure and function become likely—an ecological tipping point or threshold has been broached that can lead to a catastrophic change in an ecosystem. These “regime shifts” can move an ecosystem from one stable state to an entirely different state. Many ecosystems have been demonstrated to undergo regime shifts to alternative ecological states (Scheffer et al., 2001). Analyses of previous regime shifts in both terrestrial and marine ecosystems (e.g., rangelands (Briske et al., 2005), lakes (Carpenter et al., 1999), coral reefs (Norström et al., 2009), open ocean (Overland et al., 2008)) show that they were rarely predicted, and many appeared to be triggered by relatively small events (van Nes and Scheffer, 2004). The growing body of literature now illustrates that the underlying cause for regime shifts is a decrease in ecosystem resilience (Folke et al., 2004; Scheffer et al., 2001). Resilience can be defined as “the amount of change or disturbance that a system can absorb before it undergoes a fundamental shift to a different set of processes and structures” (West et al., 2009). In many regime shifts, once an ecological threshold has been passed, the driver of the change must be reversed to levels far beyond where the shift occurred before the system shifts back to its original state. Regime shifts are likely within those marine ecosystems that experience stress from ocean acidification, either directly (e.g., through elimination of one or more species) or indirectly (e.g., alteration of the physical environment, such as dissolution of substrate), and particularly in combination with other stressors. Ecosystems degraded by acidification also may become more sensitive to other human and climate change stressors beyond ocean acidification. As stated by Overland et al. (2008) “our current understanding of regime shifts is not a deterministic one, and while one can discuss amplitudes and mean duration of regimes, we cannot predict their precise timing other than to say that they will be a main feature of future climate and ecosystem states.” Nonetheless, developing methods for detecting, and in some cases even predicting or managing, an ecosystem’s approach toward a tipping point or critical threshold has received increasing attention (e.g., de Young et al., 2008; Scheffer et al., 2009). Multiple techniques for identifying regime shifts are now available, but only after they have occurred (Andersen et al., 2009; Carpenter et al., 2008). Recent evidence, suggests that complex systems (including ecosystems) may exhibit certain “symptoms” prior to a regime shift (Scheffer et al., 2009), such as: Page 82 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × (1) a “critical slowing down” of the dynamics which would be expressed as a slower recovery from small perturbations, increased autocorrelation (Dakos et al., 2008), or a shift of variance power spectra toward lower frequencies (Kleinen et al., 2003; Dakos et al., 2008), (2) notably increased variance (Carpenter and Brock, 2006), (3) greater asymmetry in fluctuations (Guttal and Jayaprakash, 2008), and (4) in benthic communities, a breakdown of scaling rules for spatial patterns (Rietkerk et al., 2004). Recent progress has been made toward attributing ecological shifts, particularly in terrestrial systems, to climate change (Rosenzweig et al., 2008). A major challenge in ocean acidification research is how to attribute ecological shifts to forcing from ocean acidification. In the field, ocean acidification rarely, if ever, will be the only driver of change. Climate change is simultaneously causing changes in temperature, circulation patterns, and other phenomena, so that attribution of changes (or at least part of the change) to ocean acidification will be difficult. In coral reefs, for example, whether the loss of corals is due to rising temperature or from ocean acidification may have little relevance in the overall impact on the ecosystem (loss of corals impacts the base function of the ecosystem). But systems where species are differentially impacted by temperature and/or ocean acidification may exhibit clear signs as to which factor is likely to cause a major ecological shift. Analyses of changes in food webs supporting fisheries, for example, reveal patterns that indicate whether the drivers of that change lie near the base of the food chain or at the top (Frank et al., 2007). Management of ecological systems for climate change has focused primarily on adaptations that maintain or increase ecosystem resilience (West et al., 2009). The most common recommendation for maintaining resilience is to limit local to regional stressors such as land-based pollution, coastal development, overharvesting, and invasive species. Ecosystems with high biodiversity and/or redundancy of functional groups (e.g., several species fill the role of algal grazers) tend to be more resilient, and recover more quickly following a perturbation, which suggests that managing for biodiversity is a logical means of sustaining ecosystems (Palumbi et al., 2009). Resilience of some stocks to overfishing, for example, appears to be related to warmer regions with greater species richness (Frank et al., 2006; Frank et al., 2007). This suggest that different strategies may be necessary for maintaining resilience across different ecosystems. Page 59 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 60 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 61 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 62 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. 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Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 78 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 79 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 80 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 81 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 82 Share Cite Suggested Citation:"4 Effects of Ocean Acidification on Marine Ecosystems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 2 Page 83 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 5 Socioeconomic Concerns Marine ecosystems provide humans with a broad range of goods and services, including seafood and natural products, nutrient cycling, protection from coastal flooding and erosion, recreational opportunities, and so-called “nonuse values” such as the value that people ascribe to continued existence of various marine species. As outlined in previous chapters, many of these goods and services may be affected by ocean acidification (Cooley et al., 2009), and measuring and valuing these impacts on society can help guide policy and management decisions. For example, understanding the overall economic impact of ocean acidification can enhance the discussion of national and international climate change mitigation options (e.g., reducing CO_2 emissions). However, it may be even more useful to provide information that empowers stakeholders and enables decision makers to respond constructively to ocean acidification. To provide such information, one must determine who will be affected, when, and by how much, and how those impacts might be anticipated, prepared for, or mitigated. As with the ecological effects, the economic implications of ocean acidification are presently not well understood. Potential economic harms as well as opportunities are only now being identified (Cooley and Doney, 2009). This chapter first presents a brief,1 general discussion of how the impacts can be measured and valued. It then considers three sectors— 1 Holland et al., 2010 provide a more detailed discussion of how economic evaluation frameworks and economic modeling and valuation methods can be applied to evaluating impacts on ecosystems and ecosystem services. Page 84 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × fisheries, aquaculture, and tropical coral reef systems—for which socioeconomic impacts appear most probable based on currently available data and which have attracted the most public attention and concern (e.g., Pew Center for Global Climate Change, 2009). 5.1 EVALUATING IMPACTS ON SOCIETY Economic methods and models can be used to estimate how net benefits to society may be affected by expected changes in marine ecosystems due to ocean acidification (see previous chapters) and to assess the value of responses to those changes. Economic analysis can provide information on how best to reduce economic harm or to capitalize on opportunities brought on by ocean acidification. While economic values are not the only, or even necessarily the most important, criteria for informing decisions on responses to ocean acidification, they do provide a means to compare alternative uses of society’s resources with a framework that relates value to human welfare in terms of individuals’ assessments of their personal well-being (Bockstael et al., 2000). The strong theoretical and empirical foundation of economics enables the measurement of quantitative, logically consistent, and directly comparable measures of human benefits and costs, whether realized through organized market activity or outside of markets. Like other natural or social sciences, the accuracy of these and other economic predictions is generally highest for small (marginal) or localized changes. As one moves further from the current condition, expected accuracy declines. Hence, it may not be practical or meaningful to quantify the value of loss or restructuring of an entire ecosystem, but it is possible to quantify the value of discrete changes in the ecosystem services relative to a specific baseline. Economic valuation methods can be applied both to market goods (e.g., seafood) and non-market goods (e.g., protection from coastal flooding and erosion). Many of the economic effects of ocean acidification will be on ecosystem services that are not traded in markets but still have substantial economic value. A variety of different non-market valuation methods can be used to quantify these benefits, each suited to the measurement of specific types of values (Box 5.1). These measures of value can be incorporated into economic decision support frameworks such as cost-benefit analysis (CBA) or cost-effectiveness analysis (e.g., Boardman et al., 2006) to help evaluate potential adaptation or mitigation responses. When using a CBA to compare costs and benefits of projects or policies with long-term effects, it is common practice to reduce, or discount, future costs and benefits. This is particularly relevant and problematic for ocean acidification because outcomes much further in the future than are typical of economic analysis will need to be considered. Page 85 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 5.1 Quantifying the Net Benefits Associated with Non-market Goods There are two major types of non-market values: use values and non-use values. Use values are related to observable human use (though not necessarily consumption) of a resource. Examples in the marine environment include recreational use such as beach use or scuba diving to view ocean life. Non-use values are those not related to present or future use. Examples include the value people place on the continued existence of something (existence value) or on ensuring the continued existence or availability of something for future generations (bequest value). There are a number of common methods to quantify use values. Revealed preference methods—observing and analyzing actual human behavior—can be used to measure certain types of use values; for example, by studying the choices people make about recreation. Defensive behavior methods can also approximate non-market use values based on analysis of expenditures to avoid or mitigate environmental damage; for example, the costs associated with building groins or sea walls to prevent property damage that might otherwise have been prevented by salt marshes. However, the costs of avoiding or mitigating losses do not necessarily equate with the value of what is or would be lost, so care should be taken in using these methods to quantify value. Stated-preference methods that utilize surveys can by used to estimate non-use values. Stated preference methods such as choice experiments can also be used to evaluate the relative value of alternative policies or outcomes without necessarily monetizing them. Benefit-transfer methods, which transfer value estimates from studies in other locations, are among the most commonly applied methods for non-market valuation by government agencies (e.g., see U.S. EPA, 2002 and Griffiths and Wheeler, 2005). The choice of discount rate in such analyses is thus likely to be both critical to the valuation and highly controversial (Box 5.2). There is considerable uncertainty regarding the potential impacts of ocean acidification and how those impacts might be valued or changed by future human actions. When outcomes from different courses of action are uncertain but the probabilities of discrete alternatives occurring can be quantified, economists often apply an expected value or expected utility framework to provide a single measure of value that can be compared with the value of some other course of action (Box 5.3). There are a number of methods beyond those outlined in Box 5.3, such as using expert panels or multi-attribute utility theory (Kim et al., 1998), that can be used to assist in determining appropriate investments in acidification research and devising policies. Each of these methods has strengths and weaknesses, and care must be taken to choose the most appropriate. Page 86 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 5.2 Discounting Cost-benefit analysis of policies or projects that involve costs and benefits occurring over an extended period of time will generally apply a discount rate to both future benefit and future costs. Discounting reflects the actual preferences of people for earlier consumption or delayed costs, as well as the expected growth in real consumption for future generations (Ramsey, 1928); it is generally accepted as a means of aggregating benefits and costs over time. In private investment decisions the discount rate may reflect the opportunity cost of capital. However, discounting may lead to unintended consequences when used to assess outcomes over very long time horizons. For example, in a cost-benefit analysis of a program designed to avoid a loss of $100 billion one hundred years in the future, it would be worth spending up to $24.7 billion on that program today using a discount rate of 1.4%, but only $247 million today on that program. Consequently, the choice of a discount rate can be extremely important in analyses of actions with very long term implications, and can greatly alter how policies are designed and ranked (e.g., see reviews of Stern [2006] by Nordhaus [2007] and Weitzman [2007]). The discount rate is particularly critical when evaluating actions that may have large up-front costs to forestall undesirable outcomes far in the future. Some economists have proposed using low discount rates (e.g., Stern, 2007) or alternative discounting approaches for projects with long-duration effects (see Boardman et al., 2006 for a discussion of these). However, there is a lack of consensus on what discount rates or approaches should be used to evaluate decisions and design policies that will impact future generations. Therefore, it may be desirable to present policy makers with estimates of present value reflecting alternative discount rates so that the sensitivity of the result to the discount rate is clear. An appropriate method for the assistance required and the available data. It is also important to note that performing long-time frame analysis presents difficulties for all of these analysis methods because of the challenges in weighting changes that occur far in the future. There are a variety of important factors for determining how easily and how quickly (human) communities may cope with and adjust to the impacts of ocean acidification. These include the formal and informal institutions that determine how responses are carried out, the education and training of the affected individuals, cultural values, and alternative employment availability (Kelly and Adger, 2000; Adger, 2003; Tuler et al., 2008).2 The range of issues and research questions associated with vulnerability and adaptation is broad. Though their focus is on climate change, the compiled papers in Adger et al. (2009) cover many of the issues that may be relevant to vulnerability and adaptation to ocean acidification. Page 87 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 5.3 Decision Making Under Uncertainty Expected value is simply a weighted average of the values of the potential alternative outcomes where the weights represent the probabilities that certain states of nature will occur. For example, if a fishery policy has a 20% chance of providing a benefit of $120 million and an 80% probability of accomplishing nothing, and the cost of the policy is $20 million (e.g., a net benefit of −$20 million) the expected value of the policy is $4 million (0.2*(120−20) + 0.8*(0−20)). In an expected value framework, all outcomes are weighted equally, and one does not give more weight than good ones, but an expected utility framework may weight losses more heavily than gains reflecting risk aversion. Additional value or alternative decision criteria should be considered in evaluating policies that prevent irreversible losses of uncertain value. The loss of the opportunity to learn more before making a decision represents an added cost that is called quasi-option value (Arrow and Fisher, 1974). In some cases policy makers may choose to use a safe minimum standard approach. Rather than attempt to value the loss, policies would be designed to achieve sufficient to ensure that the loss is not incurred are implemented unless the costs of doing so are catastrophic. Ciriacy-Wantrup and Phillips (1970) explained that "here the objective is not to maximize a definite quantitative net gain but to choose premium payments and losses in such a way that maximum possible losses are minimized." Though somewhat flawed from an economic logic and philosophical perspective, the safe minimum standard approach is reflected in numerous policies, including the Endangered Species Act. Access to capital or other resources is also likely to be important. It has been noted that strategies to cope with and adapt to impacts of climate change in the short run may not necessarily facilitate proactive adaptation and enhancement of social welfare in the longer term (Dasgupta, 2003) and may even be counterproductive (Schenaga and Grambeck, 1998). For example, emergency aid that allows a fishery-dependent community to sustain itself and maintain fishing infrastructure during a fishery collapse may be counterproductive if collapses are expected to be more frequent and severe in the future. In such cases investing in developing alternative economic opportunities may be more useful. The importance of focusing on long-run adaptation may be particularly important for ocean acidification because it is a slow driver of change with long-term effects and the potential for ecological regime shifts. Notwithstanding the potential for conflicts between different adaptation strategies, a great deal of synergy may occur among actions to facilitate adaptation to ocean acidification and other changes such as climate change, both cyclic and secular. However, in light of the variability in these factors, socioeconomic analysis should not be a one-time event but an iterative process that adjusts with the identification of stakeholders Page 88 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × and the impact of ocean acidification upon them. As research is performed and the effects of ocean acidification are better defined, the results of the socioeconomic analysis may change, and as a result, the research needs and adaptation policies may also need to be adjusted. It may be nearly impossible to predict how acidification will affect human communities. Indeed, the objective of prediction itself may, by necessity, be set aside for something far less ambitious—such as general understanding of basic trends or improved appreciation of risks and thresholds. Since many impacts may be hard to predict with accuracy, the development of adaptation strategies that are robust to uncertainty will likely be an important task for decision support (Edwards and Newman, 1982; Keeney, 1992; National Research Council, 1996; von Winterfeldt and Edwards, 1986; Kling and Sanchirico, 2009). Even when we do not fully understand the processes through which ocean acidification will affect changes in ecosystems and ecosystem services, it is useful to develop models to test the implications of alternative plausible hypotheses to provide insight into the range of possible outcomes. Sensitivity analysis can then be used to identify the assumptions and parameters of the models that most heavily impact predictions which can help target limited resources toward research aimed at the information that is likely to be of greatest value. 