OCS Study
BOEM 2023-009
ANL-22/87

Effects of Greenhouse Gas Emissions and Climate Change on U.S. Coastal and Marine Environments

A High-Level Harm Summary

U.S. Department of the Interior
Bureau of Ocean Energy Management
Sterling, VA

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By
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U.S. Department of the Interior
Bureau of Ocean Energy Management
Sterling, VA

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About Argonne National Laboratory

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About the Cover

An immature green sea turtle swims above a coral reef at Baker Island in the Pacific Island Remote Area. Credit: NOAA Fisheries.

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List of Acronyms

AMIP	Atmospheric Model Intercomparison Project
AR4, AR5, AR6	Intergovernmental Panel on Climate Change Fourth, Fifth, and Sixth Assessment Report, respectively
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
CAM5	Community Atmosphere Model, v. 5
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DOE	United States Department of Energy
DOT	United States Department of Transportation
EPA	Environmental Protection Agency
GCM	Global Climate Model
GHG	greenhouse gases (in this report, to mean carbon dioxide, methane, and nitrous oxide)
GOADS	Gulfwide Offshore Activities Data System
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
LDAR	leak detection and repair
N_2O	nitrous oxide
NTL	Notice to Lessees
OCS	Outer Continental Shelf
OCS AQS	Outer Continental Shelf Air Quality System
OCSLA	Outer Continental Shelf Lands Act
OGOR	Oil and Gas Operations Report
PHMSA	Pipelines and Hazardous Materials Safety Administration
SEC	Securities and Exchange Commission
SLR	sea level rise

Executive Summary

Introduction and Background

The rapid rise of atmospheric concentrations of greenhouse gases (GHGs) and their observed impacts on climate change is well-documented (Allan, et al., 2021; National Research Council, 2020), including impacts on coasts and the seas within U.S. jurisdictions. The effects of climate change have detrimental effects on local economies as well as natural resources, including those in the U.S. marine and coastal areas. While there is natural variability in the Earth's climate system, research shows that the primary driver behind the recent warming trend is the concentration of GHGs emitted from anthropogenic sources (Anderson, et al., 2012). Argonne National Laboratory (Argonne) is working with the Bureau of Ocean Energy Management (BOEM) to quantify GHG emissions from BOEM's authorized sources and, through literature review and an expert panel, summarize harms caused by GHG emissions and subsequent climate change on the U.S. coastal and marine environments. GHG emissions are defined in this report as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

GHG Emissions Scopes and Effects

This document adopts the emissions scope definition convention used by the international bodies, such as the Intergovernmental Panel on Climate Change (Allwood, et al., 2014) and the U.S. Environmental Protection Agency (EPA, 2022): Scope 1, Scope 2, and Scope 3 (Figure 3). **Scope 1** refers to GHG emissions directly related to processes at the Outer Continental Shelf (OCS) facilities and associated equipment. These emissions are reported in BOEM's Outer Continental Shelf Air Quality System (OCS AQS) database and BOEM's inventory for facilities. **Scope 2** normally refers to emissions from energy generation activities upstream of the operations captured in Scope 1; however, for U.S. offshore facilities, Scope 2 emissions cannot be readily quantified, as many facilities use locally produced gas for power generation. **Scope 3** emissions are those from the unavoidable mid- or downstream loss of the produced crude oil and gas and their combustion in end uses such as energy generation, transportation, heating, and other residential and commercial applications. Scope 3 emissions constitute the largest share of all emissions related to offshore oil and gas production. However, this report focuses on Scope 1 emissions as they are a direct consequence of BOEM-authorized activities on the OCS.

GHG Emissions from BOEM's Authorized Activities (Scope 1 Emissions)

Scope 1 GHG emissions associated with OCS activities are tracked in BOEM's OCS AQS inventory. Scope 1 emissions related to oil and gas activities reported to the Gulfwide Offshore Activities Data System and OCS AQS (which only includes Gulf of Mexico and Alaska Regions) made up roughly 0.3% of total U.S. energy GHG contributions in 2017.

According to the BOEM inventory data, some of the highest component-level emissions in 2017 were caused by CO_2 emissions from combustion cycles in natural gas turbines and natural gas engines that provide power to production facilities; CO_2 emissions from diesel combustion on drilling facilities and support vessels; CO_2 emissions from flaring of methane; and CH_4 emissions from venting, fugitive emissions, and the release of methane from pneumatic pumps and controllers, among others (Figure 5). It is important to note, however, that several studies claim suspected emissions under-reporting in OCS AQS as well as other national and global GHG inventories, dubbing certain facilities or processes "super-emitters" (examples: Ayasse, et al., 2022, Brandt, et al., 2016; Gorchov Negron, et al., 2020; and Zavala-Araiza, et al., 2017).

