1 Climate Change Impacts on Ocean and Coastal Law:

SCIENTIFIC REALITIES AND LEGAL RESPONSES

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Introduction

> *Rising sea level will be the single most profound geologic change in recorded human history. It will transform our physical world beyond anything we can imagine, dwarfing continents and eliminating some nations. Coastlines will move inland by hundreds and, in some places, thousands of feet this century. The impacts will be far greater during the next century. Trillions of dollars of the most valuable real estate and infrastructure will vanish.*[1]

The oceans and coasts of the world are under siege from a broad spectrum of climate-change-related threats. The most significant of these threats is the challenge that sea-level rise poses to ocean and coastal resources. In addition, climate change presents a series of secondary challenges to the physical, chemical, and biological integrity of ocean and coastal resources such as ocean acidification, impacts to species and habitats, increased intensity of tropical cyclone activity, changes in ocean stratification and circulation, and saltwater intrusion.

In 2013, there have been many significant responses at the international and U.S. domestic levels to the impacts of climate change on the marine environment. Three of these responses deserve mention here. First, on September 30, 2013, the Intergovernmental Panel on Climate Change (IPCC) released Part 1 of its highly anticipated Fifth Assessment Report.[2] The report concluded that it is "extremely likely"[3] that human activity is the principal cause of climate change. The Fifth Assessment Report predicts a sea-level rise between twenty-six and eighty-one centimeters by the end of the century.[4]

Second, on April 16, 2013, the White House released the National Ocean Policy Implementation Plan.[5] The Plan seeks to coordinate the actions of various government

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[1] John Englander, High Tide on Main Street: Rising Sea Level and the Coming Coastal Crisis 3 (2012).

[2] Ulrich Cubasch et al., Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis ((2014), *available at* http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf.

[3] The IPCC defines "extremely likely" as 95 to 100 percent certainty. *See id.* at TS-4. The IPCC Fourth Assessment Report in 2007 concluded that it was "very likely" that human activity was the main cause, defined as 65 to 90 percent certainty. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 (B. Metz et al. eds., 2007), *available at* http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html.

[4] Lisa Alexander et al., Intergovernmental Panel on Climate Change, Twelfth Session of Working Group I Approved Summary for Policymakers 25 (2013), http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf.

[5] Nat'l Ocean Council, *National Ocean Policy Implementation Plan* (2013), *available at* http://www.whitehouse.gov//sites/default/files/national_ocean_policy_implementation_plan.pdf.

agencies to protect the nation's oceans and coasts and calls for the creation of an Ocean Council comprised of officials from twenty-seven federal agencies to implement the Plan.[6] Among many objectives, the Plan seeks to assess the vulnerability of oceans and coastal communities to climate change impacts and implement adaptation strategies to combat the effects of ocean acidification and sea-level rise.[7]

Third, a team of experts provided technical input for a report, *Ocean and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment*,[8] which was released in June 2013. The report provides a comprehensive assessment of climate change impacts to oceans and marine resources, divided into seven categories: (1) Introduction and Context; (2) Climate-Driven Physical Changes in Marine Ecosystems; (3) Impacts of Climate Change on Marine Organisms; (4) Impacts of Climate Change on Human Uses of the Ocean; (5) International Implications of Climate Change; (6) Management Challenges, Adaptations, Approaches, and Opportunities; and (7) Sustaining the Assessment of Climate Impacts on Oceans and Marine Resources.[9] The scope of coverage in the report reflects the breadth of climate change impacts on ocean and coastal law. Several of these topics will be covered in the chapters in this volume.

These three responses are but a few significant examples of the growing concern in the United States and throughout the world regarding the impacts of climate change on ocean and coastal resources and how law and policy can respond to these challenges. This chapter provides an overview of the physical, chemical, and biological underpinnings of the climate change impacts that currently plague ocean and coastal resources and briefly addresses some of the law and policy responses to these challenges at the international, national, and sub-national levels.

I. Background

A. Earth's Climate

The primary source of energy for Earth's climate is radiation from the Sun. An energy balance exists between incoming and outgoing solar radiation, but slight imbalances can bring about global heating or cooling. "Forcing" is the term used to describe disruptions in the main elements that impact Earth's climate, including solar energy, atmospheric circulation, ocean currents, and even volcanic eruptions that lead to changes in climate.[10] Natural sources of forcing are behind geological shifts in climate from extreme glacial periods of extensive ice coverage to interglacial periods of ice retreat.

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6 *Id.*

7 *See generally* Benjamin Sloan, *White House Releases National Oceans Plan*, 12(3) SandBar 10 (2013).

8 Ocean and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment (Roger Griffis & Jennifer Howard eds., 2013)

9 *Id.* at ii–iv.

10 For an extensive review of forcing elements, *see generally supra* note 2 at 8-1; Wallace S. Broecker, The Glacial World according to Wally 1 (1995).

The amount of solar radiation arriving on Earth is affected by astronomical phenomena that occur over varying time scales from millions to hundreds of years. These phenomena include changes in the luminosity of the sun,[11] solar sunspot activity,[12] and changes in Earth's orbit. Even small changes in solar radiation are associated with large regional changes in temperature on Earth.[13]

Thirty percent of incoming solar radiation is reflected from Earth by the air, clouds, land masses, and the ocean. This reflected energy is known as the Earth's albedo, and is what causes the illumination of Earth in space.[14] The remaining percentage is absorbed at the surface and eventually reradiated into space. Radiation leaving Earth is slowed down by the presence of water vapor and other gases in the atmosphere that trap radiation and warm the Earth's surface, a process known as the greenhouse effect.[15]

Trapped heat is moved around Earth through atmospheric and ocean circulation cells. Atmospheric circulation cells affect wind patterns, which are responsible for major oceanic currents and shallow ocean circulation.[16] Oceanic western boundary currents such as the Gulf Stream and the Kuroshio Current move heat from warm equatorial waters toward the poles, which produces mild winters in northern areas such as Europe and Japan.[17]

An example of an important coupling of atmospheric and oceanic conditions is El Niño Southern Oscillation (ENSO), which occurs in the Pacific Ocean. In ENSO conditions, dominant winds weaken, which lead to shifts in atmospheric pressure, relaxation of important ocean currents, and alterations in global precipitation.[18] Increased tropical moisture during ENSO events can expand across the globe to areas of India, Africa, Central America, and South America.[19] Under normal conditions, wind patterns and currents bring nutrient-rich water to the surface, resulting in immense biological production. The reduction of nutrient flow during ENSO events has reduced primary production, collapsed fisheries, and led to mass deaths of marine mammals.[20]

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[11] *See generally* Michael J. Newman & Robert T. Rood, *Implications of Solar Evolution for the Earth's Early Atmosphere*, 198 Sci. 1035 (1977).

[12] *See generally* Richard C. Willson & Hugh S. Hudson, *Solar Luminosity Variations in Solar Cycle 21*, 332 Nature 810 (1988); Richard C. Willson & Hugh S. Hudson, *The Sun's Luminosity over a Complete Solar Cycle*, 351 Nature 42 (1991).

[13] *See generally id.*

[14] Elizabeth Kay Berner & Robert A. Berner, Global Environment: Water, Air, and Geochemical Cycles 9–12 (1995).

[15] *Id.* at 13.

[16] *Id.* at 18–19.

[17] *Id.* at 15.

[18] *See supra* note 3, at 235–40.

[19] Chester F. Ropelewski & Michael S. Halpert, *Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation*, 115 Monthly Weather Rev. 1606, 1625 (1987).

[20] Peter W. Glynn, *El Niño-Southern Oscillation 1982–1983: Nearshore Population, Community, and Ecosystem Responses*, 19 Ann. Rev. Ecology & Systematics 309 (1988).

