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EDUCATION

Undergraduate:	Haverford College	Chemistry	B.S., 1999
Graduate:	University of Georgia	Marine Science	Ph.D., 2006
Postdoctoral:	Woods Hole Oceanographic Inst.	Marine Chemistry	2007-2010

PROFESSIONAL EXPERIENCE

2016-present: Ocean Acidification Program Director, Ocean Conservancy, Washington, DC.
2014-2016: Science Outreach Manager, Ocean Conservancy, Washington, DC.
2010-2014: Research Associate III, Woods Hole Oceanographic Institution, Woods Hole, MA.
2007-2010: Postdoctoral Investigator, Woods Hole Oceanographic Institution, Woods Hole, MA. Mentor: Scott C. Doney, Ph.D. Ocean acidification implications on marine resource management.
2007-2009: Technical Editor, American Meteorological Society, Boston, MA. Edit academic manuscripts for publication in AMS journals and liaise with press.
2006-present: Freelance technical editor for private clients and companies, primarily editing academic manuscripts before review.
2000-2006: Graduate Research Assistant, University of Georgia, Athens, GA. Inorganic carbon cycling in the Western Tropical North Atlantic and North Pacific.
1999-2000: Long-term substitute teacher, Sanford School, Hockessin, DE. Teach grade 7-8 earth science and lead annual middle school science fair.
1999-2000: Private tutor, Wilmington, DE. Tutor children grades K-10 in science, math, and writing skills.
1999: Summer Undergraduate Research Fellow, Scripps Institution of Oceanography, La Jolla, CA. Shear sensitivity of phytoplankton owing to cell morphology.
1998-1999: Undergraduate researcher, Haverford College Physics Department, Haverford, PA. Atomic force microscopy of biomolecules.
1998: NSF-REU Intern, University of Delaware College of Marine Science, Lewes, DE. Causes of depressed summer primary production in the Delaware Estuary.
1996: Student researcher, Du Pont Hospital for Children, Orthopedic Department, Wilmington, DE. Oxygen consumption in children to measure walking efficiency.

REVIEWED PUBLICATIONS

Rheuban JE, Doney SC, Cooley SR, Hart DR. (2018) Projected impacts of future climate change, ocean acidification, and management on the US Atlantic sea scallop (Placopecten magellanicus) fishery. *PLoS One.* 13(9):e0203536.

Cooley SR, Cheney JE, Kelly RP, Allison EA. (2017) Ocean acidification and Pacific oyster larval failures in the Pacific Northwest United States. In *Global Change in Marine Systems: Societal and Governing Responses*. P. Guillotreau, A. Bundy, R.I. Perry, eds. Routledge, London. p. 58-71.

Bundy A, Chuenpagdee R, Cooley SR, Defeo O, Glaeser B, Guillotreau P, Isaacs M, Mitsutaku M, Perry RI. (2016) A decision support tool for response to global change in marine systems: the IMBER-ADApT Framework. *Fish and Fisheries*, 17: 1183–1193.

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Pendleton L, Comte A, Langdon C, Ekstrom JA, Cooley SR, et al. (2016) Coral Reefs and People in a High-CO2 World: Where Can Science Make a Difference to People? *PLOS ONE* 11(11): e0164699. doi: 10.1371/journal.pone.0164699

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Bundy A, Chuenpagdee R, Cooley S, Glaeser B, McManus LT. (2016) Global change, ensuing vulnerabilities, and social responses in marine environments. *Regional Environmental Change.* 16:273-276. DOI: 10.1007/s10113-015-0906-y.

Leenhardt P, Teneva L, Kininmonth S, Darling E, Cooley S, Claudet J. (2015) Challenges, insights, and perspectives associated with using social-ecological science for marine conservation. *Ocean and Coastal Management* 115: 49-60.

Mathis JT, Cooley SR, Lucey N, Colt S, Ekstrom J, Hurst T, Hauri C, Evans W, Cross JN, Feely RA. (2015) Ocean acidification risk assessment for Alaska's fishery sector. *Progress in Oceanography.* 136:71-91. Doi:10.1016/j.pocean.2014.07.001.

Magnan A, Bille R, Cooley SR, Kelly R, Portner HO, Turley CM, Gattuso J-P. (2015) *Intertwined ocean and climate: implications for international climate negotiations*. Institut du développement durable et des relations internationales, IDDRI, 4pp. (IDDRI Policy Briefs N°04/2015)

Gattuso J-P, Magnan A, Billé R, Cheung WWL, Howes EL, Joos F, Allemand D, Bopp L, Cooley SR, Eakin CM, Hoegh-Guldberg O, Kelly RP, Pörtner HO, Rogers AD, Baxter JM, Laffoley D, Osborn D, Rankovic A, Rochette J, Sumaila UR, Treyer S, Turley C. (2015) Contrasting Futures for Ocean and Society from Different Anthropogenic CO_2 Emissions Scenarios. *Science.* 349(6243): DOI: 10.1126/science.aac4722.

Cooley SR, Jewett EB, Reichert J, Robbins L, Shrestha G, Wieczorek D, Weisberg SB. (2015) Getting ocean acidification on decision makers' to-do lists: dissecting the process through case studies. *Oceanography.* 28(2):198–211.

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Gledhill DK, White MM, Salisbury J, Thomas H, Mlsna I, Liebman M, Mook B, Grear J, Candelmo AC, Chambers RC, Gobler CJ, Hunt CW, King AL, Price NN, Signorini SR, Stancioff E, Stymiest C, Wahle RA, Waller JD, Rebuck ND, Wang ZA, Capson TL, Morrison JR, Cooley SR, Doney SC. (2015) Ocean and Coastal Acidification off New England and Nova Scotia. *Oceanography* 28(2):182–197.

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Ekstrom JA, Suatoni L, Cooley SR, Pendleton LH, Waldbusser GG, Cinner JE, Ritter J, Langdon C, van Hooidonk R, Gledhill D, Wellman K, Beck MW, Brander LM, Rittschof D, Doherty C, Edwards PET, Portela R. (2015) Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change*. 5(3):207-214.

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Kelly RP, Cooley SR, Klinger T. (2014). Narratives can motivate environmental action: The Whiskey Creek ocean acidification story. *Ambio* 43(5), 592-599.

Hilmi N, Allemand D, Cinar M, Cooley S, Hall-Spencer JM, Haraldsson G, Hattam C, Jeffree RA, Orr JC, Rehdanz K, Reynaud S, Safa A, Dupont S. (2014) Exposure of Mediterranean countries to ocean acidification. *Water*. 6(6):1719-1744.

Portner HO, Karl DM, Boyd PW, et al (71 others). 2014. Ocean systems. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. P. 411-484.