While BOEM's current regulations under 30 CFR Part 550 contain provisions to regulate criteria air pollutants that can cause immediate damage to human health or the environment, any potential regulation addressing GHGs would have to be implemented with the understanding of GHGs' contribution to climate change and subsequent long-term effects.

Observed Harms of Climate Change

The primary observed effects of climate change are fueled by the warming of the ocean waters that drives the rise in the global land and surface temperature, which leads to other effects, such as ice melting leading to sea level rise, or SLR (Wigley & Raper, 1987), worsening of severe storms (Davis, et al., 2015; Knutson, et al., 2010; NOAA, 2022; Tebaldi, et al., 2012), the migration of marine species poleward (Haynie & Pfeiffer, 2012; Pinsky & Mantua, 2014; Mills, et al., 2013; Le Bris, et al., 2018), and exacerbation in the formation of hypoxic zones (Schmidtko, et al., 2017). Additionally, carbon absorbed by the ocean has the potential to make the ocean's pH more acidic and less able to sustain marine life (Orr, et al., 2005). Ultimately, research suggests that climate change, caused by anthropogenic emissions of GHGs, can disrupt coastal communities and economies through declines in commercially valuable fish stocks and recreational opportunities and increased damage to essential infrastructure. While the effects of climate change on marine and coastal regions within the jurisdiction of the U.S. and elsewhere are extensive and interconnected, those relevant for the purposes of this document can be broken down into these six broad categories:

- Effects of SLR on shoreline degradation and erosion
- Damages caused by increased severe weather effects
- Ocean acidification effects
- Effects on the health of the environment
- Impacts on the formation of hypoxic zones
- Effects on marine life and fisheries
- Damages to historically significant heritage sites

If trends continue, studies show that all of the above effects can lead to significant well-being (i.e., loss of habitat) and economic implications as investments will need to be made to adapt to these changes (Fagherazzi, 2014). Importantly, some of the harms will continue to take place for the next several decades, even if anthropogenic emissions were to suddenly stop, due to the longevity in GHGs' residence in the atmosphere (Archer & Brovkin, 2008). However, studies suggest the ability to slow some of the ill-effects of climate change if the contribution of GHGs is slowed (Knutson, et al., 2020). Studies also predict other, long-term effects that can cause new disruptions not yet felt on the global scale.

Recommended Mitigation and Adaptation Pathways

Recommendations for addressing the projected effects of climate change described above generally divide into two pathways: (1) mitigation of GHG emissions to slow the progress and effects of climate change and (2) adaptation to changes caused by effects of climate change (NASA, n.d.).

Efforts to **mitigate** GHG emissions from BOEM-authorized sources are focused on reducing Scope 1 emissions on OCS oil and gas facilities. Opportunities for technological and process improvement that may potentially lead to GHG emissions reductions can be generally categorized into three approaches:

- Improving process efficiency, which can lead to reduced CO_2 emissions and methane waste
- Recovery and routing to the sales line of fugitive and vented methane
- Recovery and sequestration of CO_2 from onsite combustion processes

BOEM also may consider using its regulatory tools, as well as collaborating and coordinating with other parts of the U.S. Government, to standardize GHG emissions reductions mandates and create incentives for implementing certain reduction opportunities.

While the above approaches may be optimized to lead to significant Scope 1 GHG emissions reductions on the OCS, implementing them to meet the goal of reducing emissions by half by 2030 might prove a technological and economic challenge. Many of the analyzed opportunities are recognized to be very costly, and caveats in the assumptions about their effectiveness in terms of GHG emission reduction potential would need to be verified. To achieve the 2050 goal of net-zero emissions, carbon offsets would be necessary, since Scope 1 emissions can only be reduced to a certain point, but further scrutiny will be required to verify the offsets' effectiveness. Although emissions reductions from BOEM's authorized sources are an important step towards addressing the overall, global issue of climate change, it is important to make note of the need for a more comprehensive action to address the overarching issues.