B. Anthropogenic Climate Change

Excess buildup of persistent greenhouse gases, primarily carbon dioxide (CO_2), in the atmosphere is the primary force driving current changes in Earth's climate.[21] Excess greenhouse gases would prevent radiation from leaving Earth and lead to warming of the surface. Greenhouse gases include CO_2, methane, chlorofluorocarbons (CFCs), and nitrous oxide. Carbon dioxide concentrations account for 80 percent of the total forcing caused by greenhouse gases[22] and exceed levels measured from the past 800,000 years.[23]

The effects of increased global temperature are already evident: ice sheet coverage is waning in polar regions, glaciers are shrinking, and spring snow cover is decreasing in the Northern Hemisphere.[24] In the last interglacial period, polar ice melt was a major contributor to sea-level rise.[25] Current estimates of sea-level rise of 2.8 mm per year balance out with estimates of glacier and sea ice melt, land water storage, and thermal expansion.[26] Ninety percent of the additional energy remaining on Earth has accumulated in the ocean, as evidenced by increased ocean temperatures.[27] The extra energy absorption leads to expansion of ocean water, which contributes to sea-level rise. The transport of warmer waters into the circumpolar deepwater current[28] is attributed to increasing rates of glacial retreat, thinning, flow, and ungrounding in Western Antarctica.[29] This faster addition of water is predicted to significantly contribute to sea-level rise and lead to the destabilization of other glaciers.

The emission of CO_2 is the major determinant in mean global surface warming. Even if current emissions stopped, the effects of the emissions will be felt for many centuries to millennia.[30] Extensive focus has been placed on the links between excess atmospheric CO_2 and changing climate; however, excess atmospheric CO_2 also causes physical and chemical changes to oceans and coasts.

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21 *See supra* note 2, at 8-1 to 8-139.

22 *See supra* note 2, at 8–20.

23 *See supra* note 4. Anthropogenic additions of ozone, atmospheric water vapor, and changes in Earth's albedo are forcings that also alter the energy balance of Earth. Many of these anthropogenic forcings are interactive, making predictions about the overall impacts of anthropogenic perturbations challenging. *See supra* note 3, at 503–05.

24 *See supra* note 4, at 5.

25 *See generally* NEEM Cmty. Members, *Eemian Interglacial Reconstructed from a Greenland Folded Ice Core*, 493 Nature 489 (2013).

26 *See supra* note 4, at 7.

27 *See supra* note 2, at 4.

28 *See generally* Stanley.S. Jacobs, et. al., *Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf*, 4 Nature Geosci. 519 (2011).

29 *See generally* E. Rignot, et al., *Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011*, 41 Geophysical Res. Letters 3502 (2014); Ian Joughin, Benjamin E. Smith & Brooke Medley, *Marine Ice Sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica*, 344 Sci. 735 (2014)

30 *See supra* note 4, at 19.

II. Physical and Chemical Changes to Oceans and Coasts

A. Scientific Underpinnings

There are two principal consequences of increased CO_2 in the atmosphere and marine ecosystems: (1) ocean acidification, and (2) increasing ocean temperature.[31] The first subsection of this part of the chapter addresses the causes and consequences of ocean acidification, whereas the remaining four subsections examine important impacts to ocean and coastal resources, which flow from increasing ocean temperature.

1. Ocean Acidification

In the last five decades, 24 percent to 33 percent of anthropogenically produced CO_2 has been absorbed by the oceans.[32] Although this additional uptake of CO_2 mitigates the rate and severity of climate change felt on land, it is not without consequences on ocean water chemistry. The current chemical alterations are collectively termed "ocean acidification" due to the effect of reduced ocean pH. Altered pH is only one symptom of changing ocean chemistry.[33]

Once a molecule of CO_2 is absorbed into the ocean it undergoes a series of chemical reactions leading to the troublesome addition of a hydrogen ion (H^+) and the loss of a carbonate ion (CO_2^{3-}). As hydrogen ions are created, the pH of ocean water decreases and becomes more acidic. Carbonate ions bond with calcium to form calcium carbonate ($CaCO_3$), which is an essential building block for the skeletons of marine invertebrates including corals, snails, crabs, and certain plankton species, as well as plant species such as coralline algae.

Surface waters, especially shallow, warm tropical waters, are generally supersaturated with carbonate ions. This condition allows for the easy formation of carbonate skeletons in marine organisms, which accounts for the abundance of coral reefs in these areas. If the saturation of carbonate ions drops, it becomes energetically costly for organisms to build and maintain carbonate skeletons, resulting in reduced growth and reduced skeleton density.[34] In some cases, drops in carbonate ion availability can lead to "dissolution," which is the dissolving of carbonate skeletons. There are naturally occurring areas such as the deep ocean and cold, high-latitude waters where the quantity of carbonate ions in addition to other physical factors such as temperature, salinity, and pressure impact the ability of organisms to absorb carbonate, which leads to skeleton

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31 Ocean and Marine Resources in a Changing Climate, *supra* note 8, at 2.

32 Jean-Pierre Gattuso et al., *Ocean Acidification and Its Impacts: An Expert Survey*, 117 Climatic Change 725, 726 (2013); Corinne Le Quéré et al., *Trends in the Sources and Sinks of Carbon Dioxide*, 2 Nature Geosci. 831, 834 (2009).

33 The current change in ocean pH is a drop of 0.1, which is a 26 percent increase in hydrogen ions. *See supra* note 2, at 3–5.

34 Richard A. Feely et al., *Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans*, 305 Sci. 362, 365, Table S1 (2004).

dissolution.[35] Dissolution and reduced saturation are becoming more prevalent in areas that were historically abundant in carbonate skeleton growth, such as coral reefs, which jeopardizes the future of these ecosystems.[36]

The ability of carbon to be stored in marine organisms allows for the oceans to absorb large quantities of atmospheric $CO_{2,}$ which has buffered the Earth from more immediate impacts of excess CO_2 in the atmosphere. Reduction in carbonate skeleton formation in addition to skeleton loss means less atmospheric CO_2 can be stored in the ocean.[37]

In addition to the impact of CO_2 on ocean acidification, the burning of fossil fuels and fertilizer usage in agriculture also introduces strong acids (HNO_3 and H_2SO_4) as well as bases (NH_3) into ocean waters. Organisms nitrify NH_3 into nitrate NO_3, leading to additional acidification in ocean and coastal regions. The global impact of this acidification amounts to only about 3 percent. Nevertheless, inputs are estimated to increase in the next several decades and may account for 10–50% of acidification in coastal waters due to the proximity of source pollution from rivers and groundwater. Introduction of nitrate species into coastal systems has profound fertilizer effects on marine primary producers, phytoplankton, and submerged aquatic species, which lead to further changes in ocean chemistry.[38]

The multifaceted changes occurring in ocean chemistry during ocean acidification result in a variety of impacts on biological organisms. If we focus only on ocean acidification, organisms are faced with changes in ocean pH, changes in carbonate availability, changes in the depth of carbonate dissolution, and addition of fertilizers. These effects impact ocean biology on a variety of spatial scales from cellular, to organismal, to ecosystematic. This complexity of effects and impacts makes generalizations about the impacts of ocean acidification on ocean biology globally difficult as some species may be positively impacted while others are negatively impacted. Changes or shifts in species that rely on carbonate skeletons are anticipated to occur, and these changes are likely to have profound impacts on marine ecosystems, including non-carbonate-dependent species. Current conditions of climate change are mild in comparison to other geological conditions; however, the unprecedented rate of change occurring in modern times may outpace marine organisms' ability to adapt to changing ocean chemistry.

Ocean acidification has profound impacts on coral reef systems. Exposure to highly acidic water can lead to complete dissolution of coral skeletons, but some coral polyps can still survive and even regrow their skeletons if pH returns to an ideal level.[39] Despite this remarkable adaptability, the current climate change conditions present several

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35 *See generally id.*

36 Scott C. Doney et al., *Ocean Acidification: The Other CO_2 Problem*, 1 Marine Sci. 169, 173–74 (2009).

37 Andy Ridgwell & Richard E. Zeebe, *The Role of the Global Carbonate Cycle in the Regulation and Evolution of the Earth System*, 234 Earth & Planetary Sci. Letters 299, 300 (2005).

38 *See generally* Scott C. Doney et al., *Impact of Anthropogenic Atmospheric Nitrogen and Sulfur Deposition on Ocean Acidification and the Inorganic Carbon System*, 104 Proc. Nat'l Acad. Sci. 14580 (2007).