Cooley SR, Mathis J. (2013) Addressing ocean acidification as part of sustainable development. In: Chircop A, Coffen-Smout S & McConnell M (Eds.), *Ocean Yearbook 27*. Leiden: Brill (Martinus Nijhoff). ISBN: 9789004250451. p. 29-46. http://www.brill.com/ocean-yearbook-27

Sumaila UR, Cheung WL, Cooley S, Flaaten O, Lam VWY, Hilmi N, Safa A, Amundsen H, Gjertsen A, Hovelsrud G. (2014) Ocean Acidification's Biophysical and Economic Impacts on Arctic Fisheries. Ch. 3, Arctic Monitoring and Assessment Programme (AMAP) report.

Cooley SR.(2012) How humans could "feel" changing biogeochemistry. *Current Opinion in Environmental Sustainability*. 4(3):258-263.

Hilmi N, Allemand D, Dupont S, Safa A, Haraldsson G, Nunes PD, Moore CC, Hattam C, Reynaud S, Hall-Spencer JM, Fine M, Turley C, Jeffree R, Orr J, Munday PL, Cooley SR. (2012) "Towards improved socio-economic assessments of ocean acidification's impacts." *Marine Biology*. DOI: 10.1007/s00227-012-2031-5

Cooley SR, Lucey N, Kite-Powell H, Doney SC. (2012) Nutrition and income from mollusks today imply vulnerability to ocean acidification tomorrow. *Fish and Fisheries*. 13:182-215. DOI: 10.1111/j.1467-2979.2011.00424.x.

Feely RA, Doney SC, Cooley SR (2009) Ocean acidification: present conditions and future changes in a high-CO_2 world. *Oceanography* 22(4): 36-47.

Cooley SR, Kite-Powell H, Doney SC (2009) Ocean acidification's potential to alter global marine ecosystem services. *Oceanography* 22(4): 172-181.

Cooley SR, Doney SC. 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, 4, doi:10.1088/1748-9326/4/2/024007. (Nominee, ERL 5th Anniversary Best Article Prize)

Subramaniam A, Yager PL, Carpenter EJ, Mahaffey C, Björkman K, Cooley S, Kustka A, Montoya JP, Sañudo-Wilhelmy SA, Shipe R, Capone DG. (2008) Amazon River enhances diazotrophy and carbon sequestration in the tropical North Atlantic Ocean. *Proceedings of the National Academy of the United States.* 105(30): 10460-10465.

Cooley SR, Coles VJ, Subramaniam A, Yager PL. (2007) Seasonal variations in the Amazon plume-related Atmospheric carbon sink. *Global Biogeochemical Cycles*. 21: doi: 10.1029/2006GB00283.

Cooley SR, YagerPL. (2006) Physical and biological contributions to the WTNA carbon sink formed by the Amazon River plume. *Journal of Geophysical Research – Oceans*. 111: doi:10.1029/2005JC002954.

Bowen TR, Cooley SR, Castagno PW, Miller F, Richards J. (1998. A method for normalization of oxygen cost and consumption in normal children while walking. *Journal of Pediatric Orthopedics*. 18(5): 589:593.

ACADEMIC RESEARCH GRANTS

Fondation Prince Albert II de Monaco: “Predicting Human Vulnerability to Ocean Acidification,” co-PI L. Pendleton (Duke). 2014-2016. [$101,658]

Socio-Environmental Synthesis Center (SESYNC) Venture Project: “Using Spatial Data and Analysis to Understand the Human Impacts of Ocean Acidification”, co-PIs L. Pendleton (Duke), L. Suatoni (NRDC). (Funds held at SESYNC, disbursed for workshops and meetings; approx. $65,000) September 1, 2012 - 2014

NOAA Funding opportunity NOAA-NOS-NCCOS-2012-2003178 “OA: Developing an Atlantic Sea Scallop Integrated Assessment Model” with co-PIs S. Doney (WHOI), J. Hare (NOAA). 2012-2015. [$218,000]

“Ocean Carbon and Biogeochemistry Program Ocean Acidification Principal Investigators' Meeting, March 22-24 2011,” funded by the National Science Foundation (ANT-1123005; March 15, 2011 – February 29, 2012; $49,944; co-PIs Sarah Cooley, Heather Benway, Joan Kleypas) for supporting the participation of NSF-affiliated researchers in the OCB OA PI meeting in March 2011.

“Riding the Carbon Cycle around the Globe,” funded by the Camille & Henry Dreyfus Foundation (2011-2012; $28,378; co-PIs Sarah Cooley, Heather Benway, Kathy Patterson) for producing an interactive introduction to the global carbon cycle for museum visitors, demonstrating how human activities are altering this cycle with multiple results.

HONORS AND AWARDS

2011: Nominee, Best Article Prize for 5th Anniversary of *Environmental Research Letters* (Cooley and Doney 2009 *ERL*)
2010: Kavli Fellow
2002-2005: NASA Earth System Science Fellow.
2000-2006: University of Georgia Presidential Graduate Fellow.
1999: Scripps Institution of Oceanography Summer Undergraduate Research Fellow.
1999: Haverford College, Chemistry Department Honors.
1998: National Science Foundation Research Experience for Undergraduates Fellow.

MEMBERSHIPS & ASSOCIATIONS

2018-present: Society for Women in Marine Science
2018-present: Association for Women in Science
2009-2012: AAAS
2001-present: American Geophysical Union
2002-2006: Earth System Science Network
2001-2014: American Society of Limnology and Oceanography.
2003-2006: The Oceanography Society
2001-2006: Marine Science Graduate Student Association, UGA.

ADVISING

Committee member: University of Delaware Ph.D. student Jean Brodeur (graduated 2018); Dalhousie University M.S. student Tyler Wilson (graduated 2018), University of Edinborough M.S. student Sylvana Gross (graduated 2018), Simon Fraser University Ph.D. student Ellie Simpson (expected 2019).

Supervisor: WHOI Postdoctoral investigator Lin Zhang (2013)

Mentor: Carnegie Mellon University graduate student Paul Welle (2012-2013); WHOI Joint Program student Elizabeth Drenkard (2010); WHOI Summer Student Fellow Nora Xu (2010)

SERVICE

Lead author: 2nd State of the Carbon Cycle Report (2018): Chapter 17; IPCC 6th Assessment Report Working Group II: Chapter 3 (expected 2021).

Review editor: 4th National Climate Assessment (2018): Chapter 4.

Expert reviewer: IPCC WG2AR5 ch. 3, 6; IPCC AR5 Oceans & Cryosphere Report.

Contributing author: Arctic Marine Assessment Programme (AMAP) report on Arctic Ocean Acidification’s economic impacts chapter; Intergovernmental Panel on Climate Change (IPCC) Working Group II Assessment Report 5, Chapters 3, 6 and 30.

Member of: SOLAS-IMBER Working Group on Ocean Acidification; IMBER Human Dimensions Working Group; Mediterranean Sea Acidification in a changing climate (MedSeA) project’s International Scientific Advisory Panel.

Co-chair of first and second national meetings for ocean acidification researchers, 22-24 March 2011, Woods Hole, MA.