5.2 MARINE FISHERIES United States wild marine fisheries had an ex-vessel value of $3.7 billion in 2007; mollusks and crustaceans comprised 49% of this commercial harvest (National Oceanic and Atmospheric Administration, 2008; Cooley and Doney, 2009). Ocean acidification may affect wild marine fisheries directly by altering the growth or survival of target species, and indirectly through changes in species' ecosystem, such as predator and prey abundance or critical habitat. This may lead to changes in abundance or size-at-age of target species, which could ultimately result in changes to sustainable harvest levels. Several experimental studies have observed the effects (positive and negative) of ocean acidification on calcification in commercially important species (e.g., Green et al., 2009; Miller et al., 2009; Ries et al., 2009; Gazeau et al., 2007). Shellfish fisheries are presumed to be particularly vulnerable to ocean acidification because of the effect on shell formation especially during early life stages (Kurihara, 2008). Many important plankton species are calcifiers, and their decline or collapse could adversely affect target species through changes in food web interactions. Fisheries could also be affected by changes in critical habitat. This could include disruption or degradation of biogenic habitat structures formed by marine calcifiers such as corals and oysters, but could Page 89 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × also include increases in seagrass and mangrove habitats with increased CO2 (Guinotte and Fabry, 2009). There may also be synergistic effects of increased acidification and other stressors, such as changes in water temperature associated with global climate change. The impacts of ocean acidification on marine fisheries are likely to vary greatly over time and across species and locations, and there may be localized impacts in areas with upwelling or large freshwater input before averages across ocean pH falls. Studies to date have been limited to only a few commercially relevant species and have been focused on individual organisms, not on predicting the overall impacts for a target stock or species. Ocean acidification may result in substantial losses and redistributions of economic benefits in commercial and recreational fisheries. Although fisheries make a relatively small contribution to total economic activity at a national and international level, the impacts at the local and regional level and on particular user groups could be quite important. Further, the net impact on social benefits will depend on whether adequate protections are available to allow affected fisheries to plan for change, as well as the ability of those fishery participants and communities to adapt. The expected long lead time of acidification impacts relative to the time scales of fisheries investments makes present day valuation a challenge. For example, a snapshot of producer surplus today may substantially underestimate future producer surplus because of the likely increase in seafood demand associated with increased population and income. Rebuilding depleted fish stocks, now mandated by law, could lead to increased catches and reduced costs (Worm et al., 2009). Furthermore, many fisheries today are overcapitalized and inefficiently regulated. New "catch share" management systems being implemented in a number of U.S. fisheries provide fishermen with incentives and more flexibility to reduce harvest costs and increase the quality and value of catch (and thus net value of fisheries) as well as growing the resource (Costello et al., 2008). Taken together, these factors suggest that the potential losses from ocean acidification could be higher than projected on the basis of the current value of fisheries. For recreational fisheries, net "consumer surplus" values must be estimated with non-market valuation techniques. As with commercial fisheries, long-term projections are likely to be highly uncertain since the number of recreational fishermen will change. Understanding likely trends in future participation in a particular fishery may help increase the accuracy of longer-term projections.3 A change in the production of a particular commercial fishery as a result of ocean acidification can be expected to result in a change of income and jobs for sellers of inputs (e.g., commercial fishing gear), pro- Page 90 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × cessors, retailers, recreational fishing outfitters and so on. Secondary impacts such as income and job losses for sellers of inputs or fish processors are generally excluded when determining the change in net benefits, especially from a longer-term perspective, since the affected labor and capital resources can be redeployed. However, these economic impacts may be minimized and the ability of communities to adapt improved if there is good information available with sufficient lead time to allow for planned adjustments to impacts. Beyond the value of commercial or recreational shellfish harvests, shellfish resources such as oyster reefs and mussel beds provide valuable ecosystem services. These include augmented finfish production (Grabowski and Peterson, 2007), improved water quality and clarity that can benefit submerged aquatic vegetation (Newell, 1988; Newell and Koch, 2004) and increase recreational value by improving beach and swimming use (Henderson and O'Neil, 2003). Shellfish beds can also reduce erosion of other estuarine habitats such as salt marshes by attenuating wave energy (Meyer et al., 1997; Henderson and O'Neil, 2003). Individuals, companies, and communities involved in fisheries may be able to adapt to changes in allowable catch levels caused by ocean acidification in a variety of ways. Timely information could improve their decisions about long-term investments, including reallocation to different fisheries, diversification into multiple fisheries, or choosing a non-fishing occupation. All of these choices are strongly influenced by the culture, values, and social institutions surrounding fishing communities; therefore, adaptation responses must take these factors into consideration if they are to be effective (Coulthard, 2009). Since accurate predictions of what fisheries will be impacted when are unlikely, it is also important to identify management strategies that are robust to uncertainty and unexpected change. The potential consequences of ocean acidification may take many years to be realized but will persist for a very long time. To determine the appropriate responses to ocean acidification it may be useful to consider which of the impacts of ocean acidification will occur. Individuals and businesses involved in fisheries are likely to be interested primarily in impacts expected to occur within 20 years or less. Because of customary practices and typical discount rates applied to capital investments, projections of changes 5 to 10 years in the future are likely to be of greatest interest. Many of the critical decisions for fisheries are made by fishery managers who must design harvest strategies and management systems. Current U.S. law requires fishery managers for federal fisheries to set reference points for biomass and exploitation rates in relation to maximum sustainable yield (MSY). These reference points, based on long time-series that reflect past conditions, will overestimate the productivity and target Page 91 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × biomass for some species that are negatively affected by ocean acidification (i.e., lower MSY), resulting in unrealistic rebuilding requirements. The reverse may be true for other fish stocks that are positively affected by ocean acidification. In both cases, the benefits from the fishery will be reduced if reference points are not adjusted to reflect changes in a fishery's productivity. Fisheries in state waters are not subject to the Magnuson-Stevens Fisheries Conservation and Management Act (the primary U.S. law regulating marine fisheries), and guidelines on controlling overfishing or rebuilding fish stocks vary, but managers of state fisheries face the same forecasting and planning challenges as their federal counterparts. 5.3 MARINE AQUACULTURE Since 2005, there have been many failures in oyster hatcheries along the U.S. west coast. While the cause is unknown, some attribute the failures to ocean acidification and the oyster industry has already begun to make investments in water treatment and monitoring (Welch, 2009). This underscores the urgent need for decision support for the marine aquaculture industry. It is presently unclear which aquaculture species will be impacted by ocean acidification. However, as the previous discussion of wild fisheries suggests, many species that are important in aquaculture, such as crustaceans or finfish aquaculture are likely affected. Many issues confronting wild fisheries also affect marine aquaculture. Estimates of the gross value of aquaculture at risk from ocean acidification (e.g., $240 million for U.S. marine aquaculture in 2006, of which $150 million was for shellfish) provide some sense of the scale of potential harm, but do not provide a measure of the net benefits that may be lost. Those can be measured through standard market-based analyses of producer and consumer surpluses (see Box 5.4) (from imported as well as domestic aquaculture) to the extent data are available. Because U.S. production has been limited mainly by markets and regulatory requirements, it is hard to forecast the level of aquaculture production a few decades from now. If aquaculture production increases significantly, the potential losses in net benefits from ocean acidification could be much higher. Even though aquaculture faces some of the same threats as wild fisheries, the research and monitoring needs and ability to respond to threats is much different. Aquaculturists can protect against ocean acidification by changing the species or broodstock they raise, relocating operations and, in some cases, by altering seawater chemistry (e.g., in intensive culture operations and hatcheries). These decisions will require information about the probability, frequency, magnitude, and timing of potential future problems created by ocean acidification. In some cases, large investments with long payoff horizons will be at stake, so information on Page 92 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 5.4 Producer and Consumer Surplus Gross revenues provide a rough indicator of the value of a fishery, but may not provide a good estimate of net societal benefits associated with that fishery (and thus the potential loss in value). A preferable approach is to project changes in producer and consumer surplus. Producer surplus is the difference between the revenues and the full costs associated with producing a good. Consumer surplus is the difference between what consumers pay for a good and the maximum they would be willing to pay. In addition to changes in producer and consumer surplus from U.S. fisheries, net benefits to the U.S. economy could be affected by loss of consumer surplus from imported seafood. Other ecosystem services such as recreational fishing also provide consumer surplus—the value participants place on the activity itself less the expenditures they incur (e.g., travel costs, boats, fuel, gear). expected impacts several years may be useful. But, as with conventional fisheries, threats of changes 5 to 10 years in the future are likely to be of greatest interest. 5.4 TROPICAL CORAL REEFS Coral reefs provide many valuable ecosystem services, including direct use values for recreation, e.g., diving, snorkeling, and viewing; indirect use values of coastal protection, habitat enhancement, and nursery functions for commercial and recreational fish; and preservation values associated with diverse natural ecosystems (Brander et al., 2007). Two coral species are listed as threatened under the U.S. Endangered Species Act—the elkhorn coral Acropora palmata and the staghorn coral Acropora cervicornis—with two others considered "species of concern" (National Oceanic and Atmospheric Administration, 2009a). Tropical coral reefs also provide habitat for other protected species. According to one estimate, coral reefs are estimated to provide around $30 billion in net annual benefits globally of which some $5.7 billion is associated with fisheries, $9.6 billion with tourism and recreation, and $3.5 billion with preserving biodiversity (Cesar et al., 2003). While only about $1.1 billion is attributed to coral reefs in U.S. waters, U.S. citizens derive value from non-U.S. reefs. Many coastal populations in less developed regions of the world are dependent on reef-based fisheries for food, including people residing in U.S. territories and protectorates. Degradation or loss of coral reefs could undermine regional food security and have political and security implications. Page 93 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × The value of reefs can vary greatly and there is little consistency or agreement on methods for economic valuation. A meta-analysis of coral reef recreational valuation studies shows a wide variation of estimated values (net value of site visits) only partially explained by site characteristics (Brander et al., 2007). The study did find significantly higher values for reefs with larger areas, more dive sites, and fewer visitors. If the number of reefs and associated biodiversity declines over time, the value of those that remain can be expected to increase due to scarcity. Consequently, the marginal damage associated with increased reef losses would be expected to increase. The tropical coral reef sector is somewhat different from the previous two sectors in that it represents a single ecosystem with a wider range of user groups that have different (and sometimes conflicting) values and goals. There are many potential users of information about ocean acidification impacts on tropical coral reefs, including a variety of government agencies that manage reefs (e.g., NOAA National Marine Sanctuaries Program), non-governmental conservation groups that work to protect reefs (e.g., Conservation International, World Wildlife Fund), tourism and recreation industry groups, native communities, and others that rely on the ecosystem services provided by reefs. Information on expected impacts on coral reefs and the vulnerabilities of these various groups may allow users to prepare for and adapt to changes. While there is virtually no information on decision support for ocean acidification, there is a growing body of literature on possible management responses for the impacts of climate change (e.g., Johnson and Marshall, 2007; Keller et al., 2008; West et al., 2009). Given the similarities of the two problems, the following discussion applies the same principles toward responding to ocean acidification. Mitigation is one possible response to predicted impacts. Analysis of the predicted impacts on coral reefs can be used to complement arguments to mitigate carbon dioxide emissions on a global scale. In addition, small reefs having important features may warrant local mitigation actions such as using carbonates to buffer seawater, but the potential effectiveness and associated ecological risks have not been studied. For large-scale operations, this is unlikely to be economically feasible. The other class of management response is to promote resilience in vulnerable components of the coral reef ecosystem and associated human communities. This will allow the system to better resist and recover from disturbances caused by acidification and is an ideal management approach given uncertainty in predictions of impacts. Approaches for managing for resilience include reducing other anthropogenic stressors such as pollution, overfishing, or habitat destruction. Managers of reef-related fisheries might need to adjust catch and effort levels to reflect Page 94 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × reductions in productivity. Reef managers could focus protection efforts on critical functional elements of the reef ecosystem. For example, herbivores have been identified as a key functional group for maintenance of coral reef ecosystems; protection efforts could ensure that herbivores are afforded special protection (Johnson and Marshall, 2007). Another example is identifying and protecting refugia—areas that are less affected by ocean acidification and other stressors and that can serve as a refuge for organisms (Johnson and Marshall, 2007; West et al., 2009). It is also important to promote the social and economic resilience and adaptive capacity of users that rely on tropical coral reefs. All of this will require a great deal more information on both the biological impacts of ocean acidification on coral reefs as well as the socioeconomic systems that will be affected. Page 95 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 83 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 84 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 85 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 86 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 87 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 88 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 89 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 90 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 91 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 92 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 93 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 94 Share Cite Suggested Citation:"5 Socioeconomic Concerns." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 95 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 96 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 97 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 6 A National Ocean Acidification Program There is growing evidence of changes in ocean chemistry and resulting biological and socioeconomic impacts due to the absorption of anthropogenic CO2 into the ocean, as summarized in chapters 2 through 5. The changes in ocean chemistry are already being detected, and because the relationship between atmospheric CO2 and seawater chemistry is well understood, future changes can also be projected. What is less predictable is the affect these changes will have on organisms, ecosystems, and society. However, there is strong evidence that acidification will affect key biological processes—calcification and photosynthesis, for example—and that it will affect different species in different ways. This will result in ecological "winners and losers," meaning some species will do better than others in a lower pH environment, and ultimately, this will cause shifts in marine community composition and ecosystem services. Acidification is happening globally and many ecosystems will be affected. Coral reefs appear to be particularly vulnerable because of the sensitivity of reef-builders to changes in seawater carbonate chemistry, compounded with other stressors such as climate change and overfishing. Coral reef ecosystems provide many important services to support a number of services, including fishing, recreation and tourism, and storm protection. They are also highly diverse ecosystems with intrinsic natural beauty whose existence often holds high value for society. Individuals who manage coral reefs, as well as the local communities that rely on the reefs, are in urgent need of information that will allow them to mitigate and adapt to acidification impacts. Reefs are one example, but there are also many commercially-important fisheries and aquaculture species that Page 96 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × may be vulnerable to, or may benefit from, acidification. Calcifying mollusks and crustaceans, which are important species for both aquaculture and wild harvest fisheries, and fish habitats essential for many marine species (e.g., oyster reefs, seagrass beds), are other examples. As research continues, many other sectors, communities, and decision makers that could feel an impact from acidification are likely to be identified. A better understanding of these potential biological and socioeconomic effects than we have today, as well as an ability to forecast changes, is needed for industry, and human communities to plan and adapt. CONCLUSION: The chemistry of the ocean is changing at an unprecedented rate and magnitude due to anthropogenic carbon dioxide emissions; the rate of change exceeds any known to have occurred for at least the past hundreds of thousands of years. Unless anthropogenic CO2 emissions are substantially curbed, or atmospheric CO2 is controlled by some other means, the average pH of the ocean will continue to fall. Ocean acidification has demonstrated impacts on many marine organisms. While the ultimate consequences are still unknown, there is a risk of ecosystem changes that threaten coral reefs, fisheries, protected species, and other natural resources of value to society. The U.S. federal government has shown a growing awareness of and response to concerns about the impacts of ocean acidification, and there is growing interest in a national ocean acidification program (see also Ocean Carbon and Biogeochemistry