39 *See generally* Maoz Fine & Dan Tchernov, *Scleractinian Coral Species Survive and Recover from Decalcification*, 315 Sci. 1811 (2007).

challenges for corals and coral communities. As oceans acidify, coral skeleton production will decrease and the rate of dissolution will increase.[40] In addition to changes in ocean chemistry, corals are also faced with perturbations from increased temperature, overfishing, and pollution that increase reef degradation. The multitude of coral reef stressors at play may suggest reefs are headed toward global-scale loss[41]; however, corals have survived through five mass extinction events in Earth's history, which suggests a capacity for coping with stress and a potential for adaptation.[42]

Reduction in calcification rates and increased dissolution also negatively impact ecologically important coralline algae species such as *Halimeda* and coralline red algae in the same ways as coral species.[43] Evidence suggests that other fleshier submerged aquatic vegetation (SAV), such as some species of seagrasses and macroalgae, may benefit from increased CO_2 concentrations in ocean water, which will enhance photosynthesis and growth rates.[44]

The increase of CO_2 into the ocean could also increase phytoplankton species growth, but studies show mixed results of positive and negative effects.[45] Some phytoplankton species have carbonate skeletons and would be negatively impacted by changes in ocean pH and carbonate dissolution depths, as seen in corals.[46] Effects of pH changes are also species specific, with some species growing well in a wide range of pH and others limited by a 1.0 pH range.[47] Predicting the effects of ocean acidification on phytoplankton abundance and diversity is complicated by simultaneous changes in temperature, nutrient availability, and light that occur related to climate change. Variations in any single factor can lead to large shifts in phytoplankton communities, which would reverberate through oceanic and coastal food webs.

The overall effect of ocean acidification on survival, calcification, growth, and reproduction of marine organisms is negative.[48] Research suggests that corals, echinoderms, fish, and mollusks have sustained the largest impacts, while crustaceans appear resistant to changes.[49]

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[40] *See* Doney et al., *supra* note 34, at 177.

[41] *See generally* Ove Hoegh-Guldberg, *Climate Change, Coral Bleaching and the Future of the World's Coral Reefs*, 50 Marine Freshwater Resources 839 (1999).

[42] John M. Pandolfi et al., *Projecting Coral Reef Futures under Global Warming and Ocean Acidification*, 333 Sci. 418, 421 (2011).

[43] *See* Doney et al., *supra* note 34, at 176.

[44] *See generally* Marguerite Koch et al., *Climate Change and Ocean Acidification Effects on Seagrasses and Marine Macroalgae*, 19 Global Change Biology 103 (2013). The benefit of CO_2 will not be uniform across all species of SAV, however. Shifts in carbon availability will likely lead to competitive interactions not only between seagrass species, but also between seagrass and their epiphytic communities. Increased shading from an overgrowth of epiphytes may lead to a rapid decline of seagrass meadows.

[45] John M. Guinotte & Victoria J. Fabry, *Ocean Acidification and Its Potential Effects on Marine Ecosystems*, 1134 Annals New York Acad. Sci. 320, 333 (2008).

[46] *See* Doney et al., *supra* note 34, at 176.

[47] *See* Guinotte & Fabry, *supra* note 43, at 333.

[48] Kristy J. Kroeker et al., *Meta-analysis Reveals Negative Yet Variable Effects of Ocean Acidification on Marine Organisms*, 13 Ecology Letters 1419, 1426–28 (2010).

[49] Astrid C. Wittmann & Hans-O. Pörtner, *Sensitivities of Extant Animal Taxa to Ocean Acidification*, Nature Climate Change 1 (2013) (advance online publication at 4–5).

2. Ocean Stratification

Oceans can be divided into two parts. The surface layer is well mixed by winds and has an abundance of light that can support large stocks of phytoplankton. Carbon dioxide, nutrients, and light are required in specific quantities to support photosynthesis and associated food webs. Phytoplankton often exhausts nutrient supplies in the surface layer, and thus nutrient supply becomes a limiting agent in phytoplankton biomass.

Below the surface layer is the remaining deep layer of the ocean. This layer is characterized by dark, cold, less-mixed oxygen-rich water. Although the deep layer is rich in nutrients, the lack of light prohibits photosynthesis. The division between the surface layer and deep layer is known as the thermocline, which is characterized by a rapid decline in temperature. The thermocline is often associated with a pycnocline, which marks differences in water density between the surface and deep layers. Differences in water density increase the amount of energy required to mix layers of ocean water.

The upper surface layer of the oceans is currently absorbing the excess heat on Earth, which causes ocean stratification.[50] Increasing temperature is expected to reinforce the strength of the thermocline, which will make mixing of the water column more difficult and limit the flow of nutrients to phytoplankton at the surface.[51] Reduction in primary production and changes in phytoplankton species composition are likely to occur with increased ocean stratification.[52]

Areas of upwelling exist where wind and currents pull surface waters away from landmasses. Surface waters are then replaced by cold nutrient-rich water from the deep layer. Upwelling occurs along coasts and islands, and along the equator. The result of upwelling is an explosion of phytoplankton biomass, which supports extensive zooplankton communities that are the basis for major fisheries. Although upwelling areas are small in size, the supported biomass rivals primary production of rainforests.[53] The anticipated changes in wind patterns and ocean currents, such as increased frequency of ENSO events due to climate change, reduce upwelling and have catastrophic impacts to the higher trophic levels including fisheries, marine mammals, and seabirds.[54]

The large quantity of organic material produced in the upper surface layers as a result of primary production falls through the water column when organisms die. The digestion of organic material by bacteria strips oxygen from the water and releases CO_2. The pycnocline acts as a barrier that builds up oxygen-depleted water known as

[50] *See supra* note 4.

[51] *See generally* Michael J. Behrenfeld et al., *Climate-Driven Trends in Contemporary Ocean Productivity*, 444 Nature 752 (2006).

[52] *See generally* Philip W. Boyd & Scott C. Doney, *Modelling Regional Responses by Marine Pelagic Ecosystems to Global Climate Change*, 29 Geophysical Res. Letters 53–1 (2002).

[53] Keith A. Sverdrup & E. Virginia Armbrust, An Introduction to the World's Oceans 369 (10th ed. 2008).

[54] *See generally* Glynn, *supra* note 20.

the Oxygen Minimum Zone. Oxygen concentrations in this zone can reach hypoxic conditions, where organisms struggle to survive.[55] Hypoxic events are prevalent in coastal estuaries due to eutrophication, and these events are associated with extensive fish and invertebrate kills.[56] Evidence exists that the lack of water mixing due to ocean stratification is causing the Oxygen Minimum Zone to expand into surface waters and onto continental shelves, exposing marine communities to a greater frequency of hypoxic events.[57]

3. Tropical Cyclone Activity

Warming of the upper layer of the ocean increases ocean thermal energy, which may lead to increases in tropical cyclone activity and intensification. The amount of energy available in the water column between the ocean surface and where water drops below 26°C is known as Tropical Cyclone Heat Potential (TCHP).[58] The greater the TCHP, the more likely tropical cyclones that pass over the area will intensify through absorbing the heat stored in the ocean.[59]

Current theory and model simulations suggest that tropical cyclone duration, intensity, and frequency are expected to increase with ocean warming.[60] Tropical cyclone activities represent natural disturbances to coastal communities and play important roles in habitat complexity and biodiversity.[61] Increased tropical storm activity may negatively impact coral and seagrass habitats, which are already under stress from a multitude of anthropogenic disturbances.[62]

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55 *See generally* Lisa A. Levin, *Oxygen Minimum Zone Benthos: Adaptation and Community Response to Hypoxia, in* 41 Oceanography and Marine Biology: An Ann. Rev. 1 (R.N. Gibson & R.J.A. Atkinson eds., 2003).

56 *See generally* J. Zhang et al., *Natural and Human-Induced Hypoxia and Consequences for Coastal Areas: Synthesis and Future Development*, 7 Biogeosci. 1443 (2010).

57 *See generally* William F. Gilly et al., *Oceanographic and Biological Effects of Shoaling of the Oxygen Minimum Zone*, 5 Ann. Rev. Marine Sci. 393 (2013).

58 *See generally* G.J. Goni & J. Knaff, *Tropical Cyclone Heat Potential*, 89 Bull. Am. Meteorological Soc'y 43 (2007).

59 *See generally* Lynn K. Shay et al., *Effects of a Warm Oceanic Feature on Hurricane Opal*, 128 Monthly Weather Rev.1366 (2000).

60 *See generally* Thomas R. Knutson et al., *Tropical Cyclones and Climate Change*, 3 Nature Geosci. 157 (2010).