WRITTEN TESTIMONY OF

SARAH COOLEY, OCEAN CONSERVANCY

OCEAN ACIDIFICATION DIRECTOR

HEARING ON:

SEA CHANGE: IMPACTS OF CLIMATE CHANGE ON OUR OCEANS AND COASTS

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY, SUBCOMMITTEE ON ENVIRONMENT

February 27, 2019

Thank you for the opportunity to testify here today. My name is Dr. Sarah Cooley, and I am the Director of the Ocean Acidification Program at Ocean Conservancy. Previously, I was a Research Associate III at Woods Hole Oceanographic Institution, a private, independent ocean research institution. I am an expert on the impacts of ocean climate change on human communities, and served as a lead author on the 2nd State of the Carbon Cycle Report and a review editor on Volume II of the 4th National Climate Assessment. Additionally, I am a lead author on the 6th Assessment Report of the Intergovernmental Panel on Climate Change, which will be complete in 2021.

Ocean Conservancy is a 501(c)(3)nonprofit organization that creates science-based solutions for a healthy ocean and the wildlife and communities that depend on it. For over 40 years, Ocean Conservancy has been deeply engaged in supporting action at the local, national, and global level to the greatest challenges facing our ocean.

Unfortunately, our ocean and the people who depend on it are facing unprecedented challenges. The ocean is a system at risk, struggling to keep pace with rising temperatures, pollution, and the absorption of greenhouse gases. With this testimony, I will describe the state of the science on ocean change as it relates to acidification, warming, and deoxygenation. I will also summarize the main findings of the "Oceans and Marine Resources" Chapter of the 4th National Climate Assessment ("Fourth National Climate Assessment" 2018), a report which is designed to serve as an authoritative assessment on the science and impacts of climate change, with a focus on the United States, and provides important context for understanding the impact of climate change on the ocean and its resources. I will conclude by identifying research gaps in measuring and understanding ocean change that, if addressed, will create a stronger base of scientific evidence from which we can develop responses to better manage the impacts of ocean change.

1. State of the Science

The ocean has absorbed many of the most immediate consequences of carbon pollution, buffering us from some of its most damaging impacts. The ocean has absorbed 93% of the total excess heat energy taken up by greenhouse gas in the atmosphere ("Climate Science Special Report: Fourth National Climate Assessment, Volume I." 2017, chap. 13).[1] Despite this, solar radiation has still heated the

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[1] Henceforth, references to the Climate Science Special Report will be abbreviated "CSSR," and the Fourth National Climate Assessment will be abbreviated "NCA4".

atmosphere, land, and ocean surfaces of our planet by about 1.8°F from 1901-2016 (NCA4, chap. 2). At the same time, the ocean has absorbed 22% of the atmospheric carbon dioxide released as waste from fossil fuel burning and land use change from 2008-2017 (Quéré et al. 2018). While this has kept those fossil fuel emissions from warming the atmosphere, it is also fundamentally changing the chemistry of the ocean via ocean acidification.

1.1 Ocean Acidification

Ocean acidification is an invisible but growing threat to the world's oceans. Time-series measurements show clearly that the dissolved carbon dioxide concentration of surface ocean water is rising at the same pace as atmospheric carbon dioxide concentrations (Figure 1). When carbon dioxide dissolves in water, carbonic acid is created, which is gradually lowering the pH of seawater and altering other chemical balances important for marine life.

We are already seeing the effects of ocean acidification. In the mid-2000s, widespread death of larval shellfish at hatcheries in the Pacific Northwest region of the United States alerted the aquaculture industry to a major region-wide problem. In partnership with federal and university researchers, the industry identified the problem as ocean acidification caused by fossil fuel emissions dissolved in Pacific Ocean water that upwelled to the surface decades earlier than previously anticipated (Feely et al. 2008). This finding, plus growing evidence of the ocean's role in taking up a large portion of the annual emissions from fossil fuel burning (e.g., Quéré et al. 2018), helped kick off a nationwide effort to understand ocean acidification's full impacts on marine ecosystems. In 2009, Congress took action to better understand the issue by passing the *Federal Ocean Acidification Research and Monitoring Act* (or FOARAM), which provided for a coordinated response by U.S. federal scientific agencies to understand, track, and address ocean acidification.

Since then, laboratory studies, many of them supported by the federal funding authorized by FOARAM, have shown that ocean acidification has an array of effects on marine species, and the effects are difficult to generalize. Global studies have determined with high confidence that increasing atmospheric carbon dioxide causes ocean acidification (Figure 2), and that acidification decreases the calcification rate of many organisms with hard shells and skeletons. Corals grow more slowly under acidification and are less able to recover from breakage or loss from heat-driven bleaching or disease. Many animals that sustain lucrative fisheries, such as oysters and crabs like Dungeness, red King, and Tanner crabs, are more sensitive at earlier life stages, and acidification causes them to grow more slowly and allows fewer to survive to adulthood. Ocean acidification changes the behavior of some fishes and sharks, impairing their ability to find prey or avoid predators. Some models suggest acidification will generally reduce fish biomass and catch.

We have high confidence that ocean acidification can stimulate growth and primary production in seagrasses and some phytoplankton. Although increased plankton growth can provide benefits to marine ecosystems, some fast growing species can out-compete others and cause harmful algal blooms. Emerging evidence suggests that harmful algal blooms could become more frequent or toxic in response to acidification.

While it is unclear exactly how ocean acidification's impacts will propagate through ocean ecosystems and food webs, there is no question that complex interactions will occur among ocean acidification and other stressors. That's especially true in the coastal zone where warming, deoxygenation, pollution, river discharge and precipitation, seasons, weather, climate, and tides intersect with human activities like fishing, dredging, development, and restoration. The end result is an especially complex system of environmental drivers that affect coastal systems and the humans that depend on them in ways that are difficult to predict. In addition, the variety of factors at play in the coastal zone often makes it difficult to attribute trends in coastal acidification directly to atmospheric carbon dioxide (Figure 3).

Overall, ocean acidification may disrupt important benefits that ocean systems and resources provide to human communities. Coral reef-associated fisheries and tourism are at risk, as well as coastal communities protected from storm waves by corals. Some studies suggest ocean acidification will alter the market qualities of fishery harvests. One study reported changes in flavor of pink shrimp raised under ocean acidification conditions (Dupont et al. 2014), and integrated assessment models show that fishery revenues will decrease if ocean acidification decreases the recruitment or slows the growth of lucrative species like sea scallops and red king or Tanner crab (Cooley et al. 2015; Punt et al. 2014). Studies of the socioeconomic impacts of ocean acidification are fewer in number than studies of its geochemical or biological impacts.