Adaptation is another technique for addressing ongoing and projected damages of climate change. Examples of potential actions include building up structures to address SLR, edging and restoring vegetation, and the protection of mangroves and reefs. Emission offsets through carbon sequestration and storage are another actively discussed strategy. However, it is unknown what will be the scope and long-term investment needs to support these strategies as a way forward without reducing or slowing the root cause of the issue through slowing of GHG emissions (Griggs & Patsch, 2019).

Key Conclusions and Recommendations

From the information gathered in this report, the documented impacts of continued increases in GHG emissions on U.S. marine and coastal environments are becoming more evident. Relevant research suggests that GHGs accumulate and reside in the atmosphere and the ocean, which will continue impacting the environment, including OCS, for hundreds of years. However, as many studies suggest, these ill-effects may be slowed through a slowing of contribution of anthropogenic GHGs. Such a slowing may be achieved through incremental steps of reducing GHG emissions wherever possible, including reductions of Scope 1 emissions from BOEM-authorized sources.

Finally, slowing exploration and production activities on the OCS may appear as an effective short-term measure to reduce Scope 1 emissions, but considering an unchanging demand in energy, it may have little effect on net emissions because of imports from other countries with potentially more carbon-intensive oil and gas activities. BOEM's efforts to examine demand trends will likely play an ever more important role in current and future planning on the OCS.

Recommended potential actions for BOEM to consider in the near-, mid-, and long-term timeframes include a review of GHG emission reduction activities already undertaken by the offshore energy industry, providing guidance on technological and process improvements that may be ripe for adoption, an interagency collaboration among Federal agencies to streamline regulatory practices for controlling GHG emissions, comparing emissions data from different inventories, identifying verifiable data sources, assessing whether instrument-based sensing could be standardized to detect unexpected releases, and supporting existing or future research efforts on evaluating the effectiveness of carbon offset projects.

1 Introduction

The U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM) has enlisted the assistance of Argonne National Laboratory (Argonne) through the Interagency Agreement (IAA) no. M21PG00021 to summarize the impacts and harmful effects of emissions of greenhouse gases (GHGs)—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—on the U.S. marine and coastal environments. This study aims to provide a summary of issues that BOEM may consider in potential regulatory policy formulation. This report is the result of a literature review of peer-reviewed publications, and Government and non-governmental organization documents; it includes information on past and ongoing research pertinent to GHG emissions' effects on U.S. marine and coastal environments. Although this report is not a reflection of original research, it is a crucial step to summarize and contextualize the problem at hand.

In response to Executive Order 14008 (*Tackling the Climate Crisis at Home and Abroad*), issued on January 27, 2021, and Secretary's Order No. 3399, issued on April 16, 2021 (*Department-Wide Approach to the Climate Crisis and Restoring Transparency and Integrity to the Decision-Making Process*), BOEM is now considering establishing regulations to control the emissions of GHGs from activities it authorizes on the U.S. Outer Continental Shelf (OCS). This direction is premised on the belief that, however small compared to global GHG emissions from oil and gas, GHG emissions from OCS sources contribute to the cumulative harm to the environment through climate change and should be addressed. This adverse effect impacts both onshore and offshore of the United States, including significant impacts on the OCS (Pershing, et al., 2018). BOEM's GHG initiative aims to minimize the release of GHG emissions from BOEM's authorized sources on the OCS and in turn minimize impacts on the OCS.

The authors of this report performed a literature review on the topics of GHG emissions and their sources, the connection between accumulation of GHGs and climate change effects, and the effects—or harms—of climate change on the U.S. marine and coastal environments. Additionally, later chapters in the report attempt to contextualize the emissions in terms of BOEM-authorized sources and offer a summary of targeted, as well as holistic, conceptual approaches to GHG emissions reductions and further climate change effect mitigation. The last chapter in this report provides the authors' analysis of potential policy pathways and recommendations.

Argonne convened a one-day webinar titled *Effects of Greenhouse Gas Emissions and Climate Change on U.S. Coastal and Marine Environments* to provide an opportunity for a two-way conversation with stakeholders among other U.S. Government organizations and industry groups, and to gain further insight into the effects of climate change on U.S. coastal and marine environments—namely sea level rise (SLR) (including shoreline degradation and erosion), increased severe weather effects, the health of the marine and coastal environment, ocean acidification, the formation of hypoxic zones, and effects on marine life and fisheries. Although these six topics are somewhat overlapping, the webinar addressed them as distinct issues.