61 *See generally* Larry G. Harris et al., *Community Recovery after Storm Damage: A Case of Facilitation in Primary Succession*, 224 Sci. 1336 (1984); R.H. Karlson & L.E. Hurd, *Disturbance, Coral Reef Communities, and Changing Ecological Paradigms*, 12 Coral Reefs 117 (1993).

62 Shaun K. Wilson et al., *Multiple Disturbances and the Global Degradation of Coral Reefs: Are Reef Fishes at Risk or Resilient?*, 12 Global Change Biology 2220 (2006); Carlos M. Duarte, *The Future of Seagrass Meadows*, 29 Envtl. Conservation 192 (2002); Frederick T. Short & Hilary A. Neckles, *The Effects of Global Climate Change on Seagrasses*, 63 Aquatic Botany 169 (1999); Toby A Gardner et al., *Hurricanes and Caribbean Coral Reefs: Impacts, Recovery Patterns, and Role in Long-Term Decline*, 86 Ecology 174 (2005).

4. Shifting Atmospheric and Ocean Circulation

The deep ocean layer is divided into water masses based on density. The density differences between layers make vertical movement of water difficult. Water masses slowly move horizontally across ocean basins in a pattern known as "thermohaline circulation."[63] The movement of deep ocean water masses begins at the surface in the North Atlantic and Antarctic where changes in water temperature, precipitation, addition of freshwater, and ice formation increase seawater density, causing it to sink into the deep layer.[64] Deep water flows south along the Atlantic Ocean into the Indian and Pacific Oceans, where some water is forced to the surface in upwelling zones and the rest eventually heats and rises to the surface.[65]

Thermohaline circulation is sensitive to changes in temperature and salinity[66] and is responsible for much of the ocean's ability to move heat from the tropics to the midlatitudes.[67] Shifts in the positions of oceanic gyres and associated atmospheric circulation cells are being observed. Due to the short data set, however, it is unclear if these are normal oscillations or evidence of climate change.[68] Decreasing sea ice coverage due to increasing surface water temperatures has increasingly been related to changes in atmospheric circulation in the Arctic and beyond.[69] Shifts in wind-driven circulation due to the changes in atmospheric circulation cells have been associated with increased ocean stratification, reduced nutrients, reduced phytoplankton biomass, shifts in phytoplankton species, and the collapse of sardine populations.[70]

5. Saltwater Intrusion

As sea level rises, water will inevitably flood onto coastlines and threaten coastal freshwater resources worldwide. Coastal estuaries exist where freshwater rivers meet the ocean, creating gradients of salinity and temperature that vary based on riverine output and tidal flow. Saltwater intrusion (SI) can occur indirectly from an increase in drought conditions, which would reduce freshwater input, or more directly through oceanic encroachment

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63 *See* Berner & Berner, *supra* note 14, at 21.

64 *Id.*

65 *Id.* at 23.

66 *Id.* at 24.

67 *See supra* note 2, at 26.

68 *Id.* at 31.

69 *See generally* Elizabeth N. Cassano et al., *Atmospheric Impacts of an Arctic Sea Ice Minimum as Seen in the Community Atmosphere Model*, 34 Int'l J. Climatology 766 (2014); Thomas J. Ballinger & Jeffrey C. Rogers, *Atmosphere and Ocean Impacts on Recent Western Arctic Summer Sea Ice Melt*, 7 Geography Compass 686 (2013).

70 *See generally* Gordon T. Taylor et al., *Ecosystem Responses in the Southern Caribbean Sea to Global Climate Change*, 109 Proc. Nat'l Acad. Sci. 19315 (2012).

due to sea-level rise.[71] Either scenario may lead to shifts in plant,[72] animal,[73] and microbial communities.[74]

A direct impact of SI on humans is the encroachment of saltwater into coastal aquifers. Groundwater flows under the surface of coastal areas in an aquifer and serves as a main source of freshwater. Ocean water penetrates into coastal aquifers below the freshwater. Differences in density between the water masses form a natural boundary that prevents contamination of oceanic minerals and salts into the freshwater layer.[75] Increased extraction of freshwater through pumping can drive ocean water farther into the aquifer rendering the freshwater unfit for consumption.[76] SI can also be exacerbated by climate change through rising sea levels, increased storm surges associated with tropical cyclone activity, increased utilization of groundwater sources associated with increased population, and reduced aquifer recharge due to changes in precipitation.[77]

B. Law and Policy Aspects

This section addresses three areas in which law and policy responses have been most active in addressing the physical and chemical changes to ocean and coastal resources from climate change: (1) ocean acidification; (2) increased intensity of tropical cyclones; and (3) sea-level rise, coastal adaptation, and takings.

Existing treaties and federal statutes have been considered to help combat the ocean acidification crisis. For example, the United Nations Convention on the Law of the Sea (UNCLOS) could help address the problem at the international level.[78] The Clean Water Act[79] and the Endangered Species Act[80] provide potential starting points for regulating aspects of the ocean acidification problem in the United States.[81]

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[71] Aat Barendregt & Christopher W. Swarth, *Tidal Freshwater Wetlands: Variation and Changes*, 36 Estuaries & Coasts 445, 451 (2013).

[72] *See generally* Caitlin Mullan Crain et al., *Physical and Biotic Drivers of Plant Distribution across Estuarine Salinity Gradients*, 85 Ecology 2539 (2004).

[73] *See generally* S. Kupschus & D. Tremain, *Associations between Fish Assemblages and Environmental Factors in Nearshore Habitats of a Subtropical Estuary*, 58 J. Fish Biology 1383 (2001).

[74] *See generally* Nathaniel B. Weston et al., *Ramifications of Increased Salinity in Tidal Freshwater Sediments: Geochemistry and Microbial Pathways of Organic Matter Mineralization*, 111 J. Geophysical Res.: Biogeosci.1(2005–2012) (2006).

[75] *See generally* Jacob Bear, Seawater Intrusion in Coastal Aquifers: Concepts, Methods and Practices (1999).

[76] *See generally* Adrian D. Werner et al., *Seawater Intrusion Processes, Investigation and Management: Recent Advances and Future Challenges*, 51 Advances Water Resources 3 (2013).

[77] *See generally id.*

[78] *See generally* Verónica González, *An Alternative Approach for Addressing CO2-Driven Ocean Acidification*, 12 Sustainable Dev. L. & Pol'y 45 (2012) (discussing how UNCLOS can be used to combat ocean acidification).

[79] Clean Water Act, 33 U.S.C. §§ 1251–1387 (2012).

[80] Endangered Species Act, 16 U.S.C. §§ 1531–1544 (2012).

[81] *See generally* Kate Halloran, *Using the Clean Water Act to Protect Our Ocean's Biodiversity*, 10 Sustainable Dev. L. & Pol'y 23 (2010) (discussing EPA's review of comments on how to address ocean

Existing law may be insufficient to manage the new and vexing challenge of ocean acidification, however. At the international level, a new treaty focused exclusively on ocean acidification may be necessary.[82] Domestic responses also are underway. For example, in an effort to mitigate the crippling impacts to its shellfish industry, the state of Washington has enacted legislation to study and respond to ocean acidification.[83]

The increased intensity of tropical cyclones associated with warmer waters from climate change has caused impacts that have triggered legal responses. Two prominent examples of these law and policy responses are the public nuisance case filed by victims of Hurricane Katrina and the adaptation response in New Jersey in the wake of Hurricane Sandy.

In *Comer v. Murphy Oil USA*, the plaintiffs sued electric utilities, oil companies, coal companies, and chemical companies seeking damages for property damages from Hurricane Katrina. The plaintiffs filed a public nuisance claim based on federal common law, alleging that the impacts from Hurricane Katrina had been intensified by the defendants' contributions to global warming. The district court dismissed the case on standing and political question grounds,[84] but the United States Court of Appeals for the Fifth Circuit reversed.[85] The Fifth Circuit ultimately dismissed the case in a rehearing *en banc*.[86] By 2013, in addition to *Comer*, U.S federal courts had dismissed all climate change public nuisance claims based on federal common law in *American Electric Power v. Connecticut* and *Native Village of Kivalina v. ExxonMobil Corp.* Therefore, the courts have effectively closed the door for possible injunctive relief or damages for these

acidification through listing of impaired waters under section 303(d) of the Clean Water Act); Blake Armstrong, *Maintaining the World's Marine Biodiversity: Using the Endangered Species Act to Stop the Climate Change Induced Loss of Coral Reefs*, 18 Hastings W.-Nw.J. Envtl. L. & Pol'y 429 (2012) (noting that the Endangered Species Act is not particularly useful for combating effects of climate change). For further discussion of U.S. environmental law's efforts to regulate ocean acidification, *see infra* Chapters 2 and 3 addressing the Clean Water Act and the Clean Air Act, respectively.