Despite the complexity of predicting ocean and coastal acidification's impacts on marine ecosystems and human communities, an active community has developed to identify, test, and share opportunities to act. In the Pacific Northwest U.S., shellfish hatchery owners have focused on protecting the multi-million dollar-a-year industry that employs thousands of people. Teaming up with researchers, hatcheries have invested in "future proofing" steps such as monitoring seawater chemistry at intake pipes, modifying the chemistry of intake water, and experimenting with selective shellfish breeding. Activities supported by the National Oceanic and Atmospheric Administration (NOAA), and authorized by FOARAM, have developed a rich observing network in the Pacific Northwest and across the nation.[2] This effort allows people who depend on ocean resources to track and respond to acidification and has been likened to "putting headlights on a car."

Engagement of multiple sectors, including university and federal researchers, the shellfish aquaculture community, resource managers and more has been a hallmark of the particularly successful work of adapting to ocean acidification in the U.S. to date. It continues even now: Ocean Conservancy helped convene shellfish industry leaders from across the country last week on the Gulf Coast to share best practices to help the sector plan ahead for ocean acidification.

In the United States, scientists, regional industry and resource management experts, educators, and science communicators are joining largely self-organized groups such as the Global OA Observing Network (GOA-ON) and the regional Coastal Acidification Networks (CANs) that are supported by the NOAA Ocean Acidification program and the U.S. Integrated Ocean Observing System. Lessons learned in one region are being transferred to other regions, accelerating the application of adaptive solutions and technology to monitor ocean acidification. Regional collaboration by the governors' offices of California, Oregon, Washington, and the premier's office of British Columbia recently helped create the International Alliance to Combat Ocean Acidification[3], a voluntary partnership of over 70 governments and nongovernmental organizations dedicated to advancing scientific understanding of acidification, reducing its causes, building adaptation and resiliency, expanding public awareness, and building sustained international support for research, monitoring, and education. At the same time, programs like the International Ocean Acidification Coordination Centre (OA-ICC), supported by the International

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[2] http://www.ipacoa.org/Explorer

[3] https://www.oaalliance.org/

Atomic Energy Agency, are increasing international scientific coordination, collaboration, and capacity building.

1.2 Warming:

The increasing heat energy content of the ocean is leading to seawater warming and expansion, along with sea ice melt. A study released this January showed, using multiple different lines of evidence, that ocean heat content is rising more quickly than previous assessments indicated (Cheng et al. 2019). Ocean model projections included in the last IPCC assessment (AR5) had predicted continued steady ocean heat uptake, but the evidence available at the time of AR5's publication, around 2013, showed surface ocean warming had slowed. This was due to redistribution of ocean heat and not reduced ocean heating. The increasing heat content of the ocean is changing ocean circulation, raising sea levels around the world ("Climate Science Special Report: Fourth National Climate Assessment, Volume I." 2017)(hereinafter referred to as CSSR), and affecting biological responses in the ocean from top to bottom.

1.2.1 Impacts of Sea Level Rise on Human Communities

One of the most immediately apparent effects of ocean warming affects coastlines, where sea level is rising. Sea level rise is primarily driven by expansion of warming seawater and melting of land-bound glaciers. Coastal communities in the United States now experience regular flooding, euphemistically called "sunny day flooding" or "king tides." 50 million housing units are within 1/8 of a mile of the coast, and projections suggest that between $66 and $106 billion of real estate value may be underwater by 2050 (NCA4, chap. 8). Moreover, 60,000 miles of roads and bridges are located along the coast (NCA4, chap. 12), many if not most of which will need to be repaired or relocated. These costs will become an increasing economic liability for municipalities and programs like the National Flood Insurance Program, which may become insolvent when properties become unsellable (NCA4, chap. 8). Ocean-dependent businesses like fishing will also be hurt when sea level rise damages or destroys coastal infrastructure like ports, marinas, and docks. And, we are already seeing these costs to our cities and military bases.

The Department of Defense has been studying the potential impacts of climate change on military readiness and installations for decades, having produced at least 64 public reports and assessments on that topic since 1990.[4] Not only is climate change likely to worsen international conflict or complicate military responses, but it will damage key assets like roads, runways, and waterfronts (NCA4, chap. 16). In Hampton Roads Virginia, the nation's largest naval base, Naval Station Norfolk, is at major risk from sea level rise (Office of the Under Secretary of Defense for Acquisition and Sustainment 2019). According to news reports, this is spurring a good deal of innovation and redevelopment in the area,[5] but questions remain about how to help the entire community adapt in a socially and economically equitable way.

Of course, these issues are not confined to military infrastructure. Coastal communities and states throughout the country are already adapting to sea level rise in hope of averting greater costs

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[4] https://climateandsecurity.org/resources/u-s-government/defense/

[5] https://insideclimatenews.org/news/15052018/norfolk-virginia-navy-sea-level-rise-flooding-urban-planning-poverty-coastal-resilience; https://insideclimatenews.org/news/10252017/military-norfolk-naval-base-flooding-climate-change-sea-level-global-warming-virginia

associated with flood recovery. In Florida, there are 120,000 properties at risk from frequent tidal flooding (NCA4, chap. 19). Current projections in Florida estimate that between $15 and $23 billion of existing property will likely be underwater by 2050 (Bloomberg et al. 2014, 24). This January, Florida's governor issued an Executive Order to create the Office of Resilience and Coastal Protection, to help prepare Florida's coastal communities and habitats for impacts from sea level rise. In Texas, natural coastal habitats protect about $2.4 billion worth of property and thousands of lives (NCA4, chap. 23) as well as 25 percent of the Nation's refining capacity, four crucial ports, much of the strategic petroleum reserves, and strategic military deployment and distribution installations. The state is planning over $12 billion in sea level rise solutions, which include storm surge protection, drainage and erosion control, and flood mitigation projects.[6]

Migration away from coastal cities is expected to place heavy growth pressure on inland urban centers. A recent modeling study suggests that 1.8 m of sea level rise [slightly more than the 0.3-1.3 m considered very likely to occur by 2100 in NCA4 chap. 2, but much less than the 2.5 m considered physically plausible but whose probability is difficult to determine in the same assessment] could cause Florida to lose more than 2.5 million residents, and Texas to gain nearly 1.5 million additional residents (Hauer 2017). Other sea level rise-impacted communities are already taking steps to leave the coastal zone altogether. In Louisiana, the Biloxi-Choctaw tribe has a $48 million grant from the federal government to develop a plan to relocate residents of Isle de Jean Charles. The island has lost 98% of its landmass since 1955 and has only approximately 320 acres (approximately 1/2 square mile) remaining. The population living on the Island has fallen from 400 to 85 people. Ad hoc migration has resulted in family separation, spreading individuals across southern Louisiana. In addition, the Tribe continues to lose parts of its livelihood and culture, including sacred places, cultural sites and practices, healing plants, traditional foods, and lifeways. (NCA4 chap. 19) In Alaska, the villages of Kivalina, Newtok, Shishmaref, Shaktoolik and others face grave risks from sea level rise and coastal erosion.