Program, 2009a). The National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA) began studying the impacts of anthropogenic CO2 on the marine carbonate system in the North Pacific in the 1980s (Feely and Chen, 1982; Feely et al., 1984, 1988) and continues to expand its research and observational efforts (e.g., Feely et al., 2008; Gledhill et al., 2008; Meseck et al., 2007). NOAA, the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA) have also provided extramural support for workshops, planning efforts, facilities, and research (Congressional Research Service (U.S. CRS), 2009; Paula Bontempi, NASA, personal communication). In the 110th and 111th sessions, the U.S. Congress demonstrated concern over the problem of ocean acidification, holding multiple hearings and passing the Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009 (Congressional Research Service (U.S. CRS), 2009; P.L. 111-11). The FOARAM Act of 2009 (P.L. 111-11) calls for an interagency working group (IWG) under the Joint Subcommittee on Page 97 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Ocean Science and Technology (JSOST) to develop a strategic research plan and to coordinate federal ocean acidification activities. CONCLUSION: Given that ocean acidification is an emerging field of research, the committee finds that the federal government has taken initial steps to respond to the nation's long-term needs and that the national ocean acidification program currently in development is a positive move toward coordinating these efforts. The FOARAM Act sets out ambitious program elements in monitoring, research, modeling, technology development, and assessment and asks the IWG to develop a national program for the ground up. Fortunately, the scope of the problem is not unlike others that have faced the oceanographic and climate change communities in the past, and there are examples of research strategies for addressing ocean acidification can be pulled from existing programs such as the European Project on Ocean Acidification (EPOCA) and other national and international ocean acidification programs (see Box 6.1); other large-scale oceanographic research programs such as the Joint Global Ocean Flux Study (JGOFS); and the U.S. Global Change Research Program (USGCRP). There have also been numerous workshops and reports that have outlined recommendations for acidification research at both the international (e.g., Raven et al., 2005; Orr et al., 2009) and within the United States (Kleypas et al., 2006; Fabry et al., 2008a; Joint et al., 2009). Fabry et al. (2008a), for example, present comprehensive research strategies for four critical major ecosystems—warm-water coral reefs, coastal margins, subtropical/tropical pelagic regions, and high latitude regions—as well as cross-cutting research issues. The U.S. reports were supported by multiple agencies (NSF, NOAA, USGS, and NASA) and represent the input of a substantial community of U.S. and international researchers. The Ocean Carbon and Biogeochemistry (OCB) Program (jointly sponsored by NSF, NOAA, and NASA) has been active in supporting ocean acidification research, and produced a white paper outlining the need for a U.S. Federal Ocean Acidification Research Program (Ocean Carbon and Biogeochemistry Program, 2009a). Finally, the components of a global ocean acidification monitoring program have been proposed by a large cohort of researchers from the international oceanographic community (Feely et al., 2010). Therefore, the committee had a wealth of community-based input upon which to could base its recommendations for a National Ocean Acidification Program. Page 98 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × CONCLUSION: The development of a National Ocean Acidification Program will be a complex undertaking, but legislation has laid the Page 98 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 6.1 Examples of International and Multinational Ocean Acidification Research Programs This box briefly describes three of several existing national and multinational ocean acidification research programs to show some similarities and differences in program elements. It also describes one program, the IMBER/SOLAS Ocean Acidification Working Group, which is not a primary research program per se, but instead works as a coordinating body. European Project on Ocean Acidification (EPOCA): EPOCA was launched as a result of the submission of a proposal to an open call by the European Union (EU). The overall goal is to advance understanding of the biological, ecological, biogeochemical, and societal implications of ocean acidification. It is a four year program which began in June 2008. The project budget is 15.9M, with a 6.5M contribution from the EU. The project plans were developed by representatives of 10 core partners and they define a complete project with goals and deliverables. EPOCA brings together more than 100 researchers from 27 institutes and 9 European countries. EPOCA has several advisory panels, including a Reference User Group which works with EPOCA to define user-related issues such as the types of data and analysis that will be most useful to managers. There is also a project office that coordinates EPOCA activities. From: Biological Impacts of Ocean Acidification (BIOACID): BIOACID is a German national initiative that came as an unsolicited proposal to the German Ministry of Education and Research. The purpose of BIOACID is to assess uncertainties, risks, and thresholds related to the emerging problem of ocean acidification at molecular, cellular, organismal, population, community and ecosystem scales. Planning began in 2007, led by a 6-member group and with a bottom-up, open competition approach among all interested German institutes and universities conducting marine-oriented research. The project began in September 2009 and is scheduled for three years (with the possibility of 3 additional years). The German government will provide 8.9M for the first three years. BIOACID involves more than 150 scientists and technicians from 14 German research institutes and universities. From: United Kingdom (UK) Ocean Acidification Research Programme: The UK program was launched as a result of the submission of a proposal to an open call by the Natural Environment Research Council and the Department for Environment, Food & Rural Affairs. The overall aim of the Research Programme is to provide a greater understanding of the implications of ocean acidification and its risks to ocean biogeochemistry, biodiversity and the whole Earth system. The science and implementation plans were written by an appointed 8-member team. Unlike EPOCA and BIOACID, the research will be determined through an open solicitation for individual proposals. The program will begin in mid 2010 and is scheduled for Page 99 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × years with £12M funding from the UK government. The project is being managed by representatives of the UK government with input from a scientific Programme Advisory Group. From: IMBER/SOLAS Ocean Acidification Working Group: This working group was initiated jointly between the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the Surface Ocean Lower Atmosphere Study (SOLAS)—two international oceanographic research programs—as a subgroup of the Ocean Carbon working group which coordinates seamless implementation of ocean carbon research between the two programs. Unlike the other programs, it is not supporting primary research but instead will coordinate international research efforts in ocean acidification and undertake synthesis activities in ocean acidification at the international level. The 8-member subgroup was launched in September 2009. From: foundation, and a path forward has been articulated in numerous reports. One of the first steps is a strategic planning process that will set priorities for understanding and responding to ocean acidification. An ocean acidification program will be a complex undertaking for a number of reasons. Like climate change, ocean acidification is a global problem with a global footprint but the impacts are likely to be felt at the regional and local level. It is a problem that cuts across disciplines and affects a diverse group of stakeholders. Assessment, research, and development of potential adaptation measures will require coordination at the international, national, regional, state, and local levels. It will involve many of the greater than 20 federal agencies that are engaged in ocean science and resource management. Investigating and understanding the problem will necessitate the close collaboration of ocean chemists, biologists, modelers, engineers, economists, social scientists, resource managers, and others from academic institutions, government labs and agencies, and non-governmental organizations. It will also involve two-way communication—both outreach to and input from—stakeholders interested in and affected by ocean acidification. Ultimately, a successful program will have an approach that integrates basic science with decision support. In this chapter, the committee Page 100 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × describes some key elements of a successful program: a robust observing network, research to fulfill critical information needs, adaptability to new findings, and assessments and support to provide relevant information to decision makers, stakeholders, and the general public. Cutting across these elements are the needs for data management, facilities, training of ocean acidification researchers, and effective program planning and management. 6.1 OBSERVING NETWORK Countless publications have noted the critical need for long-term ocean observations for a variety of reasons, including understanding the effects of climate change and acidification; they have also noted that the current systems for monitoring these changes are insufficient (e.g., Baker et al., 2007; Fabry et al., 2008a; Birdsey et al., 2009b). Currently, observations relevant to ocean acidification are being collected, but not in a systematic fashion. A global network of robust and sustained observations, both chemical and biological, will be necessary to establish a baseline and to detect and predict changes attributable to acidification (Feely et al., 2010). This network will require adequate and standardized measurements, both biological and chemical, as well as new methods and technologies for acquiring those measurements. It will also have to cover the major ecosystems that may be affected by ocean acidification, and specifically target environments that are potentially sensitive to acidification (e.g., fisheries, coral reefs). This network need not be entirely built "from scratch," and the program should leverage existing and developing observing systems. Even if anthropogenic CO2 emissions remained constant at today's levels, the average pH of the ocean would continue to decrease for some period of time, and research in the area would benefit from continuous time-series data. Thus the program should consider mechanisms to sustain the long-term continuity of the observational network. 6.1.1 Measurements The first step in developing an ocean acidification observing network is determining the requirements for biological and chemical measurements, as well as standards to ensure data quality and continuity. For ocean acidification, requirements for seawater carbonate chemistry measurements are well defined and include temperature, salinity, oxygen, nutrients critical to primary production, and at least two of the following four carbon parameters: dissolved inorganic carbon, pCO2, total alkalinity, and pH. Methods used for these measurements are well established (Dick- Page 101 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × son et al., 2007; Ocean Carbon and Biogeochemistry Program, 2009b; Riebesell et al., 2010; see Chapter 2 of this report). As discussed in previous chapters, these values vary with depth and environment, and surface measurements alone will not provide a complete picture of conditions within the ocean. Measurements of chemical parameters should be made in different zones of interest, such as the photic zone, the oxygen minimum zone, and in deeper waters. Unlike the chemical parameters, there are no agreed upon metrics for biological variables. In part, this is because the field is young and in part it is because the biological effects of ocean acidification, from the cellular to the ecosystem level, are very complex. While biological indicators specific to ocean acidification have not yet been defined, however, biological monitoring programs that serve a variety of applications could also be used to track responses to ocean acidification, and it would be beneficial to monitor general indicators of marine ecosystem processes to create a time series data set that will be of use in efforts to identify correlations and trends between the chemical and biological data. There are many potential measurements for understanding the biological response of marine ecosystems to acidification, and their relative importance will vary by ecosystem function and region. Some possible measurements include: • rates of calcification, calcium carbonate dissolution, carbon and nitrogen fixation, oxygen production, and primary productivity, • biological species composition, abundance, and biomass in protected and unprotected areas (Fabry et al., 2008a; Feely et al., 2010), • the relative abundance of various taxa of phytoplankton (i.e., diatoms, dinoflagellates, coccolithophores), • and settlement rates of sessile calcareous invertebrates (possibly commercially important species such as mussels and oysters). Although at present we cannot predict which indicators will be informative for ocean acidification specifically, general indicators of changes in ocean and coastal ecosystems will have value for understanding changes that are a consequence of ocean acidification or other long term stressors, such as temperature. Monitoring of ecological parameters may also help researchers identify those species most vulnerable to ongoing environmental changes, including ocean acidification. As critical biological indicators and metrics are identified, the Program will need to incorporate those measurements into the research plan, and thus, adaptability in response to developments in the field should be a critical element of the monitoring program. Resolution of the effects of ocean acidification on individuals, popula- Page 102 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × tions, and communities will require well-controlled manipulative experiments to assess their sensitivity and elucidate the underlying physiological mechanisms. Studies designed to understand which fundamental metabolic processes are affected by higher CO2 or lower pH are critical to clarifying which effects on marine populations are due to ocean acidification and which to long-term or acute environmental stressors. It should also be noted that to create a time series data set of chemical and biological data, chemical data must be collected whenever biological data are collected. Though chemical data may stand alone, understanding the effect of ocean acidification on biological systems will require that both types of data are available for analysis. Additionally, as ocean acidification is expected to be a concern into the future, data collected today will likely be analyzed by many different researchers from different areas of expertise. To facilitate archiving and sharing of information between investigators and across disciplines, the Program should support the development of standards and calibration methods for both chemical and biological samples. Investments in technology development could greatly improve the ability to routinely measure key chemical and biological parameters in the field with expanded temporal and spatial coverage. For ocean carbonate chemistry, current instrumentation for automated pCO2 measurements (using equilibrators and infrared detection) are robust, but similar instrumentation for continuous automated measurements of a second carbon parameter are needed. Additional autonomous sensors could be developed for measuring particulate inorganic carbon (PIC) and particulate organic carbon (POC). There are also promising new technologies being developed for in situ pH measurements (e.g., autonomous spectrophotometric pH sensors, Seidel et al., 2008; solid state pH-sensing ion-selective field-effect transistor electrodes, Martz et al., 2008; basin-scale spatially averaged acoustic pH measurements, Duda, 2009). In the absence of direct synoptic measurements for carbonate chemistry characterization, proxy measurements have proven useful. For example, salinity and temperature have been successfully used to estimate global (Lee et al., 2006) and regional (Gledhill et al., 2008) aragonite saturation state fields. Synoptic remotely sensed sea surface temperature measurements are available and complementary sea surface salinity measurements (SSS) should soon be available through NASA's Aquarius mission and will allow for a better understanding of current temporal and spatial patterns of global ocean carbonate chemistry. The temperature/salinity/alkalinity relationship may be confounded through time in the mid- to long-term in response to acidification; sustained large-scale alkalinity measurements will therefore be needed to ground-truth proxy methods if they are to be used in the long-term. Other Page 103 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × platforms, such as floats and gliders are being used to collect both chemical and biological measurements. In addition, automated sensors for detecting biological parameters are needed. Such sensors could include, for example, imaging and molecular biology tools, for detecting shifts in communities, both benthic and pelagic and across key marine ecosystems, and physiological stress markers of ocean acidification, including molecular biology tools, for key functional groups and economically important species (Byrne et al., 2010b; Feely et al., 2010). Finally, it will be important not only to develop new sensors, but also methods of deploying these on moorings, drifters, floats, gliders and underway systems. CONCLUSION: The chemical parameters that should be measured as part of an ocean acidification observational network and the methods to make those measurements are well-established. RECOMMENDATION: The National Program should support a chemical monitoring program that includes measurements of temperature, salinity, oxygen, nutrients critical to primary production, and at least two of the following four carbon parameters: dissolved inorganic carbon, pCO2, total alkalinity, and pH. To account for variability in these values with depth, measurements should be made not just in the surface layer, but with consideration for different depth zones of interest, such as the deep sea, the oxygen minimum zone, or in coastal areas that experience periodic or seasonal hypoxia. CONCLUSION: Standardized, appropriate parameters for monitoring the biological effects of ocean acidification cannot be determined until more is known concerning the physiological responses and population consequences of ocean acidification across a wide range of taxa. RECOMMENDATION: To incorporate findings from future research, the National Program should support an adaptive monitoring program to identify biological response variables specific to ocean acidification. In the meantime, measurements of general indicators of ecosystem change, such as primary productivity, should be supported as part of a program for assessing the effects of acidification. These measurements will also have value in assessing the effects of other long term environmental stressors. RECOMMENDATION: To ensure long-term continuity of data sets across investigators, locations, and time, the National Ocean Acidification Program should support inter-calibration, standards development, and efforts to make methods of acquiring chemical and biological Page 104 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × data clear and consistent. The Program should support the development of satellite, ship-based, and autonomous sensors, as well as other methods and technologies, and in situ sensors. As the field advances and a consensus emerges, the Program should support the identification and standardization of biological parameters for monitoring ocean acidification and its effects. 