82 *See generally* Heidi R. Lamirande, *From Sea to Carbon Cesspool: Preventing the World's Marine Ecosystems from Falling Victim to Ocean Acidification*, 34 Suffolk Transnat'l L. Rev. 183 (2011) (analyzing the need for an ocean acidification treaty).

83 *See* Diane Deitz, *Ocean of Change: Changing Chemistry of Seawater Poses Lethal Threat to Marine Life*, Register-Guard (Oregon), Sept. 22, 2013, http://www.registerguard.com/rg/news/local/30407375-75/ocean-waters-acidification-oyster-oregon.html.csp (based on recommendations from governor-appointed panel on ocean acidification, Washington legislature invested $1.82 million into an ocean acidification research center at the University of Washington to study the problem and assist the shellfish industry in Puget Sound and Willapa Bay); *see also* Juliet Eilperin, *Washington State Confronts Ocean Acidification*, Wash. Post, Nov. 27, 2012, http://articles.washingtonpost.com/2012-11-27/national/35512233_1_ocean-acidification-washington-state-human-generated-carbon-emissions (discussing Washington's new law requiring more funding for state agencies to fight ocean acidification). For further discussion, see infra Chapter 2 addressing the federal Clean Water Act and Washington State's ocean acidification program.

84 *See* Comer v. Murphy Oil USA, 2007 WL 6942285 (S.D. Miss. 2007).

85 *See generally* Comer v. Murphy Oil USA, 585 F.3d 855 (5th Cir. 2009).

86 *See* Comer v. Murphy Oil USA, 607 F.3d 1049 (5th Cir. 2010) (*en banc*).

climate-change-related federal common law claims on the ground that such claims are displaced by the federal Clean Air Act.[87]

A more successful legal response to hurricane-related impacts purportedly intensified by climate change occurred in the wake of Hurricane Sandy in New Jersey. Established by an Executive Order issued on December 7, 2012, the Hurricane Sandy Rebuilding Task Force released a report, which included sixty-nine recommendations to help the region devastated by Hurricane Sandy recover and rebuild in the wake of the storm. The Task Force is comprised of representatives from more than twenty federal departments and agencies, with contributions from state and local governments.[88] In January 2013, Congress passed the Disaster Relief Appropriations Act, 2013, which provided approximately $50 billion to support rebuilding in the region.[89] Therefore, the legislative and executive branches have proved to be more productive avenues than the judiciary for relief for hurricane-related damages associated with climate-change-enhanced tropical cyclones.

Sea-level rise has prompted extensive coastal adaptation measures throughout the United States and abroad. In the United States, these adaptation measures have clashed with private property rights and have prompted litigation involving claims alleging government taking of private property without just compensation.[90] Similar to the response to tropical cyclone impacts, the most productive efforts to promote adaptation to sea-level rise have been at the state and local legislative levels. Retreat from the coast has emerged as the preferred adaptation response to sea-level rise.[91]

III. Biological Changes to Oceans and Coasts

A. Scientific Underpinnings

The chemical and physical changes in the ocean that occur in periods of global climate change have profound impacts on marine organisms. Increased ocean temperatures impact species directly by influencing factors such as biochemical reactions, growth,

[87] *See* American Elec. Power Co. v. Connecticut., 131 S. Ct. 2527, 2537 (2011); Native Village of Kivalina v. ExxonMobil Corp., 696 F.3d 849, 856–58 (9th Cir. 2012).

[88] For the full report, *see* Hurricane Sandy Rebuilding Task Force, Hurricane Sandy Rebuilding Strategy (2013), http://portal.hud.gov/hudportal/documents/huddoc?id=HSRebuildingStrategy.pdf

[89] *See* Disaster Relief Appropriations Act, 2013, Pub. L. 113–2, https://www.govtrack.us/congress/bills/113/hr152/text. (last visited Aug. 2, 2014).

[90] *See generally* Donna Christie, *Sea Level Rise and Gulf Beaches:The Specter of Judicial Takings*, 26 J. Land Use & Envtl. L. 315 (2011) (discussing judicial takings analysis raised in the *Stop the Beach Renourishment* litigation in the Florida and U.S. Supreme Courts).

[91] *See, e.g.*, Peter Byrne, *The Cathedral Engulfed: Sea-Level Rise, Property Rights, and Time*, 73 La. L. Rev. 69 (2012) (arguing that regulators should encourage or mandate retreat as the preferred coastal adaptation strategy while seeking to minimize risk of and liability for regulatory takings); Robin Kundis Craig, *A Public Health Perspective on Sea-Level Rise: Starting Points for Climate Change Adaptation*, 15 Widener L. Rev. 521 (2010) (proposing construction and siting regulations and a retreat strategy to address saltwater intrusion and other public health problems associated with sea-level rise).

and reproduction. Temperature-induced alterations in sea level, ocean stratification, sea ice coverage, ocean circulation, oxygen concentration, and freshwater input lead to additional species impacts.[92] Species are also impacted by the chemical effects of CO_2 addition through changes in primary production, carbonate saturation, and ocean acidity.[93] Changes in oceanic conditions are not uniform and vary geographically, seasonally, and diurnally, which complicates predictions about the impacts of climate change on marine biota.[94] The cumulative impacts of climate can alter physiology, behavior, and demographic traits, such as reproduction and size.[95] These alterations can lead to shifts in phenology, range and distribution, community composition and interactions, and ecosystem structure.[96]

1. Physiological Changes

Physiological changes occur at the organism level in response to environmental changes and are the principal determinant of a species' ability to tolerate environmental change.[97] Temperature can influence an individual's biochemical reactions, metabolic rates, feeding, growth, and reproduction, ultimately affecting population growth and size.[98] Organisms are capable of acclimating to an environmental change by adjusting their physiology to compensate via phenotypic plasticity, or the ability to change physiology without altering genetic makeup.

Phenotypic adjustments are often at the expense of fitness.[99] For example, acclimating to a temperature shift may cause changes in reproductive output or growth, or both.[100] If the environmental change is prolonged, natural selection can occur in which certain genetic traits are favored, thereby promoting a population's ability to adapt. Genetic adaptation is slow and irreversible. If an environmental disturbance is prolonged and outside the range of an organism's ability to adapt, the population may die or be forced to immigrate to a more desirable location.[101] In some cases, environmental changes may benefit species by increasing food or nutrients, reducing physiological costs, or reducing competition; however, for some species, changes in environmental conditions are

[92] Scott C. Doney et al., *Climate Change Impacts on Marine Ecosystems*, 4 Marine Sci. 11, 12 (2012).

[93] *See supra* Section II of this chapter.

[94] Brian Helmuth et al., *Biophysics, Physiological Ecology, and Climate Change: Does Mechanism Matter?*, 67 Ann. Rev. Physiology 177, 178 (2005).

[95] Doney et al., *supra* note 90, at 12.

[96] *See generally* Gian-Reto Walther et al., *Ecological Responses to Recent Climate Change*, 416 Nature 389 (2002).

[97] Doney et al., *supra* note 90, at 16.

[98] Rebecca L. Kordas et al., *Community Ecology in a Warming World: The Influence of Temperature on Interspecific Interactions in Marine Systems*, 400 J. Experimental Marine Biology & Ecology 218, 219–20 (2011).

[99] Helmuth et al., *supra* note 92, at 179.