1.2.2 Moving marine resources

All along our coastlines, marine life is moving in response to warming oceans. There is a clear northward trend across 360 marine species at a speed of about 5 miles per decade on average (Pinsky et al. 2013). The National Climate Assessment noted that many commercially and recreationally valuable fish and invertebrates are moving poleward or into deeper water, from the net effect of temperature on productivity, recruitment, survivorship, and, in some cases, active movement to follow species' preferred temperature conditions (NCA4 chap. 4). Lobster harvests, for example, have shifted north substantially in the last fifty years, at a speed of 43 miles a decade (Pinsky et al. 2013) and [7]. Shifts in distributions of fisheries stocks can complicate fisheries management and place strain on fishing-dependent communities. Fishermen may try to follow their target species but fishing costs, port locations, regulations, management boundaries, and other factors make it hard for fishers to track species movement (NCA4, chap. 4).

1.2.3 Ocean heat waves

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[6] https://www.estormwater.com/construction-begins-houston-flood-mitigation-projects; http://www.austintexas.gov/department/creek-flooding; http://www.gccprd.com/pdfs/GCCPRD%20Phase%203%20Report%20-%20Recommended%20Actions.pdf

[7] https://www.eurekalert.org/pub_releases/2013-09/pu-mom091113.php

The NCA4 provides details on how America's fisheries are also suffering from extreme heat events. A marine heat wave in the northwestern Atlantic Ocean in 2012, and a heat wave in the northeastern Pacific Ocean during the years 2014-2016, raised temperatures more than 3.6°F [2°C] above the normal range and lasted for several months (NCA4, chap. 19). In the 2012 event, warm temperatures in the Gulf of Maine caused lobster catches to peak 3–4 weeks earlier than usual. The supply chain was not prepared for this early peak, leading to glut of lobster and a severe drop in price. (NCA4, chap. 19) The Northeastern Pacific event included an extensive bloom of a toxic algae species (*Pseudo-nitzschia)* that caused mass mortalities of sea lions and whales and closed the Dungeness crab fishery. When the crab fishery reopened in the spring of 2016, out of step with typical Dungeness fishery open times, increased fishing activity during the spring migration of humpback and gray whales led to more whales becoming entangled in crab fishing gear. Continued warm temperatures in the Gulf of Alaska during 2016 reduced the catch of Pacific cod (NCA4 chap. 19). Overall, marine heat waves are remaking marine ecosystems: for example, warmer water has made sea stars all over the West Coast susceptible to wasting disease, killing the sea stars and allowing their typical prey, sea urchins, to go unchecked and consume vast amounts of kelp (Harvell et al. 2019).

1.2.4. Loss of sea ice

Warming polar oceans are melting sea ice, affecting ecosystems, the planetary heat budget, and human access to the Arctic. In the Arctic Ocean, annual average Arctic sea ice extent has decreased precipitously since the 1980s, and it is likely that there will be an Arctic summer within this century that is sea ice-free (NCA4 chap. 26). Ice-dependent species like Arctic cod, polar bears, and walruses are losing important habitat, which is expected to affect the entire Arctic marine food chain, including Indigenous populations that depend on marine mammals (NCA4 chap. 26). Subsistence hunting will become more dangerous and difficult, which threatens the food security and continuity of ways of life that have existed in communities for millennia. In addition, reductions in sea ice extent increase the Arctic Ocean's ability to absorb solar heat, creating a positive feedback that warms the ocean further (NCA4, chap. 2).

Decreasing sea ice is also facilitating the growth of vessel traffic in the Arctic, including destinational and transarctic shipping. While increasing vessel traffic in the Arctic will bring opportunities and benefits, it also creates risks in this remote region. The National Climate Assessment notes that increased vessel traffic "would bring environmental risks to fisheries and subsistence resources" (NCA4 chap. 26). Transarctic shipping will also create a new avenue for the spread of invasive marine species. From a life and safety perspective, the U.S. Arctic currently lacks deep water ports and has insufficient search and rescue and environmental response capabilities for such a vast and remote region. The U.S. also lacks icebreaking capacity (NCA4 chap. 26)—although Congress has taken the first steps toward remedying that problem by appropriating funds in Fiscal Year 2019 for an Arctic icebreaker.

1.3. Deoxygenation

Ocean oxygen levels are declining because of ocean warming. First, warmer water holds less oxygen because gas solubility decreases as temperature rises. Second, ocean warming helps discourage deep vertical mixing by stratifying, or increasing the top-to-bottom density difference, of the ocean water column. Vertical mixing is the main way oxygen moves into the ocean. Warming and stratification also cause ecosystem changes that alter photosynthesis and respiration, further changing oxygen dynamics (NCA4, chap. 4). Researchers recently noted that ocean deoxygenation may cause short-term increases in fishery catch, as fish stocks are easier to target when squeezed into shrinking areas where oxygen levels are adequate, but ultimately ocean deoxygenation will lead to unsustainable changes as the suitable habitat shrinks (Breitburg et al. 2018).

Oxygen loss from the ocean can also affect the global nitrogen cycle. As ocean oxygen declines, nitrous oxide production may increase. Nitrous oxide is even better than carbon dioxide at trapping solar energy, so an increase in nitrous oxide production would exert an intensifying feedback on planetary warming (CSSR).

2. NCA4 key messages on Ocean and Marine Resources

The 4th National Climate Assessment (NCA4) was published in November 2018. The NCA is a periodic assessment by the U.S. Global Change Research Program, requested by Congress, that evaluates the impacts of climate change on the United States, now and in the future. It is designed to be an authoritative analysis of the science of climate change, with a focus on the United States, to serve as the foundation for efforts to assess climate-related risks and inform decision making about responses. It is the product of more than 300 individuals from governments, indigenous groups, national laboratories, universities and the private sector, and which has been exhaustively reviewed by external experts, the general public, federal agencies, and an ad hoc committee of the National Academy of Sciences, Engineering, and Medicine.[8] My work as a Review Editor on Chapter 9 of NCA4, which examines ocean and marine resources, meant that I was responsible for ensuring that the author team fully considered and responded to the reviews provided by the NAS committee and the general public. The final text of Chapter 9 was organized around three key messages, quoted below.

2.1 Key Message 1: Ocean Ecosystems

> *"The Nation's ocean ecosystems are being disrupted by increasing global temperatures, resulting in the loss of iconic and highly valued habitats and changes in species composition and food web structure. Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided."*

This message is supported by the existing evidence of climate impacts on marine resources to date, and the complex connections within marine ecosystems that are likely to be disrupted by future climate impacts. Opportunities for reducing this risk include conservation measures to reduce the effect of human-caused stressors besides climate, but there is growing evidence that many ecosystem changes can be avoided only by substantial and rapid reductions in atmospheric carbon dioxide concentration (NCA4, chap. 9).