6.1.2 Establishing and Sustaining the Network A number of existing ocean observing systems are already conducting open ocean carbon system measurements. These include existing time series sites (e.g., Hawaii Ocean Time-series [HOT], Bermuda Atlantic Time-Series Study [BATS]) and repeat hydrographic surveys (e.g., CLIVAR/CO2 Repeat Hydrography Program). Some of the sites include regular biogeochemical measurements of carbon chemistry, nutrient, and chlorophyll concentrations and the rates of biological primary production and sinking particle flux are measured approximately monthly. Additional oceanic time-series sites have been proposed (e.g., OceanSITES; Send et al., 2009). There are also several existing coastal time-series that are supported by various federal agencies, including the NSF Long-Term Ecological Research (LTER) program and NOAA National Marine Sanctuaries (Table 6.1). Monitoring is also conducted within the National Estuarine Research Reserve System under a partnership between NOAA and the coastal states. In addition, EPA is mandated to conduct monitoring within certain sanctuaries (e.g., the Florida Keys Marine Sanctuary), and conducts the Environmental Monitoring and Assessment Program (EMAP). There are also formal and informal networks of coastal marine laboratories that provide opportunities for assessing past historical conditions and trends, leveraging ongoing observation programs, and establishing new observational systems and process studies. There are two additional ocean observing systems in development within the United States: the Ocean Observatories Initiative (OOI) and the Integrated Ocean Observing System (IOOS). The NSF-supported OOI will provide an integrated network of sensors for sustained observations at four open-ocean sites in the north and south Atlantic and Pacific, a regional observing network off the Pacific Northwest, and a coastal pioneer array, initially to be deployed at the shelf-break off New England (Consortium for Ocean Leadership, 2009). The IOOS, a federal, regional, and private-sector partnership, provides potential observational opportunities through a sub- Page 105 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × stantial network of open-ocean, coastal, and Great Lakes measurement sites and systems that are Integrated Ocean Observing System, 2009). Many of these existing chemical and ecological monitoring sites could serve as a backbone for an ocean acidification observational network. However, to understand and manage effects of acidification fully, new observational efforts likely will be required in additional locations, in particular for ecosystems that may be sensitive to acidification but are currently undersampled. Fabry et al. (2008a) identify four broad ecosystem areas that will require observations: warm-water coral reefs, subtropical/tropical pelagic regions, high latitude regions, and coastal margins. Within coastal regions, they highlight several specific areas: the Gulf of Alaska, western North American continental shelf, Bering Sea, Chukchi Sea, Arctic Shelf, the Scotian Shelf, Pacific coast of Central America, and the Gulf of Mexico. While existing and developing observing networks obtain measurements relevant to ocean acidification, they were not originally designed with ocean acidification in mind and thus do not have adequate coverage of these regions. The ocean inorganic carbon observing network is primarily in the open ocean with a U.S. coastal system just being developed (Doney et al., 2004; Borges et al., 2009); in contrast, the ecological monitoring networks are almost entirely in coastal areas (see Table 6.1). Similarly, not all sites have adequate measurements of carbonate chemistry or relevant ecological parameters relevant to ocean acidification. Current oceanic inorganic carbon monitoring programs do not always ensure enough parameters to fully constrain the seawater carbonate system; additional inorganic carbon measurements could greatly increase the value of existing monitoring programs for understanding acidification (Ocean Carbon and Biogeochemistry Program, 2009b; Feely et al., 2010). Ecosystem monitoring sites measure a number of biological parameters, but have not yet been addressing acidification effects directly. The observing network can be further expanded into additional poorly sampled, but critical, coastal, estuarine and coral reef ecosystems by incorporating ocean acidification related measurements on existing long-term ecological monitoring studies (e.g., marine Long-Term Ecological Research Network sites, NOAA Marine Sanctuaries, the National Estuarine Research Reserve System). Some systems may require finer spatial and temporal resolution of observations to match the environmental variability in chemical and biological parameters (e.g., tropical coral reefs and estuaries). Fine-scale measurements may also be necessary and cost-effective in areas where critical services may be affected, for example in locales with intensive aquaculture. The ocean acidification network could also become a component of or partner with OOI and IOOS; this would allow the network to leverage the assets of a developing integrated network Page 106 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × TABLE 6.1 Examples of Existing Federal Marine Ecosystem Monitoring Efforts that Could Be Leveraged for Ocean Acidification Observing and Research Program Name Location Long Term Ecological Research Stations (NSF) California Current Ecosystem California Florida Coastal Everglades Florida Georgia Coastal Ecosystems Georgia Moorea Coral Reef French Polynesia Palmer Stations Antarctica Plum Island Ecosystems Massachusetts Santa Barbara Coastal California Virginia Coast Reserve Virginia National Marine Sanctuaries (NOAA) Channel Islands California Cordell Bank California Florida Keys Florida Flower Garden Banks Texas Gray's Reef Georgia Gulf of the Farallones California Northwestern Hawaiian Islands Hawaii Monitor North Carolina (ship wreck) Monterey Bay California Olympic Coast Washington Hawaiian Islands Humpback Whale Hawaii Fagatele Bay American Samoa Stellwagen Bank Massachusetts Thunder Bay Great Lakes National Monuments (FWS & NOAA) Papahnaumokukea NW Hawaiian Islands Rose Atoll American Samoa Pacific Islands Baker, Howland, Jarvis, Johnston, Kingman, Palmyra, and Wake Is. Mariana Trench Northern Mariana Islands of observing systems. The OOI and IOOS networks complement existing U.S. subtropical ocean biogeochemical time-series stations by expanding into temperate and subpolar open-ocean environments and coastal waters, ecosystems that are currently identified as undersampled in community assessments of ocean carbon cycle and acidification research needs (e.g., Doney et al., 2004; Fabry et al., 2008a). Thus the existing network of ocean carbon and marine ecosystem observing sites and surveys, complemented by the ongoing develop- Page 107 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × ment of OOI and IOOS, will serve as a strong foundation upon which to build an ocean acidification observing network. However, the current network would be enhanced by adding monitoring sites and chemical and biological surveys in undersampled areas, particularly in areas of high variability (e.g., coastal regions), ecosystems projected to be vulnerable to ocean acidification (e.g., coral reefs and polar regions), and at depth. A community-based plan has been developed for an international ocean acidification observational network (Feely et al., 2010). The plan contains details on measurement requirements, information on data management, and an inventory of existing and planned monitoring sites and surveys. This document could serve as the basis for a national observing strategy. CONCLUSION: The existing observing networks are inadequate for the task of monitoring ocean acidification and its effects. However, these networks can be used as the backbone of a broader monitoring network. RECOMMENDATION: The National Ocean Acidification Program should review existing and emergent observing networks to identify existing measurements, chemical and biological, that could become part of a comprehensive ocean acidification observing network and to identify any critical spatial or temporal gaps in the current capacity to monitor ocean acidification. The Program should work to fill these gaps by: • ensuring that existing coastal and oceanic carbon observing sites adequately measure the seawater carbonate system and a range of biological parameters; • identifying and leveraging other long-term ocean monitoring programs by adding relevant chemical and biological measurements at existing and new sites; • adding additional time-series sites, repeat transects, and in situ sensors in key areas that are currently undersampled. These should be prioritized based on ecological and societal vulnerabilities. • deploying and field testing new remote sensing and in situ technologies for observing ocean acidification and its impacts; and • supporting the development and application of new data analysis and modeling techniques for integrating satellite, ship-based, and in situ observations. Sustainability of long-term observations is a perpetual challenge (e.g., Baker et al., 2007). Given the gradual and long-term pressure of ocean acidification on marine ecosystems, it is important to ensure continuity Page 108 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × of an ocean acidification observing system for a decade or more, beyond the typical time period of many research grants. Lack of sustained funding models for ecological time-series is a significant issue (Ducklow et al., 2009), and innovative funding approaches will be necessary to ensure the sustained operations of the ocean acidification observational network. To be sustainable and efficient, the ocean acidification network will have to leverage, coordinate, and integrate with existing observing systems, other components of international ocean acidification observing networks, and other efforts to build national and international integrated ocean observing systems. RECOMMENDATION: The National Ocean Acidification Program should plan for the long-term sustainability of an integrated ocean acidification observation network. 6.2 RESEARCH PRIORITIES The previous chapters describe the current state of knowledge regarding ocean acidification and its impacts. There is not yet enough information on the biological, ecological, or socioeconomic effects of ocean acidification to adequately guide management efforts. Most of the existing research has been on understanding acute responses in a few species. Very little is known about the impacts of acidification on many ecologically or economically important organisms, their populations, and communities, the effects on a variety of physiological and biogeochemical processes, and the capacity of organisms to adapt to projected changes in ocean chemistry (Boyd et al., 2008). There is a need for research that provides a mechanistic understanding of physiological effects; estimates the lifelong consequences on growth, survival, and reproduction; elucidates the acclimation and adaptation potential of organisms; and that scales up to ecosystem-level effects taking into account the role and response of humans in those systems. There is also a need to understand these effects in light of multiple, potentially compounding, environmental stressors. For some systems, particularly corals, there is strong indication of impacts, but little information on how best to manage the affected system beyond reducing other stressors and promoting general resilience. CONCLUSION: Present knowledge is insufficient to guide federal and state agencies in evaluating potential impacts of ocean acidification for management purposes. The committee notes that ocean acidification research is a growing field and that there have been concerns over appropriate experimental Page 109 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × design and techniques. For example, the interdependency of the inorganic carbon and acid-base chemistry parameters of seawater provides opportunities for multiple approaches, but also complicates the design of experiments and, in some cases, the comparison of results of different studies. This concern is expressed in the community development of The Guide to Best Practices in Ocean Acidification Research and Data Reporting, which provides guidance on measurements of seawater carbonate chemistry, experimental design of perturbation experiments, and measurements of CO2 sensitive processes (Riebesell et al., 2010). The use of appropriate analytical techniques and experimental design is obviously critical. To enable comparison among studies and across organisms, habitats, and time, the use of standard protocols may be necessary. Several recent workshops and symposia have brought together ocean acidification experts to identify critical information gaps and research priorities. In particular, detailed research recommendations on specific regions and topics exist in five community-based reports: Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide (Raven et al., 2005), Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research (Kleypas et al., 2006), Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles (Fabry et al., 2008a), Research Priorities for Ocean Acidification (Orr et al., 2009), and Consequences of High CO2 and Ocean Acidification for Microbes in the Global Ocean (Joint et al., 2009). Fabry et al. (2008a) provide detailed recommendations for four critical marine ecosystems that include prioritization and timelines (immediate to long term). The committee believes this report provides adequate detail to appropriately balance short- and long-term research goals, as well as research, observations, and modeling requirements. Appendix D briefly summarizes these five reports and their overarching recommendations; the committee notes that the reports build upon each other and reflect a community consensus on research direction. The committee surveyed these reports and compiled eight top research priorities, as well as some basic research approaches. The eight priorities are not ranked; the committee considers them complementary priorities to be addressed in parallel. RECOMMENDATION: Federal and federally funded research on ocean acidification should focus on the following eight unranked priorities: • understand the processes affecting acidification in coastal waters; • understand the physiological mechanisms of biological responses; • assess the potential for acclimation and adaptation; • investigate the response of individuals, populations, and communities; Page 110 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × • understand ecosystem-level consequences; • investigate the interactive effects of multiple stressors; • understand the implications for biogeochemical cycles; and • understand the socioeconomic impacts and inform decisions. The research priorities are described below in greater detail. They are complementary to and synergistic with the observational priorities presented in Section 6.1 (Observing Network). Both elements are critical to addressing the ocean acidification questions facing the nation, and the two approaches will benefit from close integration during the planning, implementation, and synthesis phases of the program. For example, long-term time-series and coastal- and basin-scale surveys provide an essential context for short-duration field process studies; in turn, laboratory and field experiments provide invaluable mechanistic information for interpreting the temporal and spatial patterns found from observational networks (Doney et al., 2004). Because ocean acidification is an emerging scientific endeavor, the research priorities presented below cannot be expected to be as detailed or explicit as the observational priorities from Section 6.1. They form a framework of key questions that should be addressed, and the details of the experimental approaches and designs would be best left to the creativity and innovation of individual researchers and research teams. Further, new priorities will undoubtedly arise over time based on new discoveries. Given the varying missions of the federal agencies that will fund and undertake acidification research, the committee has intentionally described broad priority areas derived from these reports; however, the committee encourages the agencies to refer to the reports for additional guidance. 6.2.1 Understand the Processes Affecting Acidification in Coastal Waters Coastal margins are already subject to extreme variability in acid-base chemistry due to natural and anthropogenic inputs such as acidic discharge of river water (Salisbury et al., 2008) and atmospheric deposition of nitrogen and sulfur (Doney et al., 2007), and eutrophication of coastal waters from elevated river nutrient inputs due to land-use changes and agriculture (Borges and Gypens, 2010). However, the processes affecting the variability in coastal carbonate chemistry are presently not well understood, and better understanding of these processes will be necessary to predict and manage the responses of important organisms, ecosystems, and industries in coastal waters. For example, the pH variability and range that a particular coastal location experiences may be strongly affected by fresh water runoff, which Page 111 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × tends to have higher dissolved CO_2 concentrations, and hence lower pH, than ocean water. Coastal pH is also affected by variations related to the physical and chemical dynamics of the ocean water column, such as variations in upwelling intensity and source water depth. In general, deep, old waters are the most acidic ocean waters, but because they have not been in contact with the atmosphere for some time, there is little invasion of fossil fuel CO_2. However, the lifetime of waters in the thermocline of the ocean is measured in decades, so some acidification of upwelling source waters by anthropogenic CO_2 is expected and detected already, and acidification of this old water is projected to increase strongly in coming decades (Feely et al., 2008; see also Chapter 2). Field surveys and synoptic reconstructions based on satellite data are only now revealing this variability and the mechanisms driving it; additional research and observations will improve understanding of oceanographic and hydrological forcing of pH variability in coastal regions, which provide a wealth of ecosystem services and are already subject to numerous stressors. Experimental research is also needed to characterize the impact of reduced carbonate ion concentrations and saturation states on non-living calcium carbonate particles, sediments, and reef structures. Laboratory and field studies indicate that the dissolution rates of unprotected carbonate materials increases sharply as the calcium carbonate saturation state drops below 1.0. In the water column, the shoaling of the saturation horizons and enhanced dissolution of sinking particles could alter the downward transport of food particles, carbon, and other materials to the subsurface ocean. In coastal environments, dissolution or weathering of carbonate sediments could partially buffer the effects of ocean acidification, but the faster dissolution rates could also lead to the reduction and eventual disappearance of reef structures that are valuable habitats. 6.2.2 Understand the Physiological Mechanisms of Biological Responses Studies have shown effects of changes in the carbonate system on calcification, photosynthesis, carbon and nitrogen fixation, reproduction, and a range of other metabolic processes (see Chapter 3). However, the underlying mechanisms for these responses remain unclear in many cases. While data on the overall physiological responses of various organisms to acidification are useful, they are difficult to interpret and generalize without a fundamental understanding of the underlying chemical or biochemical mechanisms. An important aspect of mechanistic studies is that they may be useful in establishing fundamental critical thresholds beyond which the biochemical machinery of organisms cannot cope with the change in particular environmental parameters. Page 112 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × A striking example of a need for mechanistic studies is that of calcification—the biogenic formation of calcium carbonate minerals. Over the last few years, it has become clear that the apparently simple response of calcifying organisms to ocean acidification is a product of complex biochemical processes (see Chapter 3). Continued refinement of the understanding of how organisms such as coccolithophores or corals utilize carbon and precipitate carbonate minerals will improve the ability to predict organism responses and could eliminate exhaustive laboratory testing on a species by species basis. A suite of improved genomic, molecular biological, biochemical, and physiological approaches using representative taxa are needed to better elucidate the mechanisms underlying those biological processes that show a response to ocean acidification. Particular examples of such processes, as highlighted in Chapter 3, include photosynthesis and photosynthetic carbon concentrating mechanisms, pathways for calcification, and physiological controls on acid-base chemistry. Mechanistic studies will also facilitate the development and interpretation of physiological stress markers needed as part of the observing system. But basic molecular and genetic tools are generally not available for marine organisms. Extending the genomic and proteomic data base to key species and developing new molecular tools, such as genetic transformation protocols for those species, would greatly enhance the ability to perform fundamental studies on marine organisms. 