[100] *Id.*

[101] *Id.*

stressful, leading to higher mortality, reduced growth, smaller size, and reduced reproduction.[102] Changes on an organism level are the mechanisms behind larger patterns observed in populations and shifts in ecosystems.[103]

2. Phenology

Phenology relates to the timing and seasonal activity of animals and plants.[104] Increases in global temperature have led to earlier timing of seasonal activities such as reproduction, migration, and food production in freshwater, marine, and terrestrial ecosystems.[105] Seasonal timing takes advantage of conditions that maximize growth and reproduction while minimizing sensitive life history stages' exposure to stress.[106] For example, fish reproduce at optimal prey densities and minimal predator densities to improve larval survivorship.[107]

Shifts in the pulse of primary production may lead to trophic mismatch, where optimal prey for key life history stages are misaligned, leading to poor recruitment of higher trophic levels and ecosystem changes.[108] Middle and high latitudes may have greater sensitively to trophic mismatch due to the presence of pulsed plankton production.[109] Phenological shifts are linked to reductions in fitness and population declines, which may increase population extinctions and reduce biodiversity and fisheries production.[110]

3. Range and Distribution

Warming oceans have altered the latitudinal and depth distributions of marine organisms.[111] Northward expansion of southern species from a variety of taxonomic groups has already been observed, while the range of coldwater species has contracted.[112] In

[102] Doney et al., *supra* note 90, at 16.

[103] *See generally* Helmuth et al., *supra* note 92.

[104] Walther et al., *supra* note 94, at 389.

[105] *See generally id.*; William J. Sydeman & Steven J. Bograd, *Marine Ecosystems, Climate and Phenology: Introduction*, 393 Marine Ecology Progress Series 185 (2009); Stephen J. Thackeray et al., *Trophic Level Asynchrony in Rates of Phenological Change for Marine, Freshwater and Terrestrial Environments*, 16 Global Change Biology 3304 (2010); Camille Parmesan & Gary Yohe, *A Globally Coherent Fingerprint of Climate Change Impacts across Natural Systems*, 421 Nature 37 (2003).

[106] Rubao Ji et al., *Marine Plankton Phenology and Life History in a Changing Climate: Current Research and Future Directions*, 32 J. Plankton Res. 1355, 1356 (2010).

[107] *See generally* D.H. Cushing, *Plankton Production and Year-Class Strength in Fish Populations: An Update of the Match/Mismatch Hypothesis*, 26 Advances Marine Biology 249 (1990).

[108] *See generally* Martin Edwards & Anthony J. Richardson, *Impact of Climate Change on Marine Pelagic Phenology and Trophic Mismatch*, 430 Nature 881 (2004).

[109] Ji et al., *supra* note 104, at 1359; *see generally* Edwards & Richardson, *supra* note 106.

[110] *See* Thackeray et al., *supra* note 103, at 3310.

[111] Doney et al., *supra* note 90, at 16.

[112] *See generally* Raphael D. Sagarin et al., *Climate-Related Change in an Intertidal Community over Short and Long Time Scales*, 69 Ecological Monographs 465 (1999); Sally J. Holbrook et al., *Changes in an*

the Gulf of Mexico, where landmasses prohibit northward expansion, species have been observed migrating to deeper, cooler depths.[113]

Range shifts are also being documented with invasive species related to changes in sea surface temperature.[114] Many invasive species are introduced via anthropogenic vectors, such as ballast water in ships, to distant locations that they would normally not be able to reach independently.[115] Nevertheless, shifting communities due to changes in ocean conditions have the same potential negative impacts on the recipient communities that invasive species do.[116] Shifts in species range and distribution contribute to changes in community composition and biodiversity, which can lead to alterations in ecosystems.[117]

4. Community Composition and Species Interactions

Phenology and range shifts of marine species lead to complex changes in community structure and interactions between species, particularly related to food webs and predator-prey relationships.[118] A change in phytoplankton composition from diatoms to dinoflagellates is associated with shifts in zooplankton composition and, ultimately, the loss of fish recruitment.[119] Range shifts lead to interspecific competition between species, which are important components in structuring marine ecosystems. As ranges shift, novel interactions between species are likely to occur, which will further influence ecosystem structure.[120] Interacting species will differ in their environmental tolerances, leading to one species outcompeting the other for resources.[121] If the competitive interactions related to temperature involve

Assemblage of Temperate Reef Fishes Associated with a Climate Shift, 7 Ecological Applications 1299 (1997); Sarah K. Berke et al., *Range Shifts and Species Diversity in Marine Ecosystem Engineers: Patterns and Predictions for European Sedimentary Habitats*, 19 Global Ecology & Biogeography 223 (2010); A.J. Southward et al., *Seventy Years' Observations of Changes in Distribution and Abundance of Zooplankton and Intertidal Organisms in the Western English Channel in Relation to Rising Sea Temperature*, 20 J. Thermal Biology 127 (1995); Rachel Przeslawski et al., *Using Rigorous Selection Criteria to Investigate Marine Range Shifts*, 113 Estuarine, Coastal & Shelf Sci. 205 (2012).

113 Malin L. Pinsky et al., *Marine Taxa Track Local Climate Velocities*, 341 Sci. 1239, 1240 (2013).

114 *See generally* Marc Ruis et al., *Range Expansions across Ecoregions: Interactions of Climate Change, Physiology and Genetic Diversity Physiology and Genetic Diversity*, 23 Global Ecology & Biogeography 76 (2014).

115 Cascade J.B. Sorte et al., *Marine Range Shifts and Species Introductions: Comparative Spread Rates and Community Impacts*, 19 Global Ecology & Biogeography 303, 304 (2010).

116 *Id.* at 310.

117 Doney et al., *supra* note 90, at 18.

118 Walther et al., *supra* note 94, at 393.

119 *See generally* Jürgen Alheit, *Consequences of Regime Shifts for Marine Food Webs*, 98 Int'l J. Earth Sci. 261 (2009).

120 Marco Milazzo et al., *Climate Change Exacerbates Interspecific Interactions in Sympatric Coastal Fishes*, 82 J. Animal Ecology 468, 469 (2012).

121 Kordas et al., *supra* note 96, at 220–21.

keystone species,[122] the changes in communities will be larger than the effects of temperature changes alone.[123]

Warmer water temperatures are also expected to increase disease in marine communities, as growth rates of bacteria, virus, and fungi show positive correlations with temperature.[124] Corals in particular may be influenced by opportunistic pathogens that occur during bleaching events or because pathogens may induce bleaching events.[125] Overall, changes in community structure and species interactions are complicated. Therefore, it is difficult to make predictions about how climate change influences ecosystems.[126]

5. Ecosystem Structure

How ecosystems are impacted by changing environmental conditions depends on how food webs are controlled. "Bottom-up" controls depend on sufficient resources being available at the previous trophic level, "top-down" control is exerted by predators that keep lower trophic levels in check, and "wasp-waste" controls are regulated by intermediate species that control both lower trophic levels and the presence of top predators.[127] Increased temperature, vertical stratification, and reduced nutrient availability negatively impact bottom-up controls on marine primary production.[128] Overfishing and invasive species introductions lead to alterations in top-down and wasp-waste systems.[129] The loss of even a single species can have important consequences for community and ecological structure.[130]

a. Effects on Habitats

One-quarter of marine species associate with coral reefs,[131] which are ecosystems that are highly sensitive to changes in temperature and pH.[132] A symptom of coral stress is

[122] "Keystone species" refers to a species that has a disproportionate impact on a marine ecosystem in relation to its abundance. *See generally* R.T. Paine, *A Conversation on Refining the Concept of Keystone Species*, 9 Conservation Biology 962 (1995).

[123] *See generally* Eric Sanford, *Regulation of Keystone Predation by Small Changes in Ocean Temperature*, 283 Sci. 2095 (1999).

[124] *See generally* C. Drew Harvell et al., *Climate Warming and Disease Risks for Terrestrial and Marine Biota*, 296 Sci. 2158 (2002).

[125] *See id.* at 2161.

[126] Doney et al., *supra* note 90, at 19.

[127] Aleheit, *supra* note 115, at 266.Jurgen Alheit. *Consequences of regime shifts for marine food webs*, 98 Int'l J. Earth Sci. 261 (2009).

[128] *See supra* Section II of this chapter for physical details on these conditions.

[129] *Se generally* Julia K. Baum & Boris Worm, *Cascading Top-Down Effects of Changing Oceanic Predator Abundances*, 78 J. Animal Ecology 699 (2009); Kenneth T. Frank et al., *The Ups and Downs of Trophic Control in Continental Shelf Ecosystems*, 22 Trends Ecology & Evolution 236 (2007).