2.2 Key Message 2: Marine Fisheries

> *"Marine fisheries and fishing communities are at high risk from climate-driven changes in the distribution, timing, and productivity of fishery-related species. Ocean warming, acidification, and deoxygenation are projected to increase these changes in fishery-related species, reduce catches in some areas, and challenge effective management of marine fisheries and protected species. Fisheries management that incorporates climate knowledge can help reduce impacts, promote resilience, and increase the value of marine resources in the face of changing ocean conditions."*

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[8] https://nca2018.globalchange.gov/chapter/front-matter-about/

This message is supported by the existing impacts to marine fisheries that have been observed, and projected changes in fish location and effort that will follow from continued climate impacts. To effectively reduce risks to marine fisheries, we must take steps to quickly and significantly reduce greenhouse gas emissions. Other opportunities for reducing risk to fisheries include instituting climate-ready, ecosystem-based fisheries management that anticipates changing ecosystem conditions and resulting changes in species diversity and relationships, detailing human community vulnerability to climate change and ocean acidification, seeking to diversify fisheries, and using precautionary and dynamic fisheries management (NCA4, chap. 9).

2.3. Key message 3: Extreme events

> *"Marine ecosystems and the coastal communities that depend on them are at risk from significant impacts from extreme environmental events where very high temperatures, very low oxygen levels, or very acidified conditions interact. These events are projected to become more common and more severe in the future, and they expose vulnerabilities that can motivate change, including technological innovations to detect, forecast, and mitigate adverse conditions."*

This message is supported by impacts from extreme ecosystem events to date, such as heat waves, regionally intense ocean acidification, and deoxygenation (Figure 4). In addition to quickly and significantly reducing greenhouse gas emissions, opportunities for reducing this risk include embracing technological adaptation designed to offset the most immediate impacts of extreme events (such as adaptations implemented by shellfish hatcheries), developing operational forecasts for ocean environmental conditions (temperature, acidity, oxygen level) and biological events like harmful algal blooms and fishery opening times (NCA4, chap. 9).

3. Research gaps

Our understanding of climate change in the ocean has grown vastly in the last half-century, but key knowledge gaps remain, and can be addressed with coordinated, transdisciplinary activities founded upon comprehensive monitoring, observations, and research. Detailed examinations of existing uncertainties and the evidence base exist in a number of recent national and international scientific assessments, including the U.S. National Climate Assessment's Volumes I and II (here, CSSR and NCA4), the 2nd State of the Carbon Cycle Report, the Intergovernmental Panel on Climate Change's 5th Assessment Report, its Special Report on Global Warming of 1.5°C, its forthcoming Special Report on Oceans and the Cryosphere, and its 6th Assessment Report. Some of the needs identified in these and other studies include the following:

- *Detecting and attributing the role of overlapping drivers, like acidification, warming, oxygen loss, fishing, pollution, and more, on influencing ocean species at the individual, population, and ecosystem levels.* Tools like numerical ecosystem models, meta-analyses, mesocosms, and in situ studies are useful for this work, but they also require large teams and long studies, which can be difficult to fund.

- *Measuring the ability of species to acclimatize or adapt to ocean change* (recommended in NCA4 chap. 19). Long-term evolutionary studies and "-omics" (genomics, proteomics, metabolomics, etc.) techniques are some of the tools being refined to study this.

- *Identifying the most useful biological indicators of change to use as part of long-term ocean ecosystem monitoring.* Currently, long-term ocean observing skews heavily toward measuring chemical and physical variables, and a full suite of appropriate biological metrics to assess the impacts of stressors like acidification and deoxygenation are still being developed.[9]

- *Determining how best to incorporate ecosystem-scale information in precautionary fisheries management, while maintaining equitable and transparent decision making about fisheries resources*. Fishery management councils in the U.S. are beginning to tackle this challenge, but need support and new tools to adapt their management practices.

- *Evaluating the multitude of non-economic ways in which human communities depend on marine resources.* While food, energy, or natural materials resources are frequently evaluated using economic methods, ocean systems provide a host of additional services (e.g., carbon storage, temperature regulation, support of tourism, cultural meaning) that cannot be well measured with conventional/traditional economic techniques and require different multidisciplinary assessments.

- *Incorporating traditional and indigenous knowledge into ocean resource management and decision making.* Traditional knowledge often spans a longer timescale and a broader range of environmental conditions than contemporary scientific data, but can be captured in ways (e.g., language, the arts) that are not directly compatible with other data used in decision making.

- *Connecting ocean governance across geographic and jurisdictional scales to support robust, coordinated decision making about ocean resources.* Tools such as regional ocean data portals and processes such as collaborative decision making are supporting inclusive, multi-sectoral decision making, and need to be employed in more situations.

4. Future Opportunities

I would like to leave the Committee with one final thought. When looking at an unsolved problem, scientists sometimes fall into the trap of focusing on the unanswered questions and the knowledge gaps where more data and research are needed in order to make informed decisions. However, as an expert on the ocean impacts of climate change, I am here to tell you that we already know a lot about carbon pollution, climate change, and the impacts they have on the ocean and on human communities. What I see is alarming, and it is very clear that the fundamental solution to ocean warming, acidification, and oxygen loss is to decrease greenhouse gas emissions, particularly of carbon dioxide.

Even if we stopped emitting greenhouse gases today, there are still years of “momentum” in the system, as the existing measure of greenhouse gases in the atmosphere will continue to warm and acidify the ocean. As nations around the world work collectively toward reducing greenhouse gas emissions, there are also steps we can take to reduce the stress on marine ecosystems and the human communities they support.

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[9] http://goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

First, we must take steps to decrease other ocean stressors. Studies show that multiple layered stressors on ocean ecosystems have a greater chance of acting synergistically than of counteracting each other (Harley et al. 2006). As a result, reducing overall stress on ocean life requires reducing ocean stressors. This should include combatting oxygen loss, nitrogen pollution, sedimentation, disease, and other types of chemical pollution (Kelly & Caldwell, 2013). Marine resource management has sought to reduce these problems as part of general water quality improvement for decades, with progressive success in doing so (Côté et al. 2017), but the need is even more pressing in the face of climate change. Preventing the expansion of offshore oil and gas activities, especially in sensitive or remote places where the risks of these activities far outweigh any potential benefits, is also an important way to decrease additional ocean stressors. Decreasing marine pollution and other stressors to ecosystems is a "no-regrets" policy approach because of the multiple benefits that accrue—both the immediate value of reducing single stressors, and decreasing the likely value of reducing synergistic effects of multiple stressors acting together (Côté et al. 2017).

Second, we need to support community adaptation planning. To date, ocean climate change has driven piecemeal adaptation. As more adaptation efforts begin, there is an increasing risk that overlapping, uncoordinated efforts could be at best inefficient and at worst counterproductive. Around the world, nations are currently planning both mitigation and adaptation actions to address climate change, but little guidance exists to ensure coordination and inclusion of the ocean in these activities. A similar situation exists within the U.S., where state and local governments nationwide are at widely different stages and levels of coordination in adopting ocean-smart climate policies.