6.2.3 Assess the Potential for Acclimation and Adaptation Acclimation is the process by which an organism adjusts to an environmental change that gives individuals the ability to tolerate some range of environmental variability. Though focused on the response of individuals to survive stress, survival of individuals can lead to population-level effects. The potential for individuals of most species to acclimate to higher CO_2 and lower pH is not known, but will become increasingly important as ocean CO_2 levels rise. Adaptation is the ability of a population to evolve over successive generations to become better suited to its habitat. Adaptation to changing ocean chemistry is likely on some level for most taxa that have sufficient genetic diversity to express a range of tolerance for ocean acidification. It remains unknown whether populations of most species possess both the genetic diversity and a sufficient population turnover rate to allow adaptation at the expected rate and magnitude of future pH/pCO_2 changes. The persistence of various taxa under increasing ocean acidification will depend on either the capacity for acclimation (plasticity in phenotype within a generation) or adaptation (plasticity in genotype over successive Page 113 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × generations) or a combination of both. The relative capabilities of various taxa in terms of both acclimation and adaptation will likely influence the composition of marine communities and therefore result in a range of consequences for marine ecosystems. Currently, too little is known about the ability of marine species to acclimate and adapt to ocean acidification to allow for assessments or predictions about how individuals and populations will respond over time. A greater understanding of these topics would help fill the gaps between physiological studies and population and community-level effects. 6.2.4 Investigate the Response of Individuals, Populations, and Communities Well-controlled experiments, including perturbation experiments, observational studies (i.e., natural experiments) that exploit naturally-occurring spatial or temporal gradients or differences in ocean carbonate chemistry, and long-term observations of ecosystem responses to developing ocean acidification, are needed to investigate the sensitivity of individuals, populations, and communities to ocean acidification. Available information on the biological effects of acidification is currently limited to a few model organisms. While useful, this incomplete data set makes any forecast or assessment of possible impacts of acidification subject to error because of the strong potential for differential sensitivities to acidification among taxa. Extending experimentation to a range of representative organisms from key taxa in potentially affected ecosystems would allow for the identification of species or phyla that are particularly sensitive or insensitive to acidification. This is, of course, also the case for commercially important fish and shellfish. For aquaculture, it would be useful to identify tolerant subpopulations that may be used for selective breeding. In the case of deep sea ecosystems, about which very little is known, acquiring basic data on the effects of acidification on taxa representative of major phyla is an essential first step. There are clear indications that the sensitivity of higher organisms to acidification is often greater during early life stages. The evaluation of the sensitivity of various species to acidification must thus include due consideration of the life histories of these species. Experiments designed to detect effects on multiple life stages and acclimation potential are thus essential. The present knowledge of pH and pCO_2 sensitivities of marine organisms is based almost entirely on short-term experiments. Interpreting and extrapolating such data requires a careful consideration of time scales. For example, the long-term success of organisms depends equally on their ability to overcome nonproductive periods, such as seasonal low light or low nutrient periods, as on rapid growth during Page 114 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × productive periods. As indicated by some experiments, the sensitivities of organisms to acidification may depend on the duration of exposure. Some organisms may be able to withstand the stress for only short exposure times; others may be able to acclimate or the population may adapt over long periods. In addition, measured positive and negative effects of ocean acidification on specific physiological processes may not always result in a net and lifelong benefit or harm for the individual. There is thus a need to design and carry out acidification experiments that test the effect of exposure time and consider cumulative effects over the entire lifespan of an organism. Therefore, manipulative experiments are required on a variety of scales, from laboratory culture incubations of single species to mesocosms and in situ perturbations with natural assemblages. Where feasible, it will be important to expand classical dose-response studies to encompass long-term and multi-generational high-CO_2 exposure experiments. It will also be necessary to design these studies to allow for reproduction and genetic recombination to test for (1) acclimation and adaptation potential and (2) cross-generational effects (those emerging in offspring generations). The use of paleo analogs and the improvement of paleo proxies may help to cover evolutionary timescales of longer-lived organisms. 6.2.5 Understand Ecosystem-level Consequences There is little information on how the effects of ocean acidification on individual species will cascade through food webs, ultimately affecting the structure and function of ecosystems. Possible mechanisms for the transmission of the effects of ocean acidification through ecosystems include changes in microbial processes, nutrient recycling, species competition, species symbioses, calcium carbonate production, disease, and others. In some cases, effects can be transmitted from remote locations. For example, a change in upper ocean productivity and plankton composition could affect deep-sea organisms through a change in the downward flux of organic matter even before the deep sea experiences acidification. Particularly difficult is the problem of predicting possible regime shifts (e.g., the collapse of a fishery or the shift from a coral-dominated to an algal-dominated system) which result from poorly understood nonlinearities in the internal dynamics of ecosystems. Future research on thresholds and ecological tipping points should help define indicators of regime shifts could help managers to anticipate shifts before they occur (de Young et al., 2008; Scheffer et al., 2009) and take action to either avoid them or cope with them. Because resilience allows ecosystems to resist change, another important research challenge is how to maintain or increase resilience in marine ecosystems despite continued ocean acidification, occurring alongside Page 115 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × increases in temperature and other stressors. To promote resilience in ecosystems threatened by ocean acidification, it will be important to understand what, when, and how keystone species or key functional groups will be affected. Ocean acidification will not only cause declines in some species, but increases in others; ways to understand the effects of both of these shifts need to be considered in future research strategies. A suite of complementary approaches at various scales are needed to better understand and perhaps even predict ecosystem responses to acidification. These include controlled laboratory experiments on single organisms or cultures, bottle incubation microcosm experiments with natural microbial communities, mesocosm experiments in large enclosures, studies of natural high CO_2 environments, and field surveys along gradients in carbonate chemistry. In addition, modeling studies can be used to integrate our knowledge of physical, chemical, and biological processes to large scales. As illustrated in Figure 6.1, all these approaches have their advantages and inherent limitations. Whereas small-scale incubation experiments, also known as culture experiments, are well controlled and allow for high replication, they lack trophic complexity and reality. At the other extreme, in situ manipulations and open water experiments allow for trophic complexity, but they are still limited in their spatial and temporal scales, allow for only a small number of replicates, and provide limited control of environmental conditions. Studies along natural, temporal, and spatial CO_2 gradients and in systems with high CO_2 variability, such as natural CO_2 vents, upwelling systems, coastal waters, and poorly buffered seas can provide the basis to help infer the response of marine ecosystems to future ocean acidification. These studies have the advantage of covering the "real" world, but they rarely approximate the actual ecosystems of interest and the data interpretation is often confounded by other variables. The insight gained from modeling studies is currently limited by imperfect knowledge of processes and parameters that are included in the model. To supplement these approaches, it might be possible in some cases to adapt to particular ocean ecosystems such as coral reefs the whole ecosystem manipulation approach that has been used extensively in terrestrial systems, particularly in lakes. In addition to examining the effects of ocean acidification, ecosystem studies can be designed to assess the efficacy and environmental consequences of ocean carbon management approaches including ocean acidification mitigation. Finally, insight into possible thresholds and tipping points may come from studies of other systems that undergo regime shifts. Progress on understanding the future consequences of ocean acidification for marine ecosystems will require innovative methods for laboratory and ocean research and observation. Because studies of whole ecosystems are technically difficult, particularly in ocean settings, Page 116 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × FIGURE 6.1 Experimental approaches with indication of their respective strengths and weaknesses. Photographs at top show phytoplankton bottle experiments in a culture chamber (left, courtesy of Kai Schulz, IFM-GEOMAR), cold-water corals in experimental aquaria (center left, courtesy of Armin Form, IFM-GEOMAR), an offshore mesocosm experiment in the Baltic Sea in spring 2009 (center right, Ulf Riebesell, IFM-GEOMAR), and a natural CO_2 venting site off Naples in the Mediterranean Sea (right, R. Rodolfo-Metalpa, reprinted with permission from Macmillan Publishers Ltd., Riebesell, 2008, Nature). (Gattuso et al., 2009) types of studies will require coordination during planning and execution, perhaps including a 'task force' approach for targeted experiments. For example, research on an important and potentially vulnerable system (e.g., cod, salmon, and sardine/anchovy) may benefit from a coordinated research program including elements such as: • overlap with the regional ocean acidification observation network; • field studies documenting changes in ecosystem structure and function over natural pH gradients; • mesocosm experiments to understand the response of phytoplankton and micrograzer communities to ocean acidification; Page 117 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × • laboratory experiments on the performance and survival of key food web taxa over multiple life stages in response to ocean acidification; • field and laboratory studies of the effects of ocean acidification on early life history phases and adults of the target fishery species; and • whole ecosystem manipulation studies (if possible). This approach could increase the value of focused experimental and observational studies and may be a key approach in understanding critical links in ecosystems that are sensitive to ocean acidification. 6.2.6 Investigate the Interactive Effects of Multiple Stressors The problem of ocean acidification is intrinsically one that involves multiple stressors (Miles, 2009). First, the increase in CO_2 concentration and the decrease in the pH and carbonate ion concentration occur simultaneously and cause a variety of other chemical changes in the chemistry of seawater. Organisms subjected to ocean acidification must also cope with the other effects of increasing atmospheric CO_2 on the climate, such as warming and increased stratification of surface waters. And, of course, marine ecosystems are affected by a variety of human activities such as fishing or pollution of coastal waters. It is inherently difficult to study the interaction of ocean acidification with other stressors such as warming or expanding hypoxia on marine ecosystems, if only because of the large number of parameter combinations that need to be studied. In addition, environmental stresses often act synergistically, as illustrated by the simultaneous effects of high temperature events and acidification on coral bleaching or acidification and hypoxia on deep-sea crabs. For the same reason, it may also be difficult to assign any future changes in the ocean biota to a particular cause such as a decrease in pH or a decrease in carbonate ion concentration, but it will also be important to understand how acidification will impact organisms and ecosystems in light of these multiple stressors. The perplexing problem of multiple stressors will require demanding and perhaps innovative experimental designs. In addition to factorial experiments, carefully constructed cross-site comparisons, fundamental studies of mechanisms, and synthetic modeling efforts may prove most valuable. As a whole, the field would benefit from the development and discussion of unifying concepts as foundations for research on stressors that could encompass a range of effects, from the molecular to the ecosystem level. Such a conceptual base would enable identification of similarities and differences across taxa which would be of value to the field. Page 118 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 6.2.7 Understand the Implications for Biogeochemical Cycles Changes in ocean chemistry and biology due to ocean acidification have the potential to alter the oceanic cycles of carbon, nitrogen, oxygen, trace metals, other elements, and trace gases. Many of the biogeochemical priorities identified in community research plans can be grouped broadly into several interrelated themes. Ocean acidification will likely affect ocean CO_2 storage, though magnitude of the perturbation is not known because of possible counter-balancing effects. Reduced water-column and benthic calcification and faster sub-surface calcium carbonate dissolution will result in increases in surface ocean alkalinity, which in turn enhance oceanic uptake of atmospheric CO_2. CO_2 storage is also influenced by biological export production, which may decline in some locations due to shifts away from calcifying plankton and thus reduced ballast material for sinking particles. On the other hand, export production may grow in other locations from elevated nitrogen fixation and possibly higher carbon to nutrient elemental ratios for biologically produced particulate material. These same processes would also significantly alter the subsurface distribution and cycling of carbon, nutrients and oxygen. In particular, it has been argued that elevated carbon to nutrient ratios in sinking particles could drive an expansion of tropical and subtropical oxygen minimum zones and increase marine denitrification. Ocean acidification could also influence climate and atmospheric chemistry via altered marine trace gas emissions (e.g., nitrous oxide, dimethylsulfide, and methyl halides). Finally, the impact of reduced pH on trace metal bioavailability and the chemical reactivity of dissolved organic matter are poorly understood at present. More research is needed to understand the mechanisms governing these biogeochemical impacts and the magnitudes of the overall effects. Observations of natural systems and manipulative experiments in laboratory and field settings are essential approaches for understanding the effects of ocean acidification on biogeochemical cycles. Numerical models also provide an important tool for quantitatively assessing the global impacts of acidification, exploring interactions among different chemical, physical and biological processes, testing hypotheses, developing projections of future behavior, and exploring feedbacks between ocean dynamics and the larger Earth system and climate. An understanding of these changes could also be informed by studying the geological record of ocean acidification. New proxy measurements, such as boron isotopes, give the promise of an estimate of surface and deep ocean pH changes over time. Although not analogous, the geological record might provide some insights on the impact of ocean acidification through quantification of the marine ecological disruption of corals, the benthos, and the plankton in the ocean and shelf environments. Page 119 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 6.2.8 Understand the Socioeconomic Impacts and Inform Decisions To promote effective and informed decision making, it will be critical to integrate socioeconomic research—both for and on decision support—with natural science research. Research is needed to identify socioeconomic impacts by sector and region, to predict time frames of impacts, and to understand how to increase adaptability and resilience of socioeconomic systems. This information will enable individuals, organizations, and communities to plan for and adapt to the impacts of ocean acidification. Quantifying the cost to society of ocean acidification—its effect on the economic and social value of affected marine resources—is necessary to prioritize research efforts and decide on possible mitigation or adaptation strategies. Performing these analyses will need to be an iterative process that builds on the available research and understanding of the scope of the potential impact of acidification. As more research is performed, the boundaries of the socioeconomic analyses will shift, and research priorities may need to be adjusted. It is important to remember that standard economic methods can be applied to market goods such as seafood, but a major part of the value of the marine resources that may be affected derives from non-market goods such as recreation or ecosystem services. These will require the use of valuation methods adapted to each type of good. Because non-market valuation studies are expensive, it may be useful to use benefit transfer methods based on studies in other areas. The impact of ocean acidification is likely to last far in the future so that valuation of its economic and social cost will need to give due consideration to the likely increase in value of some of the affected resources in the future and to the choice of appropriate discount rate. Understanding, predicting, and valuing impacts of ocean acidification on marine ecosystems are only the first steps. Research is also needed to improve strategies and approaches for marine ecosystem management (see section 6.3). Communities in areas with affected marine resources may be highly dependent on them both for income and sustenance. There is thus a need to assess vulnerability and adaptation capabilities of these communities over different time frames. Vulnerability assessments for fishing communities are already called for as a normal input to regulatory review for fisheries management (Clay and Olson, 2008); however, they may tend to take a short term outlook as they are typically most concerned with current or imminent changes. Since many impacts may be hard to predict with any accuracy, there is also a need to develop (and test through modeling) adaptation strategies that are robust to uncertainty about what the specific impacts will be and when they will happen. Research focused on understanding the value of advance information (e.g., more accurate and earlier predictions of biological and ecological impacts on fisheries) Page 120 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × in improving adaptation can help determine the research expenditures that are justified in providing these predictions. There may be substantial similarity or synergy between the types of impacts on fisheries and fishing communities resulting from climate change and those due to ocean acidification. Ideally, research on vulnerability and adaptation strategies will take this into account and attempt to identify adaptation strategies that address changes on a variety of time scales and minimize conflicts between short-term and long-term objectives. 