[130] *See generally* Christopher D.G. Harley et al., *The Impacts of Climate Change in Coastal Marine Systems*, 9 Ecology Letters 228 (2006).

[131] Doney et al., *supra* note 90, at 23.

[132] Hoegh-Guldberg, *supra* note 41, at 843.

mass bleaching events, where endosymbiotic dinoflagellates are expelled from coral tissue, making the white coral skeleton visible.[133] Bleaching events have been increasing in intensity and frequency worldwide.[134] Severe bleaching results in coral death whereas moderate bleaching results in reduced fitness,[135] including reduced growth, calcification, and fecundity.[136] Additionally, corals that survive bleaching events may be more susceptible to disease.[137] A shift of 1°C (1.8°F) for three to four weeks is enough of a stressor to trigger massive coral bleaching.[138] Ocean acidification and the reduction in carbonate saturation depth make secreting and maintaining coral skeletons more difficult, may lead to skeleton loss, and disrupts growth of new recruits.[139] Reduced coral growth may inhibit the ability of corals to keep up with rising sea levels, known as "drowned reefs."[140] Reduced skeleton density may leave corals fragile and more vulnerable to storm damage.[141] Even small declines in coral abundance have been attributed to a reduction in fish and fish diversity.[142]

The stressors that coral reefs face in addition to those associated with climate change, such as overfishing, sedimentation, and eutrophication, increase their vulnerability to future changes.[143] A reduction in coral habitat complexity and structure would have major impacts on socioeconomics around the world, from reduction in fishing, tourism, storm protection, and protection from coastal erosion.[144]

Important energy exchanges exist between coral reefs and coastal wetlands such as mangrove forests and seagrass beds, which are imperiled from climate change.[145] These nearshore ecosystems must keep pace with sea-level rise through accretion of sediments; however, the current rate of sea-level rise may surpass these ecosystems' ability to adapt.[146] Additionally, the presence of coastal infrastructure and armoring along coasts may impede the ability of nearshore ecosystems to expand landward in response to rising sea levels.[147] Migration of habitats may lead to displacement of ecosystems. For example,

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133 B.E. Brown, *Coral Bleaching: Causes and Consequences*, 16 Coral Reefs S129, S135 (1997).

134 Ove Hoegh-Guldberg et al., *Coral Reefs under Rapid Climate Change and Ocean Acidification*, 318 Sci. 1737, 1740 (2007).

135 Doney et al. *supra* note 90, at 23.

136 *See generally* Ove Hoegh-Guldberg. *Climate change, coral bleaching and the future of the world's coral reefs*. 50 Marine Freshwater Resources. 839 (1999).

137 Laura D. Mydlarz et al., *Innate Immunity, Environmental Drivers, and Disease Ecology of Marine and Freshwater Invertebrates*, 37 Ann. Rev. Ecology, Evolution, & Systematics 251, 274–78 (2006).

138 Hoegh-Guldberg, *supra* note 41, at 843.

139 Doney et al., *supra* note 90, at 23.

140 *See generally* R. Grigg et al., *Drowned Reefs and Antecedent Karst Topography, Au'au Channel, SE Hawaiian Islands*, 21 Coral Reefs 73 (2002).

141 Doney et al., *supra* note 90, at 23.

142 *See generally* Wilson et al., *supra* note 60.

143 Doney et al., *supra* note 90, at 24.

144 Hoegh-Guldberg et al., *supra* note 134, at 1741–42.

145 Doney et al., *supra* note 90, at 21.

146 Barendregt & Swarth, *supra* note 69, at 451.

147 *Id.*

migration of mangroves may displace salt marsh communities, which will influence ecosystem structure and biogeochemical cycling.[148] Coastal wetlands face multiple anthropogenic disturbances that impact their resiliency to climate change such as sedimentation, nutrient addition, physical disturbance, invasive species, disease, overfishing, aquaculture, overgrazing, and algal blooms.[149]

Seagrasses are important habitats for marine fish, marine mammals, and sea turtles; however, accelerating seagrass loss is being documented worldwide.[150] Mangrove forests are decreasing by 1–2 percent per year due to deforestation, and are predicted to decrease by 10–20 percent by 2100.[151] Loss of coastal wetlands would negatively impact the important ecosystem services that these habitats provide for humans, including serving as nursery grounds for commercially and recreationally important species, filtering sediment and pollutants, protecting against storms and coastal erosion, and storing carbon.[152]

b. Effects on Species

Marine mammals are faced with indirect and direct impacts of climate change. Ocean temperature can play a crucial role in determining ranges of mammal species, whether they are northern or southern limits.[153] Large migrating species have a greater tolerance to changing temperatures, but restricted species located in polar regions may be more susceptible to warming temperatures.[154] Abundance of prey species impacts distributions, abundance, migration, and reproductive success of marine mammals. Changing ocean conditions including temperature, ocean currents, and ocean chemistry can lead to dramatic changes in food webs that support marine mammals.[155] Changes in phenology of prey species could also lead to trophic mismatch with mammal species, and shifting distributions can lead to increased competition among mammal species.[156] Increased temperature and reduced fitness from changes in prey abundance can leave mammal species more susceptible to disease, contaminants, and death.[157]

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148 *See generally* Michael J. Osland et al., *Winter Climate Change and Coastal Wetland Foundation Species: Salt Marshes vs. Mangrove Forests in the Southeastern United States*, 19 Global Change Biology 1482 (2013).

149 *See generally* Robert J. Orth et al., *A Global Crisis for Seagrass Ecosystems*, 56 Biosci. 987 (2006).

150 *Id.* at 990; *see generally* Michelle Waycott et al., *Accelerating Loss of Seagrasses across the Globe Threatens Coastal Ecosystems*, 106 Proc. Nat'l Acad. Sci. 12377 (2009). Many recreationally and commercially important species, such as seahorses, are seagrass-dependent, and are threatened or in danger of overexploitation and extinction. *See generally* A. Randall Hughes et al., *Associations of Concern: Declining Seagrasses and Threatened Dependent Species*, 7 Frontiers Ecology & Env't 242 (2009).

151 *See generally* Daniel M. Alongi, *Mangrove Forests: Resilience, Protection from Tsunamis, and Responses to Global Climate Change*, 76 Estuarine, Coastal & Shelf Sci. 1 (2008).

152 Doney et al., *supra* note 90, at 21.

153 J.A. Learmonth et al., *Potential Effects of Climate Change on Marine Mammals*, 44 Oceanography & Marine Biology 431, 446 (2006).

154 *Id.*

155 *See generally supra* Sections II and III of this chapter.

156 Learmonth et al., *supra* note 151, at 447–48.

157 *Id.* at 449.

Changes in polar bear prey species due to reductions in sea ice coverage has led to increased contaminate concentrations in polar bear tissue, which can lead to endocrine, immune, and reproductive issues.[158] In polar regions, reduction in ice coverage negatively impacts the reproductive success of many mammal species as ice is used for breeding, birthing, and feeding of pups.[159] Polar bears in particular have shown negative correlations of survival and reproduction with sea ice coverage.[160]

Increased temperature is a major concern for sea turtle populations, which experience temperature-dependent sex determination. Increased temperatures may lead to single-sex populations of females within the next decade.[161] However, males in some populations have been shown to increase their frequency of breeding, which reduces the effects of a female-biased population.[162] Shading of nests has been successful in reducing female-biased hatchlings, but is not a realistic solution to preventing sex-biased populations in the long term.[163] Sea turtle nesting locations occupy specific temperature and precipitation niches that may be impacted by climate change, leading to shifts in the location of nesting areas.[164] Climate change also impacts sea turtle populations through loss of coastal wetlands used for feeding grounds.[165]

Fisheries distribution and abundance are tied to oceanographic features such as prey abundance, temperature, oxygen content, and acidity, all of which demonstrate shifts due to climate change.[166] Climate change has a variety of direct and indirect impacts on fishery species that reverberate throughout ecosystems and impact global food production.[167] The most vulnerable fisheries may be bottom-dwelling, benthic invertebrates, where habitat loss or shifts are occurring, in addition to top predators.[168] The combined

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158 *See generally* Melissa A. McKinney et al., *Sea Ice-Associated Diet Change Increases the Levels of Chlorinated and Brominated Contaminants in Polar Bears*, 43 Envtl. Sci. & Tech. 4334 (2009).