Resources and support for long-term resilience and adaptation planning are desperately needed. At a minimum, this should include support for regional ocean planning through tools that support coordinated data and management like regional ocean data portals. Comprehensive planning approaches underpin community and ecosystem resilience and ecosystem-based management. States and regional ocean partnerships across the country have found value in comprehensive planning, and resources should support the priorities outlined by states. Regional ocean planning should also include support for policies and programs, particularly those within NOAA, that support ocean and coastal resilience. This includes priorities such as ocean acidification monitoring and funding, ocean and coastal habitat and coral reef restoration, and fisheries management adaptation. In addition, there is a particular need to increase resilience and adaptation planning in the Arctic. Funding and support is needed for communities that must relocate, and there are opportunities to plan for coming changes and ensure that Alaskan communities, ecosystems, and economies will be resilient in a changing future.

5. Conclusion

Our ocean and its resources are facing unprecedented challenges. The state of ocean change science indicates that ocean acidification, warming, and deoxygenation are having large effects on marine ecosystems. As detailed by the 4th National Climate Assessment, these changes are rippling through the human-ocean connection, and there are knowledge and research gaps that can be addressed to better help our nation respond to large-scale ocean changes.

I believe there is an opportunity to continue American leadership on ocean science and technology, combining that history of excellence with a forward-looking vision to steward the main resource that makes life on Earth possible: our ocean. Thank you for the opportunity to provide this testimony.

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Figures

Figure 1: The dissolved carbon dioxide concentration of surface ocean water (blue) is rising at the same pace as the atmospheric carbon dioxide concentration (red). This is decreasing the pH (black) and the carbonate ion concentration (green) of surface seawater. These data are from the Hawai'I Ocean Time Series Program in the North Pacific Ocean from 1988-2015. (Figure 13.4, CCSR)

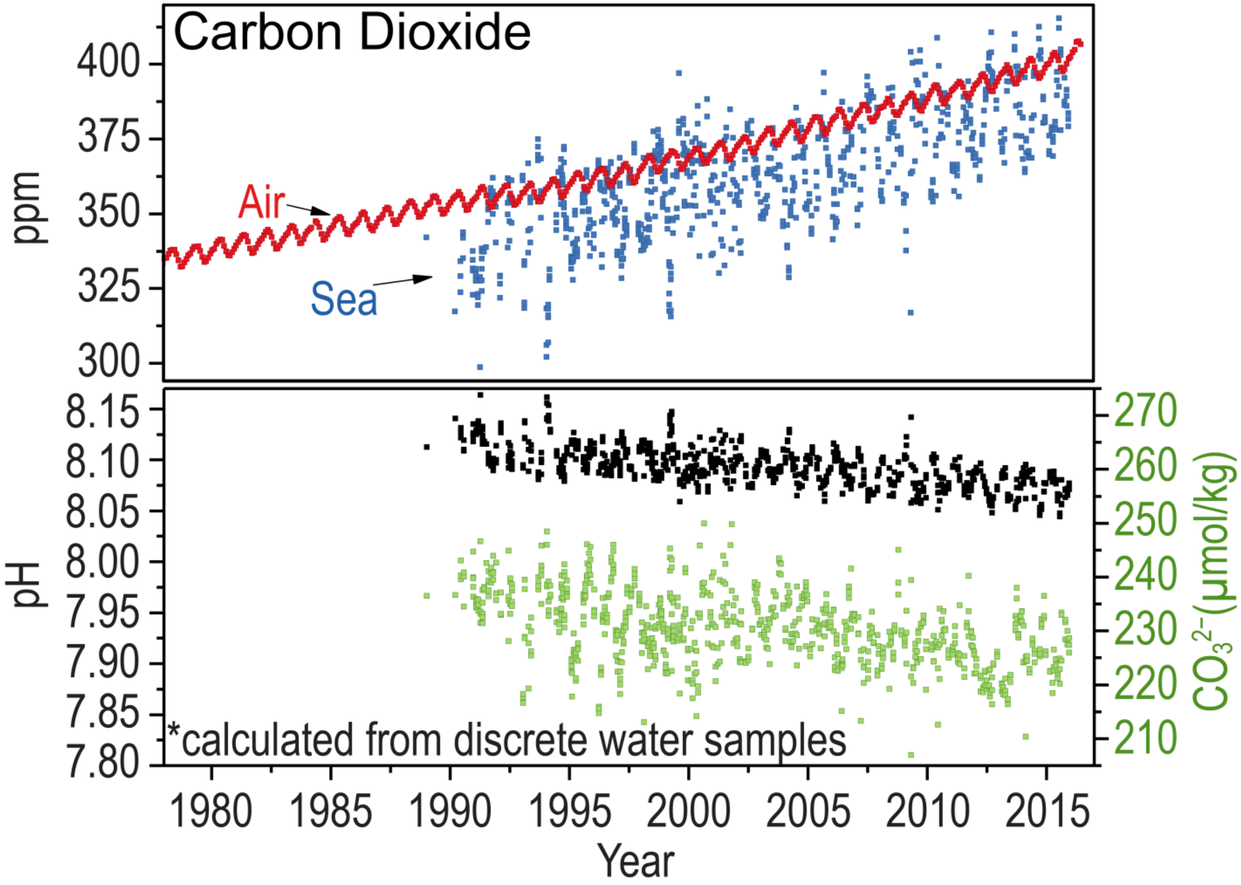

Figure 2: We have high certainty that atmospheric carbon dioxide levels drive ocean acidification, moderate certainty about how it will change organisms and ecosystems, and the lowest certainty about the best policy options for action. (Excerpted from Figure OA-1, IPCC AR5 WG II)