6.3 ASSESSMENT AND DECISION SUPPORT The FOARAM Act of 2009 charges the IWG with overseeing the development of impacts assessments and adaptation and mitigation strategies, and with facilitating communication and outreach with stakeholders (P. L. 111-11). In the previous chapters, the committee identified some economic sectors and geographical regions that may be impacted by ocean acidification. The committee also identified some potential stakeholder groups, including the fishing and aquaculture industries and coral reef managers (and communities and industries that rely on services provided by reefs). However, this is not an exhaustive list; as understanding of ocean acidification impacts improves, so will identification of stakeholder groups. Given the range of potential ecological and socioeconomic impacts outlined in the previous chapters, the need for decision support is clear. Moving from science to decision support is often a major challenge. Indeed, it has been noted that, for climate change, "discovery science and understanding of the climate system are proceeding well, but use of that knowledge to support decision making and to manage risks and opportunities of climate change is proceeding slowly" (National Research Council, 2007b). Because ocean acidification is a relatively new concern and research results are just emerging, it will be even more challenging to move from science to decision support. Nonetheless, ocean acidification is occurring now and will continue for some time, regardless of changes in carbon dioxide emissions. Resource managers will need the ability to assess and predict these impacts on ecosystems and society, develop management plans and practices that support ecosystem resilience, identify and remove barriers to effective management response, and promote flexible decision making that adapts to challenging time scales and to altered ecosystem states (West et al., 2009). The National Research Council (2009a) describes a comprehensive framework for decision support, including six principles for effectiveness: 1. Begin with users' needs, identified through two-way communication between knowledge producers and decision makers Page 121 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 2. Give priority to process (e.g., two-way communication with users) over products (e.g., data, maps, projections, tools, models) to ensure that useful products are created 3. Link information producers and users 4. Build connections across disciplines and organizations 5. Seek institutional stability for longevity and effectiveness 6. Design for learning from experience, flexibility, and adaptability. (National Research Council, 2009a) Given the limited current knowledge about impacts of ocean acidification, the first step for the National Ocean Acidification Program will be to clearly define the problem and the stakeholders (i.e., for whom is this a problem and at what time scale?), and build a process for decision support. For climate change decision support, there have been pilot programs within some federal agencies (e.g., National Integrated Drought Information System, the Environmental Protection Agency's National Center for Environmental Assessment, NOAA Regional Integrated Sciences and Assessments [RISA] and Sectoral Applications Research Program [SARP]) and there is growing interest within the federal government for developing a national climate service to further develop climate-related decision support (National Oceanic and Atmospheric Administration, 2009b). Potentially useful tools and approaches for ecosystems and fisheries are also being developed in the context of marine ecosystem-based management and marine spatial planning (e.g., McLeod and Leslie, 2009; Douvere, 2008). The National Ocean Acidification Program could leverage the expertise of these existing and developing programs. Decision support for ocean acidification could even become an integrated component of other climate service or marine ecosystem-based management programs. In addition, several recent reports have been produced on effective assessments and decision support for climate change that are equally applicable to ocean acidification (e.g., National Research Council 2005a, 2007a, b, c, 2008, 2009a; Adger et al., 2009); in particular, the committee notes two recent NRC reports—Analysis of Global Change Assessments: Lessons Learned (National Research Council, 2007a) and Informing Decisions in a Changing Climate (National Research Council, 2009a)—which build on previous reports and provide a strong foundation for developing an assessment and decision support strategy for ocean acidification. In particular, the FOARAM Act of 2009 (P.L. 111-11) repeatedly calls for various assessments of ocean acidification impacts. A similar mandate was given for periodic climate change assessments in the Global Change Research Act (GCRA) of 1990 (P. L. 101-606). To improve its assessment process, the U.S. Climate Change Science Program asked the NRC to look at lessons learned from past global change assessments (National Research Council, Page 122 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × 2007a). The 11 essential elements of effective assessments determined in the NRC (2007a) report could serve as useful guidance for the development of an ocean acidification assessment strategy. RECOMMENDATION: The National Ocean Acidification Program should focus on identifying, engaging, and responding to stakeholders in its assessment and decision support process and work with existing climate service and marine ecosystem management programs to develop a broad strategy for decision support. 6.4 DATA MANAGEMENT Data quality and access with both be integral components of a successful program. As previously discussed, appropriate experimental design and measurement protocols are required for high-quality data. Data reporting and archiving is important to ensure that data and associated metadata (i.e., the information about where, when, and how samples were collected and analyzed, and by whom) are accessible to researchers now and in the future. In many cases, metadata are often as important as the actual data; detailed metadata is particularly essential for manipulative experiments. Similar large-scale research programs such as U.S. JGOFS, U.S. Global Ocean Ecosystems Dynamics (GLOBEC), the LTER network, and USGCRP have developed data policies that address data quality, access, and archiving to enhance the value of data collected within these programs. The Guide to Best Practices in Ocean Acidification Research and Data Reporting provides guidance on data reporting and usage (Riebesell et al., 2010). The data management component of a National Ocean Acidification Program could build on lessons learned from previous ocean research programs (e.g., Glover et al., 2006). Elements of a successful program include: • devoting sufficient resources, about 5–10% of the total cost of the program—investments include both hardware and competent staff; • a management office established early in the program to shepherd data management even before field programs begin; • the development of conventions for standard methods, names, and units, as well as an agreed-to list of metadata to be collected along with the data, before field programs begin; • an agreement among investigators to share their data with each other, leading to more rapid scientific discovery (in some cases, this requires changes in the scientific culture and incentives for investigators); • ongoing two-way interactions between the data managers and Page 123 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × the principal investigators to make the database a living database and improve the final data quality; and • linkages between data management and data synthesis. Data rescue efforts that compile, analyze and make publicly available existing historical data that are not currently available in electronic form would be beneficial to the field. There are many existing data management offices and data centers that could support ocean acidification observational and research data, including: • The Biological and Chemical Oceanography Data Management Office (BCO-DMO) is funded by the NSF Division of Ocean Sciences and manages new data from biological and chemical oceanographic investigations, as well as legacy data from U.S. JGOFS and GLOBEC. • Carbon Dioxide Information Analysis Center (CDIAC) is supported by the Department of Energy and provides data management support for a range of climate change projects including FACE and the Ocean CO_2 Data Project. • The CLIVAR and Carbon Hydrographic Data Office (CCHDO) is supported by NSF and serves as a repository for CTD and hydrographic data from WOCE, CLIVAR, and other oceanographic research programs. • The World Data Center for Marine Environmental Sciences (WDC-MARE) is maintained by the Alfred Wegener Institute for Polar and Marine Research (AWI) and the Center for Marine Environmental Sciences at the University of Bremen. It is a collection of data from international (primarily European) oceanographic projects including EPOCA and BIOACID. RECOMMENDATION: The National Ocean Acidification Program should create a data management office and provide it with adequate resources. Guided by experiences from previous and current large-scale research programs and the research community, the office should develop policies to ensure data and metadata quality, access, and archiving. The Program should identify appropriate data center(s) for archiving of ocean acidification data or, if existing data centers are inadequate, the Program should create its own. The FOARAM Act calls for an "Ocean Acidification Information Exchange to make information on ocean acidification developed through or utilized by the interagency ocean acidification program accessible through electronic means, including information which would be use- Page 124 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × ful to policymakers, researchers, and other stakeholders in mitigating or adapting to the impacts of ocean acidification" (P. L. 111-11). The committee agrees that information exchange is an important priority for the program. The Information Exchange proposed by the Act would go beyond chemical and biological measurements and also include syntheses and assessments that would be accessible to and understandable by managers, policy makers, and the general public (see section 6.3). It could also act as a conduit for two-way dialogue between stakeholders and scientists to ensure that decision support products are meeting needs of the stakeholders. A "one-stop shop" of ocean acidification information would be an extremely powerful tool, but would require resources and expertise, particularly in science communication, to perform effectively. The committee was asked to consider the appropriate balance among research, observing, modeling and communication. While the appropriate balance of research, observing, and modeling activities will best be determined by the IWG and individual agencies relative to their missions, the committee would like to stress the importance of communication. To successfully engage stakeholders in a two-way dialogue, the National Ocean Acidification Program will require a mechanism for effectively communicating results of the research and receiving feedback and input from managers and others seeking decision support. Inadequate progress in communicating results and engaging stakeholders, largely due to the lack of a communication strategy, has been a criticism of the U.S. Climate Change Science Program (National Research Council, 2007b). It will be important that the Ocean Acidification Information Exchange avoid a similar outcome. Both the EPOCA and OCB Program have web-based approaches for communicating science information on ocean acidification to the general public, and the National Program is encouraged to build on and learn from existing efforts in its development of an Ocean Acidification Information Exchange. RECOMMENDATION: In addition to management of research and observational data, the National Ocean Acidification Program, in establishing an Ocean Acidification Information Exchange, should provide timely research results, syntheses, and assessments that are of value to managers, policy makers, and the general public. The Program should develop a strategy and provide adequate resources for communication efforts. 6.5 FACILITIES AND HUMAN RESOURCES Additional facilities and trained researchers will be needed to achieve the research priorities and high quality observations described in previ- Page 125 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × ous sections. In some instances, ocean acidification research is likely to require large community resources and facilities, including central facilities for high-quality carbonate chemistry measurements, free-ocean CO_2 enrichment (FOCE)-type experimental sites, mesocosms, wet labs with well-controlled carbonate chemistry systems, facilities at natural analogue sites, and intercomparison studies to enable integration of data from different investigators. Currently, some common facilities exist but are fairly limited. Internationally, several large-scale facilities exist or are being developed, including a mesocosm facility at the Korean Ocean Research and Development Institute in Jangmok (Kim et al., 2008) and a European Union network of aquatic mesocosm facilities (: six in-shore mesocosm facilities and a mobile off-shore mesocosm system. Comparable facilities are being developed within the United States: Friday Harbor Laboratories of the University of Washington (James Murray, University of Washington, personal communication); a FOCE prototype is in development at MBARI (; and "natural laboratories" have been suggested at deep and shallow CO_2 vents near the Northern Mariana Islands and other hydrothermal vents (Fabricius, 2009). These larger facilities may be required to scale up to ecosystem-level experiments; however, it is important to note that there are trade-offs in the various types of facilities—for example, open-ocean mesocosms are a significant scale up from coastal mesocosms but are also more costly—and that a mix of facilities will be necessary to achieve the appropriate cost-effective balance of research scales. Ocean acidification is a highly interdisciplinary growing field, which will attract graduate students, postdoctoral investigators, and principal investigators from various fields. Training opportunities to help scientists make the transition to this new field may accelerate the progress in ocean acidification research. It may also be necessary to engage researchers in fields related to management and decision support. Preliminary capacity building efforts for ocean acidification are being developed by the OCB and EPOCA programs (e.g., ... RECOMMENDATION: As the National Ocean Acidification Program develops a research plan, the facilities and human resource needs should also be assessed. Existing community facilities available to support high-quality field- and laboratory-based carbonate chemistry measurements, well-controlled carbonate chemistry manipulations, and large-scale ecosystem manipulations and comparisons should be inventoried and gaps assessed based on research needs. An assessment should also be made of community data resources such as genome sequences for organisms vulnerable to ocean acidification. Where facilities or data resources are lacking, the Program should support their development, which in some cases also may require additional investments in technology development. The Program should also support the development of human resources through workshops, short-courses, or other training opportunities. 6.6 PROGRAM PLANNING, STRUCTURE, AND MANAGEMENT The committee presents ambitious priorities and goals for the National Ocean Acidification Program, which are also echoed in the FOARAM Act and many other reports. To achieve these goals, the Program will have to lay out clear strategic and implementation plans. While the ultimate details of such plans are outside the scope of this study, there are some elements that the committee believes are necessary for a successful program. In considering recommendations on program implementation, the committee took lessons learned from large-scale research projects such as the NSF LTER Network, the USGCRP, and in particular, major oceanographic programs in its analysis and recommendations for the successful implementation of a National Ocean Acidification Program. It is important to stress, however, that a National Ocean Acidification Program—which must also link the science to decision making—will have challenges beyond these largely research-oriented programs. The challenges to improve understanding of large-scale oceanographic phenomena with global implications has led to the rise of major U.S. oceanographic programs such as Climate VARiability and Predictability (CLIVAR), Global Ocean Ecosystems Dynamics (GLOBEC), Joint Global Ocean Flux Study (JGOFS; see Box 6.2 for case study), Ocean Drilling Program (ODP), Tropical Ocean Global Atmosphere (TOGA), and World Ocean Circulation Experiment (WOCE) programs (National Research Council, 1999). These major oceanographic programs have been recognized for their important impact on the ocean sciences, achieving an understanding of large-scale phenomena not likely without such a concentrated effort; they also produced a legacy of high-quality data, new facilities and technologies, and a new generation of trained scientists (National Research Council, 1999). In 1999, the NRC reviewed the major oceanographic programs and devised a list of guidelines and recommendations for the creation and management of large-scale oceanographic programs (see Box 6.3). The FOARAM Act calls for the IWG to develop a detailed, 10-year strategic plan for the National Ocean Acidification Program. The committee first addresses the issue of program length. The committee agrees that a clearly defined end is appropriate because it allows for the develop- Page 126 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 6.2 The Joint Global Ocean Flux Study: A Model for Success The U.S. Joint Global Ocean Flux Study (JGOFS) was a multi-agency and multi-disciplinary research and monitoring program, linked to an international program, which coordinated an ambitious agenda to study the ocean carbon cycle. The U.S. JGOFS program, a component of the U.S. Global Change Research Program, was launched in the late 1980s and ran until 2005. The international program, which began a few years after the U.S. program, had over 30 participating nations; it began under the auspices of the Scientific Committee on Oceanic Research (SCOR) and eventually became a core program of the International Geosphere-Biosphere Program (IGBP). The main goal of the JGOFS program was to understand the controls on the concentrations and fluxes of carbon and associated nutrients in the ocean. Some of the accomplishments include improved understanding of the roles of physical and biological controls on carbon cycling, improved understanding of the role of the North Atlantic in the global carbon cycle, and improved modeling of oceanic carbon dioxide uptake (National Research Council, 1999). As a result of the JGOFS program, ocean biogeochemistry emerged as a new field, with emphasis on quality measurements of carbon system parameters and interdisciplinary field studies of the biological, chemical, and physical processes which control the ocean carbon cycle. U.S. JGOFS was supported primarily by the U.S. National Science Foundation in collaboration with the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Energy, and the Office of Naval Research. FROM: ment of milestones and assessment to ensure that goals are met (National Research Council, 1999). A 10-year time frame may be adequate time to achieve many of the goals set out, but based on the experience of other major oceanographic programs, the program in its entirety may need to span a longer period (possibly 15–20 years) to incorporate an adequate synthesis phase following the field and laboratory components (e.g., Doney and Ducklow, 2006). The ultimate length of the plan will have to reflect the minimum time needed to adequately address the questions posed, and will require community input. Further, a National Ocean Acidification Program will have many elements (e.g., operational elements such as decision support) that will naturally continue beyond the initial decade; it will be critical to establish a legacy program for extended ocean acidification observation, research, and management at the outset. In applying the guidelines from the NRC review of major oceanographic programs (National Research Council, 1999) to the design of a National Ocean Acidification Program, the committee identified some Page 128 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × BOX 6.3 Lessons Learned from Major Oceanographic Programs The following paraphrases the recommendations made in Global Ocean Science: Toward an Integrated Approach (National Research Council, 1999) that address management of major programs. These recommendations are directly relevant to the development of a National Ocean Acidification Program. • The federal sponsors ... should encourage and support a broad spectrum of interdisciplinary research activities, varying in size from a collaboration of a few scientists, to intermediate-size programs, to programs perhaps