159 Learmonth et al., *supra* note 151, at 451.

160 Andrew E. Derocher, *Climate Change: The Prospects for Polar Bears*, 468 Nature 905, 905 (2010).

161 *See generally* Juan Patino-Martinez et al., *A Potential Tool to Mitigate the Impacts of Climate Change to the Caribbean Leatherback Sea Turtle*, 18 Global Change Biology 401 (2012).

162 *See generally* Graeme C. Hays et al., *Breeding Periodicity for Male Sea Turtles, Operational Sex Ratios, and Implications in the Face of Climate Change*, 24 Conservation Biology 1636 (2010).

163 *See generally* Patino-Martinez et al., *supra* note 159.

164 *See generally* David A. Pike, *Climate Influences the Global Distribution of Sea Turtle Nesting*, 22 Global Ecology & Biogeography 555 (2013).

165 *See generally* MMPB Fuentes et al., *Management Strategies to Mitigate the Impacts of Climate Change on Sea Turtle's Terrestrial Reproductive Phase*, 17 Mitigation & Adaptation Strategies for Global Change 51 (2012).

166 *See generally* Georg H. Engelhard et al., *Nine Decades of North Sea Sole and Plaice Distribution*, 68 ICES J. Marine Sci.: J. du Conseil 1090 (2011); William WL Cheung et al., *Integrating Ecophysiology and Plankton Dynamics into Projected Maximum Fisheries Catch Potential under Climate Change in the Northeast Atlantic*, 68 ICES J. Marine Sci.: J. du Conseil 1008 (2011).

167 *See generally* Anne B. Hollowed et al., *Projected Impacts of Climate Change on Marine Fish and Fisheries*, 70 ICES J. Marine Sci.1023 (2013).

168 E.A. Fulton, *Interesting Times: Winners, Losers, and System Shifts under Climate Change around Australia*, 68 ICES J. Marine Sci.: J. du Conseil 1329, 1334 (2011).

impacts of climate change and the long history of human exploitation of fisheries greatly impacts ecosystem function, biodiversity, and resilience to disturbance.[169] The future success of marine fisheries will depend on an integrated approach to managing the negative effects caused by climate change.[170]

B. LAW AND POLICY ASPECTS

Three federal statutes primarily govern the possible legal response to biological impacts from climate change: the Endangered Species Act (ESA), the Marine Mammal Protection Act (MMPA), and the Magnuson-Stevens Act (MSA). However, none of these statutes is well equipped to directly respond to climate change impacts.

The polar bear was the first species to be listed as threatened under the Endangered Species Act exclusively on the basis of climate change impacts. The listing first occurred in 2007, and has been the subject of controversy[171] and extensive litigation since that time. In March 2013, the D.C. Circuit upheld the polar bear's listing under the Endangered Species Act as a threatened species on the basis of the continued destruction of sea ice habitat caused by climate change.[172] The initial listing decision, and the D.C. Circuit's decision to uphold it, provides important confirmation that climate change imperils polar bears and other Arctic species.

Due to the threats from ocean acidification and other stressors, many coral species are being considered for protection or reclassification under the ESA as threatened or endangered species. Two coral species in the Caribbean, elkhorn and staghorn, have been listed as threatened species under the ESA since 2006.[173] In 2013, the National Marine Fisheries Service (NMFS) proposed to reclassify the protection of elkhorn and staghorn coral species from threatened to endangered status.[174] In addition, NMFS has proposed the listing of sixty-six coral species (fifty-nine in the Pacific and seven in the Caribbean) for threatened or endangered status. NMFS anticipates final decisions on these proposed listings in June 2014.[175]

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169 *See generally* Carl Folke et al., *Regime Shifts, Resilience, and Biodiversity in Ecosystem Management*, 35 Ann. Rev. Ecology, Evolution & Systematics 557 (2004).

170 *See generally* R Ian Perry et al., *Sensitivity of Marine Systems to Climate and Fishing: Concepts, Issues and Management Responses*, 79 J. Marine Sys. 427 (2010).

171 *See, e.g.*, Peyton Knight & Amy Ridenour, *Listing the Polar Bear under the Endangered Species Act because of Projected Global Warming Could Harm Bears and Humans Alike*, 566 Nat'l Policy Analysis 1 (2008), http://www.nationalcenter.org/NPA566.html.

172 *See In re* Polar Bear Endangered Species Act Listing and Section 4(d) Rule Litigation, 709 F. 3d 1, 9 (D.C. Cir. 2013).

173 *See* NOAA Fisheries Service, Threatened Elkhorn and Staghorn Corals (Acropora sp.), http://sero.nmfs.noaa.gov/pr/esa/acropora.htm (last visited Oct. 21, 2013).

174 *See* Office of Protected Resources, NOAA Fisheries Service, Corals Proposed for Listing under the ESA (Sept. 19, 2013), http://www.nmfs.noaa.gov/pr/species/invertebrates/corals.htm.

175 *Id.*

The MMPA has not been nearly as effective as the ESA in addressing climate change impacts to marine species. Climate change has had an impact on seagrass beds, which in turn has had a negative impact on manatees, which rely on seagrass as a food source.[176] The MMPA focuses on specific human-caused harms to select groups of marine mammals, including the manatee. Habitat protection is not a specified harm included in the MMPA, however.[177]

Climate change has impacted fisheries throughout the United States and the world in many ways. The MSA is the federal statute that addresses fisheries management in the United States. The MSA has generally worked well in helping U.S. fisheries rebound from near collapse from overfishing.[178] Despite widespread awareness of the devastating impacts that climate change has on fisheries, the need to address these impacts at the domestic and international levels is only in the early stages of development. For example, merely half of the regional fisheries management organizations (RFMOs) in the world have incorporated climate change considerations into their regulations.[179] The principal challenge is to develop enhanced regional fisheries management domestically and internationally because climate-change-induced shifts in cells is causing species of fish to relocate to areas in which they have not traditionally been found.

Conclusion

Climate change is impacting marine and coastal resources globally. Ocean temperature has increased due to energy being trapped by excess CO_2 in the atmosphere. Increased temperatures can lead to physical changes in oceans including: thermal expansion, which increases saltwater intrusion into coastal aquifers; ocean stratification; tropical cyclone activity; and atmospheric and ocean circulation. Excess CO_2 and other anthropogenic acids have dissolved into oceans creating more-acidic water. Physical changes in the ocean related to excess CO_2 have complex impacts on marine organisms and ecology.

Biological impacts are not universal, due to geographical and temporal variation. Variations also occur among and within species as well as between individuals. Physical ocean changes affect physiology, phenology, range and distribution, community composition, and species interactions of marine organisms. Physical ocean changes have a combination of direct and indirect impacts on marine species, habitats, and ecosystems.

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[176] *See* Dr. Katie Tripp, Manatees and the Changing Climate, http://www.savethemanatee.org/news_feature_global_warming.html (last visited Oct. 21, 2013).

[177] Michael Bhargava, *Of Otters and Orcas: Marine Mammals and Legal Regimes in the North Pacific*, 32 Ecology L.Q. 939, 971 (2005); Susan C. Alker, *The Marine Mammal Protection Act: Refocusing the Approach to Conservation*, 44 UCLA L. Rev. 527, 567 (1996).

[178] *See generally* Pew Charitable Trusts and Ocean Conservancy, The Law That's Saving American Fisheries: The Magnuson-Stevens Fishery Conservation and Management Act (2013), http://www.oceanconservancy.org/our-work/fisheries/msa-the-law-thats-saving.pdf.

[179] *See generally* Ocean and Marine Resources in a Changing Climate, *supra* note 8, section 5.

Positive and negative changes in marine resources are being observed throughout the globe. These changes will ultimately result in different compositions and quantities of marine resources for humans.

International and U.S. domestic law responses to the complex reality of climate change have just begun and face many challenges in the years ahead. All of these legal responses—treaties, statutes, and creative common law theories—rely heavily on the growing body of scientific literature addressing climate change impacts on ocean and coastal systems. This chapter has outlined some of the complexities of these scientific realities and how the law must find ways to regulate the impacts of climate change on these fragile and indispensable marine and coastal resources. The chapters that follow explore multiple dimensions of these regulatory challenges and offer some strategies and hope in our efforts to manage these impacts at the domestic and international levels.