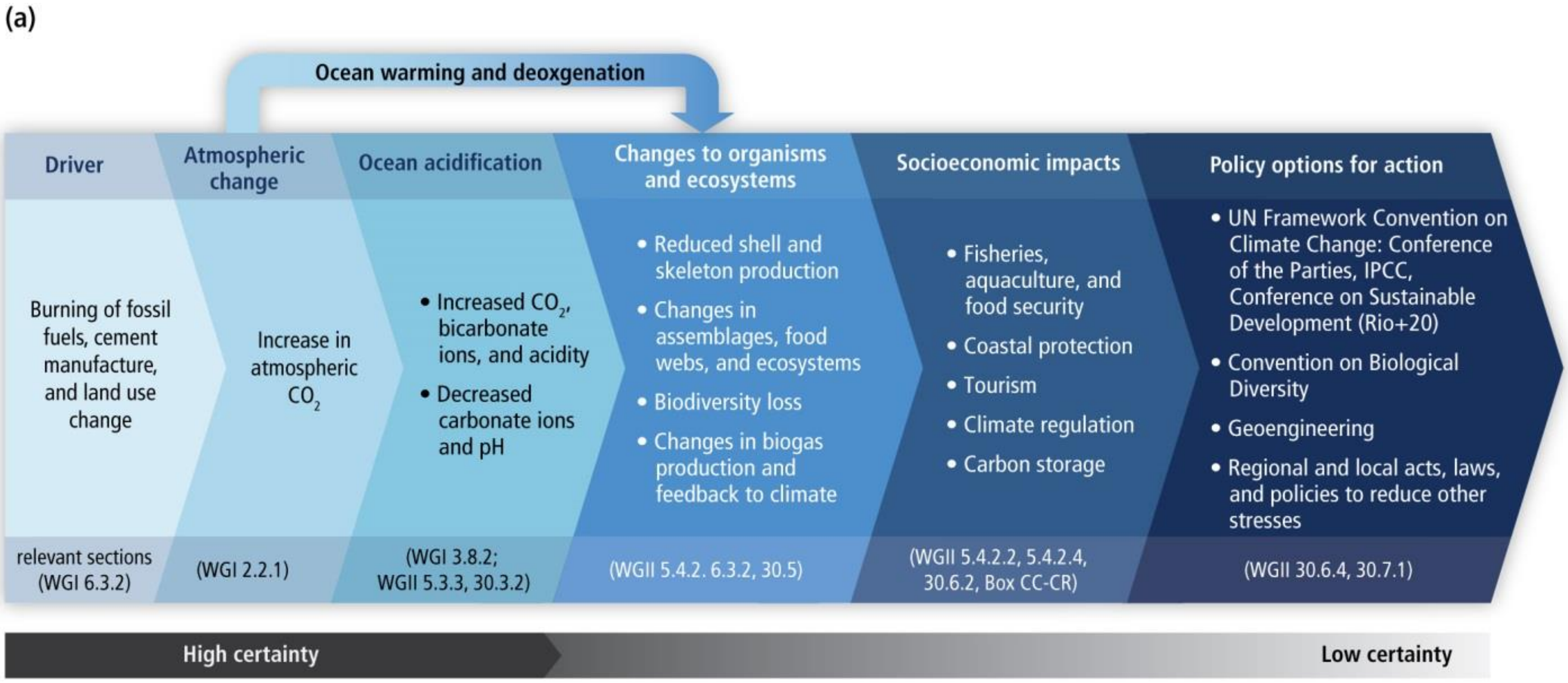

Figure 3: Coastal waters become acidified through a combination of atmospheric CO2, point and nonpoint sources of pollution and runoff, as well as river input and upwelling (Figure from(Kelly et al. 2011).

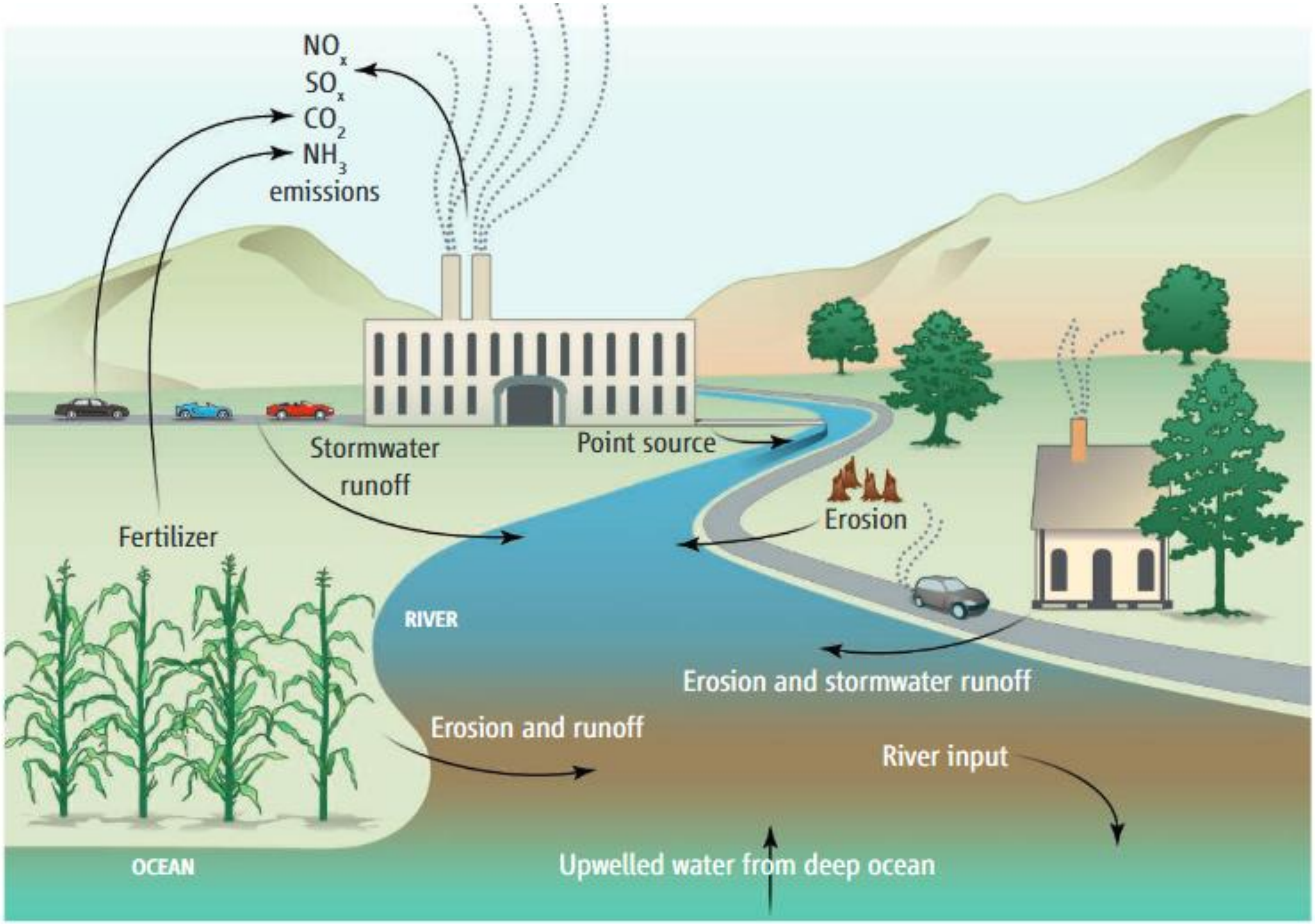

Figure 4: Recent marine heat waves. In 2012 a North Atlantic heat wave was concentrated in the Gulf of Maine; however, shorter periods with very warm temperatures extended from Cape Hatteras to Iceland during the summer of 2012. American lobster and longfin squid and their associated fisheries were impacted by the event. The North Pacific event began in 2014 and extended into shore in 2015 and into the Gulf of Alaska in 2016,leading to a large bloom of toxic algae that impacted the Dungeness crab fishery and contributed directly and indirectly to deaths of sea lions and humpback whales. U.S. coral reefs that experienced moderate to severe bleaching during the 2015–2016 global mass bleaching event are indicated by coral icons (NCA4 chap. 9)