even larger in scope than the present major oceanographic programs. • Major allocation decisions (for example, extramural and internal funding of agency research) should be based on wide input from the community and the basis for decisions should be set forth clearly to the scientific community. • ... Sponsors and organizers of any new oceanographic program should maintain the flexibility to consider a wider range of program structures before choosing one that best addresses the scientific challenge. • During the initial planning and organization of new oceanographic programs, an effort should be made to ensure agreement between the program's scientific objectives and the motivating hypotheses given for funding. • The structure should encourage continuous refinement of the program. • The overall structure of the program should be dictated by the complexity and nature of the scientific challenges it addresses. Likewise, the nature of the administrative body should reflect the size, complexity, and duration of the program. • All programs should have well defined milestones, including a clearly defined end. An iterative assessment and evaluation of scientific objectives and funding should be undertaken in a partnership of major ocean program leadership and agency management. • Modelers, [experimentalists,] and observationalists need to work together during all stages of program design and implementation. • A number of different mechanisms should be implemented to facilitate communication among the ongoing major ocean programs [and other ocean acidification programs], including (but not limited to) joint annual meetings of SSC chairs and community town meetings. • When the scale and complexity of the program warrants, an interagency project office should be established. Other mechanisms, such as memoranda of understanding (MOU), should also be used to ensure multi-agency support throughout the program's lifetime. • ... The program and sponsoring agencies should establish (with input from the community) priorities for moving long-time series and other observations initiated by the program into operational mode. Factors to be considered include data quality, length (i.e., duration of program), number of variables, space and time resolution, accessibility for the wider community, and relevance to established goals. • ... Federal sponsors and the academic community must collaborate to preserve and ensure timely access to the data sets developed as part of each program's activities. FROM: National Research Council, 1999. Page 129 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × priorities for program planning, structure, and management that will help to bring about a successful program. While the strategic plan being developed by the IWG may not contain all of the details necessary, the committee believes it is critical that an implementation plan define, at a minimum: (1) Goals and objectives: Clear research, observational, and operational priorities and objectives are essential to develop a National Ocean Acidification Program. Without them, meaningful program assessment is not conceivable. (2) Metrics for evaluation: Without well-defined metrics tied to both goals and objectives, meaningful or effective program evaluation is not possible. One cannot manage without measurement. Program operation includes and requires process, outcome, and impact evaluations—all of which depend upon well-defined measurement (National Research Council, 2005b). (3) Mechanisms for coordination, integration, and evaluation: Given the proposed Program's complexity, particular care and attention will be required to assure needed coordination between, integration of, and communication among the numerous, diverse program elements and entities. Mechanisms will also need to be put in place to facilitate true two-way communication among research community, decision makers, and stakeholders. (4) Means to transition research and observation to operations: The plan will need to anticipate and account for the transition of some research and observational program elements to operational status. The transition plans will ensure the continuity of long-term observations and research products and facilitate the establishment, where called for, of legacy elements that continue beyond the termination of the Program. (5) Agency roles and institutional responsibilities: Roles and responsibilities of every federal agency participating in the Program must be carefully specified and clearly conveyed to all the involved (Ocean Carbon and Biogeochemistry Program, 2009a). The Program could take advantage of existing and new mechanisms for interagency funding of targeted research and observational elements. (6) Coordination with existing and developing national and international programs: Ocean acidification is being recognized and taken seriously in numerous countries and diverse organizations in the United States and around the world. Given the global scope of ocean acidification, significant efforts are required to take advantage of and leverage joint research and observational opportunities. Coordination is also needed to avoid possible duplications of effort. In particular, there are several different types of natural linkages with: a. ongoing large-scale ocean and climate projects in the United States such as CLIVAR and OCB, the USGCRP, OOI, and IOOS; Page 130 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × b. other national and multi-national carbon cycle, climate change, and ocean acidification programs (e.g., EPOCA, BIOACID, UK Ocean Acidification Research Programme, IMBER, SOLAS) and in particular the recently formed SOLAS-IMBER ocean acidification working group; d. international scientific bodies such as the Intergovernmental Oceanographic Commission (IOC), the International Council for Science Scientific Committee on Oceanic Research (SCOR), the World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP), the International Council for the Exploration of the Sea (ICES), and the North Pacific Marine Science Organization (PICES) that have had demonstrated success in planning and coordinating international oceanographic research programs. (7) Resource requirements: Based on the Program's stated goals and objectives, realistic resources must be identified and allocated to ensure success. Scrupulous attention to specific program elements, including those devoted to program management, data management, training, outreach and decision support, will be necessary. Given the dynamic and complex character of the ocean acidification problem, the commitment of significant resources for exploratory, innovative, and high-risk research will also be necessary. (8) Community input and external review: Progress toward achievement of the Program's goals and objectives can only be measured and weighed based on periodic, transparent, and effective assessments and reviews. Peer reviews for proposals and performance are critical to keep the Program on course toward its targeted goals and objectives. RECOMMENDATION: The National Ocean Acidification Program should develop a detailed implementation plan with community input. The plan should define (1) goals and objectives; (2) metrics for evaluation; (3) mechanisms for coordination, integration, and evaluation; (4) means to transition research and observational elements to operational status; (5) agency roles and responsibilities; (6) coordination with existing and developing national and international programs; (7) resource requirements; and (8) community input and external review. If fully executed, the elements outlined in the FOARAM Act and recommended in this report—monitoring, interdisciplinary research, Page 131 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × assessment and decision support, data management, facilities, training, reporting, and outreach and communication—would create a large-scale and highly complex program that will require sufficient support. These program goals are certainly on the order of, if not more ambitious than, major oceanographic programs and will require a high level of coordination that warrants a program office. This program office would not only coordinate the activities of the program, but would also serve as a central point for communicating and collaborating with outside groups such as Congress and international ocean acidification programs. Ocean acidification is a global problem that presents challenges for research, but it also presents opportunities to share resources and expertise that may be beyond the capacity of a single nation. Therefore, international collaboration is critical to the success of the Program. It will be important to coordinate with the various other national and multi-national ocean acidification programs, as well as other international ocean carbon cycle, climate change, and marine ecosystem research programs to leverage existing resources and avoid duplication of efforts. There are many models for such an office. The IWG called for in the FOARAM Act can be an effective approach for linking research efforts across the federal government because it resides within the JSOST, which provides for the coordination of science and technology across ocean agencies; however, a mechanism for outside input from academic scientists would be required since IWG membership is limited to federal agencies. An outside scientific steering committee consisting of representatives from the community, usually principal investigators, has been used in many major oceanographic programs (e.g., U.S. JGOFS), but this group would need to represent all stakeholders and there would still need to be a mechanism for interagency coordination of resources. An approach that combines both elements may be the best for a National Ocean Acidification Program; for example, some current interagency working groups such as the Carbon Cycle IWG work closely with an external Scientific Steering Group. Many large-scale programs (e.g., U.S. CLIVAR, U.S. GCRP) also include dedicated administrative staff that can coordinate logistics, reporting requirements, integration between program elements, communication, and other program elements. A program office is likely warranted for the National Ocean Acidification Program given the large number of stakeholders, reporting requirements, and broad research portfolio that covers both basic and applied research. Adequate resources will need to be supplied to staff a program office to support the activities of the IWG, whose participants are typically drawn from program managers and federal scientists. Where possible, efficiencies in the program office could minimize overall costs and maximize funds available to support research while completing all required tasks. Page 132 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × RECOMMENDATION: The National Ocean Acidification Program should create a program office with the resources to ensure successful coordination and integration of all of the elements outlined in the FOARAM Act and this report. COMPILATION OF CONCLUSIONS AND RECOMMENDATIONS CONCLUSION: The chemistry of the ocean is changing at an unprecedented rate and magnitude due to anthropogenic carbon dioxide emissions; the rate of change exceeds any known to have occurred for at least the past hundreds of thousands of years. Unless anthropogenic CO_2 emissions are substantially curbed, or atmospheric CO_2 is controlled by some other means, the average pH of the ocean will continue to fall. Ocean acidification has demonstrated impacts on many marine organisms. While the ultimate consequences are still unknown, there is a risk of ecosystem changes that threaten coral reefs, fisheries, protected species, and other natural resources of value to society. CONCLUSION: Given that ocean acidification is an emerging field of research, the committee finds that the federal government has taken initial steps to respond to the nation's long-term needs and that the national ocean acidification program currently in development is a positive move toward coordinating these efforts. CONCLUSION: The development of a National Ocean Acidification Program will be a complex undertaking, but legislation has laid the foundation, and a path forward has been articulated in numerous reports that provide a strong basis for identifying future needs and priorities for understanding and responding to ocean acidification. CONCLUSION: The chemical parameters that should be measured as part of an ocean acidification observational network and the methods to make those measurements are well established. RECOMMENDATION: The National Program should support a chemical monitoring program that includes measurements of temperature, salinity, oxygen, nutrients critical to primary production, and at least two of the following four carbon parameters: dissolved inorganic carbon, pCO_2, total alkalinity, and pH. To account for variability in these values with depth, measurements should be made not just in the surface layer, but with consideration for different depth zones of interest, such as the deep sea, the oxygen minimum zone, or in coastal areas that experience periodic or seasonal hypoxia. Page 133 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × CONCLUSION: Standardized, appropriate parameters for monitoring the biological effects of ocean acidification cannot be determined until more is known concerning the physiological responses and population consequences of ocean acidification across a wide range of taxa. RECOMMENDATION: To incorporate findings from future research, the National Program should support an adaptive monitoring program to identify biological response variables specific to ocean acidification. In the meantime, measurements of general indicators of ecosystem change, such as primary productivity, should be supported as part of a program for assessing the effects of acidification. These measurements will also have value in assessing the effects of other long-term environmental stressors. RECOMMENDATION: To ensure long-term continuity of data sets across investigators, locations, and time, the National Ocean Acidification Program should support inter-calibration, standards development, and efforts to make methods of acquiring chemical and biological data clear and consistent. The Program should support the development of satellite, ship-based, and autonomous sensors, as well as other methods and technologies, as part of a network for observing ocean acidification and its impacts. As the field advances and a consensus emerges, the Program should support the identification and standardization of biological parameters for monitoring ocean acidification and its effects. CONCLUSION: The existing observing networks are inadequate for the task of monitoring ocean acidification and its effects. However, these networks can be used as the backbone of a broader monitoring network. RECOMMENDATION: The National Ocean Acidification Program should review existing and emergent observing networks to identify existing measurements, chemical and biological, that could become part of a comprehensive ocean acidification observing network and to identify any critical spatial or temporal gaps in the current capacity to monitor ocean acidification. The Program should work to fill these gaps by: • ensuring that existing coastal and oceanic carbon observing sites adequately measure the seawater carbonate system and a range of biological parameters; • identifying and leveraging other long-term ocean monitoring programs by adding relevant chemical and biological measurements at existing and new sites; Page 134 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × • adding additional time-series sites, repeat transects, and in situ sensors in key areas that are currently undersampled. These should be prioritized based on ecological and societal vulnerabilities. • deploying and field testing new remote sensing and in situ technologies for observing ocean acidification and its impacts; and • supporting the development and application of new data analysis and modeling techniques for integrating satellite, ship-based, and in situ observations. RECOMMENDATION: The National Ocean Acidification Program should plan for the long-term sustainability of an integrated ocean acidification observation network. CONCLUSION: Present knowledge is insufficient to guide federal and state agencies in evaluating potential impacts for management purposes. RECOMMENDATION: Federal and federally funded research on ocean acidification should focus on the following eight unranked priorities: • understand processes affecting acidification in coastal waters; • understand the physiological mechanisms of biological responses; • assess the potential for acclimation and adaptation; • investigate the response of individuals, populations, and communities; • understand ecosystem-level consequences; • investigate the interactive effects of multiple stressors; • understand the implications for biogeochemical cycles; and • understand the socioeconomic impacts and inform decisions. RECOMMENDATION: The National Ocean Acidification Program should focus on identifying, engaging, and responding to stakeholders in its assessment and decision support process and work with existing climate service and marine ecosystem management programs to develop a broad strategy for decision support. RECOMMENDATION: The National Ocean Acidification Program should create a data management office and provide it with adequate resources. Guided by experiences from previous and current large-scale research programs and the research community, the office should develop policies to ensure data and metadata quality, access, and archiving. The Program should identify appropriate data center(s) for Page 135 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × archiving of ocean acidification data or, if existing data centers are inadequate, the Program should create its own. RECOMMENDATION: In addition to management of research and observational data, the National Ocean Acidification Program, in establishing an Ocean Acidification Information Exchange, should provide timely research results, syntheses, and assessments that are of value to managers, policy makers, and the general public. The Program should develop a strategy and provide adequate resources for communication efforts. RECOMMENDATION: As the National Ocean Acidification Program develops a research plan, the facilities and human resource needs should also be assessed. Existing community facilities available to support high-quality field- and laboratory-based carbonate chemistry measurements, well-controlled carbonate chemistry manipulations, and large-scale ecosystem manipulations and comparisons should be inventoried and gaps assessed based on research needs. An assessment should also be made of community data resources such as genome sequences for organisms vulnerable to ocean acidification. Where facilities or data resources are lacking, the Program should support their development, which in some cases also may require additional investments in technology development. The Program should also support the development of human resources through workshops, short-courses, or other training opportunities. RECOMMENDATION: The National Ocean Acidification Program should create a detailed implementation plan with community input. The plan should address (1) goals and objectives; (2) metrics for evaluation; (3) mechanisms for coordination, integration, and evaluation; (4) means to transition research and observational elements to operational status; (5) agency roles and responsibilities; (6) coordination with existing and developing national and international programs; (7) resource requirements; and (8) community input and external review. RECOMMENDATION: The National Ocean Acidification Program should create a program office with the resources to ensure successful coordination and integration of all of the elements outlined in the FOARAM Act and this report. Page 136 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × This page intentionally left blank. Page 95 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 96 Share Cite Suggested Citation:"6 A National Ocean Acidification Program." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. 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In 2004, Dr. Fabry presented testimony to the U.S. Senate Committee on Commerce, Science, and Transportation on the "Impacts of Anthropogenic CO2 on Coral Reefs and Other Marine Calcifiers." Gretchen E. Hofmann is a professor in the Department of Ecology, Evolution, and Marine Biology at the University of California, Santa Barbara. Dr. Hofmann earned a Ph.D. in Environmental, Population, and Organismal Biology from the University of Colorado in 1992. Her research focuses on the effects of climate and climate change on the performance of marine species, specifically on the impact on marine organisms of rising atmospheric CO2 concentrations via global warming and ocean acidification. She served on the NRC Committee on the National Ecological Observatory Network. Daniel S. Holland is a Research Scientist at the Gulf of Maine Research Institute. He was awarded his Ph.D. in environmental and natural resource economics from the University of Rhode Island in 1998. Dr. Holland's research is focused on the design and evaluation of fishery management tools and strategies that will lead to profitable and sustainable fisheries and a healthy marine ecosystem. His research methods include bioeconomic simulation modeling, econometric analysis, experimental economics, and qualitative policy analysis. He actively participates in the development of fishery policy by working with fishery stakeholders and managers to develop and evaluate policy. He is also the associate editor of Marine Resource Economics. Joan A. Kleypas is a Scientist III at the National Center for Atmospheric Research. Dr. Kleypas earned a Ph.D. in Tropical Marine Studies from James Cook University, Australia in 1991. Her research focuses on how coral reefs and other marine ecosystems are affected by environmental changes associated with global climate change, such as increases in sea surface temperature and ocean acidification. Dr. Kleypas has testified at three separate U.S. Congressional hearings regarding the effects of climate change on marine ecosystems. Frank J. Millero is a professor of marine and physical chemistry at the University of Miami Rosenstiel School of Marine and Atmospheric Science. Dr. Millero earned a Ph.D. in physical chemistry from Carnegie- Page 6 Page 167 Share Cite Suggested Citation:"Appendix B: Acronyms." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Page 7 Page 171 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals, and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × C The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals, and Carbonate-dominated Systems This appendix serves as an example of the wide variety of experimental studies on the effects of ocean acidification on calcifying marine organisms. We focus here on calcifying algae, corals, and carbonate-dominated systems, because more studies have been conducted on this collective group than on others. This table lists only those studies published through 2009 that used realistic carbonate chemistry manipulations; i.e., those that were consistent with projected changes in the carbonate chemistry of seawater due to natural forcing. Note that pCO2 is reported both in units of parts per million (ppm) and microatmospheres (µatm); the two units can be considered essentially equivalent. Page 172 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Organism/System Summary of findings Reference Calcifying Algae Crustose coralline algae (unidentified species) Manipulation: Acid additionDuration: 7 weeksDesign: Outdoor continuous-flow mesocosms: control at ambient reef pCO2 (average 380 ppm), others manipulated to ambient + 365 ppm. Recruitment and growth of crustose coralline algae were measured on clear acrylic cylinders after 7 weeks in control and manipulated flumes.Results: Under high CO2 conditions, CCA recruitment rate decreased by 78% and percentage cover decreased 92% relative to ambient; non-calcifying algae percent cover increased by 52% relative to ambient. Kuffner et al., 2008 Rhodoliths of mixed crustose coralline algae including Lithophyllum cf. pallescens, Hydrolithon sp. and Porolithon sp. Manipulation: Acid additionDuration: 9 monthsDesign: Outdoor continuous-flow mesocosms: control at ambient reef pCO2 (average 380 ppm), others manipulated to ambient + 365 ppm. Rhodolith growth was measured with buoyant weighing. Results: Rhodolith growth in control mesocosms was 250% lower than those in acidified mesocosms; that is, they experienced net dissolution. Jokiel et al., 2008 Porolithon onkodes Manipulation: Bubbled CO2Duration: 8 weeksDesign: Algae placed in flow-through aquaria: 2 temperatures: 25–26°C and 28–29°C; 3 pH levels: 8.0–8.4 (control) 7.85–7.95 and 7.60–7.70.Results: P. onkodes calcification rate in low pH treatment was 130% less (25–26°C) and 190% less (28–29°C) than in control (i.e., net dissolution). Anthony et al., 2008 Page 173 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Lithophyllum cabiochae Manipulation: Bubbled CO2Duration: 1 yearDesign: Algae were maintained in aquaria at ambient or elevated temperature (+3°C) and at ambient (~400 ppm) or elevated pCO2 (~700 ppm).Results: No clear pattern of reduced calcification at elevated pCO2 alone, but combination of elevated pCO2 and temperature led to high rates of necroses and death. The dissolution of dead algal thalli at elevated pCO2 was 2–4x higher than under ambient pCO2. Martin and Gattuso, 2009 Calcareous epibionts on seagrasses (Hydrolithon boreale, H. cruciatum, H. farinosum, Pneophyllum confervicola, P. fragile and P. zonale) Manipulation: Bubbled CO2 and field observationsDuration: 2 weeksDesign: In field, calcium carbonate mass on seagrass blades was measured across a natural pH gradient. In lab, seagrass blades with 50–70% cover of coralline algae were collected from the field and placed in aquaria of pH = 8.1 (control) or pH = 7.0. Coralline algal cover was estimated before and after treatments.Results: In field, coralline algal cover was highly correlated with pH, decreasing rapidly below pH = 7.8 and absent at pH = 7.0; in lab experiment, coralline algae were completely dissolved after two weeks at a pH of 7.0, whereas control samples showed no discernable change. Martin et al., 2008 Rhodoliths of Hydrolithon sp. Manipulation: Both acid/base addition and bubbled CO2Duration: 5 daysDesign: Acid/base additions used to alter pH to multiple levels (7.6, 7.8, 8.2, 8.6, 9.0, 9.4 and 9.8) control was 8.1); CO2 bubbling used to alter pH and DIC to 7.8.Results: Calcification rate was positively correlated with pH in both light and dark experiments; decreasing the pH to 7.8 with CO2 bubbling lowered calcification by 20%. Semesi et al., 2009a Hydrolithon sp.Mesophyllym sp.Halimeda renschii Manipulation: Drawdown of CO2 by seagrass photosynthesisDuration: 2.5 hoursDesign: In situ open-bottom incubation cylinders; pH and algal calcification rates measured in presence or absence of seagrasses.Results: Seagrass photosynthesis caused pH to increases from 8.3–8.4 to 8.6–8.9 after 2.5 hours; calcification rates increased > 5x for Hydrolithon sp., and 1.6x for Mesophyllum sp. and Halimeda sp. Semesi et al., 2009b Page 174 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Corallina sessilis Manipulation: Bubbled CO2Duration: 30 daysDesign: Controlled laboratory experiments to investigate the interactive effects of pCO2 and UV radiation on growth, photosynthesis, and calcification. 2 pCO2 levels (280 and 1000 ppmv), combined with 3 light conditions: PAR alone (solar radiation wavelengths > 395 nm); PAR+UVA (> 320 nm); PAR+UVA+UVB (> 295 nm).Results: Under PAR alone, elevated pCO2 decreased net photosynthetic rate by 29.3%, and calcification rate by 25.6% relative to low pCO2. Elevated pCO2 exacerbated the effects of ultraviolet radiation in inhibiting rates of growth (from 13% to 47%), photosynthesis (from 6% to 20%), and calcification (from 3% to 8%). The authors suggest that the decrease in calcification in C. sessilis at higher pCO2 levels increases its susceptibility to damage by UVB radiation. Gao and Zheng, 2009 Halimeda incrassata (green alga) and Neogoniolithon spp. (coralline red alga) Manipulation: CO2 bubblingDuration: 60 daysDesign: Controlled laboratory experiment to examine changes in calcification under Ωarag = 3.12, 2.40, 1.84, and 0.90 (approx. pCO2 = 409, 606, 903, 2856 ppmv, respectively). SST maintained at 25°C.Results: Calcification rates in both species were higher at Ωarag = 2.40, then declined at lower saturation states. Ries et al., 2009 Page 175 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Corals Stylophora pistillata Manipulation: Altered Ca2+ ion concentration1Duration: 2.5 hoursDesign: Controlled laboratory experiment; aragonite saturation changes from 98 to 390% were obtained by manipulating the calcium concentration.Results: Nonlinear increase in calcification rate as a function of aragonite saturation level. Gattuso et al., 1998 Porites compressa Manipulation: Acid additionDuration: 5 weeksDesign: 760 and 3980 µatm (pH = 8.2 versus 7.2); nitrate additions as wellResults: Corals grown in low pH water grew half as fast. Marubini and Atkinson, 1999 Porites compressa Manipulation: Acid additionDuration: 10 weeksDesign: Controlled laboratory experiments: measured calcification at pCO2 = 199 and 448 µatm, at 3 light levels. In Biosphere 2 coral mesocosm: measured calcification at pCO2 = 186, 336, and 641 µatm.Results: Calcification decreased 30% from pCO2 = 186 to 641, and 11% from pCO2 = 336 to 641 µatm, regardless of light level. Marubini et al., 2001 Galaxea fascicularis Manipulation: Altered Ca2+ ion concentration while maintaining pH at 8.11–8.12; temperatures maintained at ambient temperature of collections site1Duration: HoursDesign: Calcium additions to estimated Ωarag from 3.88 (present-day) to 4.83 and 5.77; calcification rate measured with 14C incorporation in skeleton.Results: Calcification rate increased 30–60% at Ωarag = 4.83 and 50–80% at Ωarag = 5.77 relative to Ωarag =3.88. Marshall and Clode, 2002 Page 176 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Stylophora pistillata Manipulation: Bubbled CO2Duration: 5 weeksDesign: 2 pCO2 values (460 and 760 µatm) and 2 temperatures (25 and 28°C)Results: Calcification under normal temperature did not change in response to an increased pCO2. Calcification decreased by 50% when temperature and pCO2 were both elevated. Reynaud et al., 2003 Acropora verweyi Galaxea fascicularis Pavona cactus Turbinaria reniformis Manipulation: Acid/base additionDuration: 8 daysDesign: 2 pCO2 values (407–416 and 857–882 µatm), 26.5°CResults: calcification rate in all 4 species decreased 13–18% Marubini et al., 2003 Porites compressa + Montipora capitata Manipulation: acid/base additionDuration: 1.5 hoursDesign: Corals placed in flumes, multiple summer experiments at pCO2 = 460 and 789 µatm; multiple winter experiments at pCO2 = 391, 526, and 781 µatm; additional experiments included additions of PO4 and NH4.Results: Summer calcification rate declined 43% with increase in pCO2 from 460 to 789 µatm; winter rates declined 22% from 391 to 526 µatm; and 80% from 391 to 781 µatm. Langdon and Atkinson, 2005 Acropora cervicornis Manipulation: Bubbled CO2Duration: 16 weeks totalDesign: Nubbins cultured for 1 week at pCO2=367 µatm, 2 weeks at 714–771 µatm, 1 week at 365 µatmResults: 60–80% reduction in calcification rate at 714–771 µatm relative to controls (357–361 µatm); note that calcification rate did not substantially recover with return to normal pCO2 during 4th week. Renegar and Riegl, 2005 Page 177 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Acropora eurystoma Manipulation: Acid/base additionDuration: HoursDesign: Separation of effects of different carbonate chemistry parameters by maintaining a) constant total inorganic carbon, b) constant pH, or c) constant CO2; temperatures = 23.5–24.5°CResults: calcification rate was correlated with [CO32−]: 50% decrease in calcification with 30% decrease in [CO32−]; 35% decrease in calcification with increase in pCO2 from 370 to 560 ppm. Schneider and Erez, 2006 Porites lutea and Fungia sp. Manipulation: Acid/base additionDuration: 3 hours (night-time) and 6 hours (day-time)Design: Coral colonies were acclimated for several months, then subjected to seawater adjusted to one of 3 Ωarag levels: 1.56, 3.43, 5.18 (note that ambient Ωarag was 3.43); temperature was constant at 25°C.Results: Both day and night calcification decreased with decreasing pH; calcification rate at 2x preindustrial CO2 level (Ωarag = 3.1) was reduced by 42% relative to preindustrial level (Ωarag = 4.6). Ohde and Hossain, 2004; Hossain and Ohde, 2006 Montipora capitata Manipulation: Acid additionDuration: 10 monthsDesign: Corals places in flumes: control at ambient reef pCO2 (average 380 ppm), others manipulated to ambient + 365 ppm.Results: Calcification decreased 15–20% with a doubling of pCO2 (380 to 380+365 ppm). Jokiel et al., 2008 Porites astreoides (larvae/juveniles) Manipulation: Acid addition Duration: 21–28 daysDesign: Flow-through seawater system; 3 aragonite saturation states: Ωarag = 3.2 (control), 2.6 (mid), and 2.2 (low); constant temperature at 25°CResults: Lateral skeletal extension in larvae was positively correlated with saturation state (P=0.007); juveniles in mid Ωarag treatment grew 45–56% slower than controls; those in low Ωarag treatments grew 72–84% slower than controls. Albright et al., 2008 Page 178 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Porites lobata Acropora intermedia Manipulation: Bubbled CO2Duration: 8 weeksDesign: Corals placed in flow-through aquaria: 2 temperatures: 25–26°C and 28–29°C; and 3 pH levels: 8. 0–8.4 (control) 7.85–7.95 and 7.60–7.70.Results: Acropora intermedia and Porites lobata calcification rates were 40% lower at low pH treatment than in control. Anthony et al., 2008 Favia fragrum (larvae/juveniles) Manipulation: Acid additionDuration: 8 daysDesign: Newly settled coral larvae reared in a range of Ωarag from ambient (3.71) to 3 treatments (Ωarag = 2.40, 1.03, 0.22); culture temperatures =25°C.Results: Aragonite was secreted by all corals even in undersaturated conditions; however, in Ωarag = 2.40 treatment, cross-sectional area of skeletons was more than 20% less than the control, and average weight of skeletal mass was 26% less than control. Similar trends occurred in the more extreme treatments. Cohen et al., 2009 Madracis mirabilis Manipulation: Acid/base addition and bubbled CO2Duration: 2 hour incubations following 3-hour acclimation period Design: Separation of effects of different carbonate chemistry parameters by manipulating chemistry to reflect 6 combinations of normal, low and very low pH, with normal low and very low [CO32−]; temperature maintained at 28°CResults: For pH/[CO32−] combinations that simulate natural ocean acidification (pCO2 = 390, 875 and 1400 µatm), calcification rate was not correlated with [CO32−], but rather with [HCO3-]. Jury et al., 2009 Page 179 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Oculina arbuscula (temperate coral) Manipulation: CO2 bubblingDuration: 60 daysDesign: Controlled laboratory experiment to examine changes in calcification under Ωarag = 3.12, 2.40, 1.84, and 0.90 (approx. pCO2 = 409, 606, 903, 2856 ppmv, respectively). SST maintained at 25°C.Results: Calcification rate remained unchanged Ωarag > 1.84, then declined rapidly at Ωarag = 0.90. Ries et al., 2009 Lophelia pertussa (cold water coral) Manipulation: Acid additionDuration: 24 hoursDesign: On-board incubations of deep-water corals at ambient pH, ambient pH − 0.15 units, and ambient pH − 0.3 units. Calcification rates measured using 45Ca labeling.Results: Calcification rates were reduced by 30% and 56% at pH reduced by 0.15 and 0.3 units, respectively, as compared to calcification rate at ambient pH. Calcification in young polyps showed a stronger reduction than in old polyps (59% reduction versus 40% reduction, respectively). Maier et al., 2009 Carbonate-dominated systems Gr. Bahama Banks Manipulation: NA; field measurementsDuration: DaysDesign: Measured changes in pCO2, DIC, temperature salinity, and residence time of Bahama Banks waters.Results: CaCO3 precipitation rate correlated with CaCO3 saturation state. Broecker and Takahashi, 1966; Broecker et al., 2001 B2 mesocosm Manipulation: Acid/base and CaCl2 additions and natural alkalinity draw-downDuration: Days to months/years (3.8 years total)Design: Biosphere 2 coral reef mesocosm; time series of net community calcification measurements in relation to carbonate chemistry.Results: Calcification rate well correlated with saturation state; calcification rate decreased 40% between preindustrial and doubled CO2 conditions. Langdon et al., 2000; Langdon et al., 2003 Page 180 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Monaco mesocosm Manipulation: Bubbled CO2Duration: 24-hour incubationsDesign: Coral community mesocosm subjected to continuous flow with a range of pCO2 values (134–1813 µatm; temperature maintained at 26°CResults: Community calcification was reduced by 21% between preindustrial and double pCO2 levels. Leclercq et al., 2000 Monaco mesocosm Manipulation: Bubbled CO2Duration: 9–30 daysDesign: Coral community mesocosm subjected to continuous flow with mid (647 µatm) pCO2 for 12 weeks, low (411 µatm) for 4 weeks, and high (918 µatm) for 4 weeks; temperature maintained at 26°CResults: Daytime community calcification was reduced by 12% between low and high treatments. Leclercq et al., 2002 Molokai Reef System Manipulation: Natural alkalinity drawdown by organismsDuration: Several daysDesign: Large benthic chambers placed on reef bed; in situ carbonate chemistry, salinity, temperature, and net calcification/dissolution measured continuously.Results: Calcification and dissolution were linearly correlated with both CO32− and pCO2. Threshold pCO2 and CO32− values for individual substrate types showed considerable variation. Results indicate that average threshold for shift to net dissolution for Molokai reef is when pCO2 = 654 ±195 µatm. Yates and Halley, 2006 Page 181 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × Northern Red Sea Reef Manipulation: NA; field measurementsDuration: 2 yearsDesign: Eulerian measurements of carbonate system in seawater and community calcification/dissolution rates as a function of saturation state; adjusted for residence time of water.Results: Based on seasonal differences in calcification rate, determine that net reef calcification rate was well-correlated with precipitation rates of inorganic aragonite; projected a 55% decrease in reef calcification at 560 ppm CO2 and 30°C relative to 280 ppm and 28°C Silverman et al., 2007 Calcifying community dominated by Montipora capitata Manipulation: Acid addition Duration: 24 hoursDesign: See Jokiel et al., 2008 and Kuffner et al. 2008. Compared Net ecosystem calcification (NEC) in coral community mesosms exposed to ambient pCO2 (380 ppm) and 2x ambient (380+365 ppm). NEC was determined every 2 hours by accounting for changes total alkalinity in the entire system.Results: NEC was 3.3 mmol CaCO3 m−2 h−1 under ambient and −0.04 mmol CaCO3 m−2 h−1. Andersson et al., 2009 1These studies manipulated Ca2+ rather than the carbon system. They are included here for completeness and because they provide insights into calcification mechanisms, but the results should not be strictly interpreted as a response to ocean acidification. Page 182 Share Cite Suggested Citation:"Appendix C: The Effect of Ocean Acidification on Calcification in Calcifying Algae, Corals,and Carbonate-dominated Systems." National Research Council. 2010. Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. Washington, DC: The National Academies Press. doi: 10.17226/12904. × This page intentionally left blank. 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Research Priorities for Ocean Acidification, report from the Second Symposium on the Ocean in a High-CO2 World, Monaco, October 6-8, 2008, convened by SCOR, UNESCO-IOC, IAEA, and IGBP, 25 pp. Summary: The Research Priorities Report resulted from the 2nd symposium on The Ocean in a High-CO2 World, held in 2008 in Monaco. The symposium was sponsored by SCOR, IOC, other international groups, and the U.S. NSF, and included 220 scientists from 32 countries to assess what is known about the impacts of ocean acidification on marine chemistry and ecosystems. The Research Priorities Report highlights new findings and details the research priorities identified by the symposium participants during discussion sessions on 1) perturbation experiments, 2) observation networks, and 3) scaling organism-to-ecosystem acidification effects and feedbacks on climate: Observations • Develop new instrumentation for autonomous measurements of CO2 system parameters, particulate inorganic (PIC), particulate organic carbon (POC), and other indicators of impacts on organisms and ecosystems; • Maintain, enhance, and extend existing long-term time series that are relevant for ocean acidification; establish new monitoring sites and repeat surveys in key areas that are likely to be vulnerable to ocean acidification; • Develop relaxed carbon measurement methods and appropriate instrumentation that are cheaper and easier, if possible, for high-variability areas that may not need the highest measurement precision; • Establish a high-quality ocean carbon measurement service for those unable to develop their own measurement capabilities; • Establish international collaborations to create a data management and synthesis program for new ocean acidification data as well as data mining and archival for relevant historical data sets; • Work on developing an ocean acidification index (e.g., a CaCO3 saturation index based on a standard carbonate material); • Initiate specific activities for education, training, and outreach. Perturbation Experiments • Controlled single-species laboratory experiments to look at species responses, to improve understanding of physiological mechanisms, and

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