In the webinar, researchers and subject matter experts from leading U.S. research institutions and universities provided a summary of key findings with respect to each of the above effects. They also helped to identify relevant literature that was reviewed by the authors and is cited throughout this report. The webinar agenda consisted of formal presentations, followed by a question-and-answer session, where the participants could ask open-format questions. The session concluded with a moderated panel.

Invited audience participants included recognized experts from U.S. Government organizations, such as the U.S. Environmental Protection Agency (EPA), Bureau of Land Management (BLM), Bureau of Safety and Environmental Enforcement (BSEE), and U.S. Department of Transportation's Pipeline and

Hazardous Material Safety Administration (DOT/PHMSA). Other industry groups and environmental non-government organizations participated, including the American Petroleum Institute, Offshore Operator's Committee, and the Environmental Defense Fund. Similarly, large, publicly traded energy companies also participated in the webinar. The appendices of this report provides a summary of the webinar presentations.

Through this report, Argonne is supporting BOEM in assessing the impact of GHG emissions on the coast and continental shelf of the U.S. A second and overlapping research effort under the same Interagency Agreement is focused on the evaluation of potential approaches to reduce GHG emissions from activities regulated by BOEM on the OCS. Finally, a third task under the same IAA provides an overview and potential applicability to BOEM of pertinent GHG regulations, proposed or promulgated, from other regulatory agencies, such as EPA, PHMSA, and BLM, as well as regulations at the state level, such as California Air Resources Board and international organizations, such as the International Maritime Organization. Results of these studies are expected to become available to the public in mid-2023.

2 Setting the Stage: Causes of Climate Change and Their Effects on U.S. Marine and Coastal Environments

Atmospheric measurements of GHGs like carbon dioxide, a significant contributor to observed climate change (Allan, et al., 2021), have continued to increase since the late 1950s due to continued emissions of GHGs, with human activities leading to these increases in GHG concentrations, as shown in Figure 1 (National Research Council, 2020; NOAA, n.d. a). As the effect of rising concentrations of GHGs on coastal environments becomes increasingly visible, it is essential to understand the causes of rising GHG concentrations.

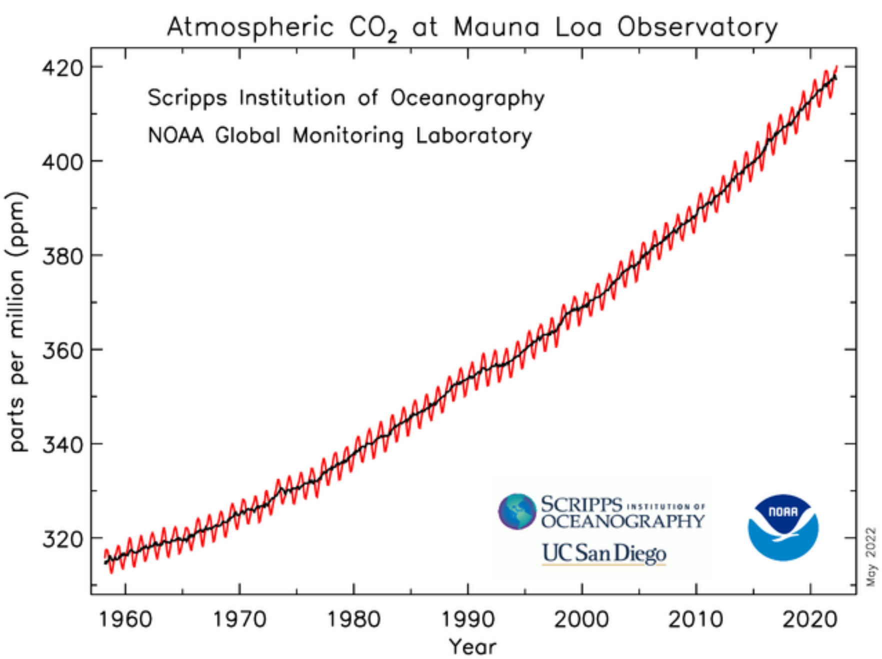

Figure 1: Evolution of cumulative atmospheric concentration of the GHG carbon dioxide (CO_2) since 1958 as measured at the Mauna Loa Observatory (NOAA, n.d. a)

In 2022, the Intergovernmental Panel on Climate Change (IPCC)—the United Nations body charged with assessing the science related to climate change—stated that "global net anthropogenic GHG emissions during the decade (2010–2019) were higher than any previous time in human history" and grew by 1.3% per year (IPCC WGIII, 2022). Worldwide average yearly GHG emissions for 2010–2019 were 56 billion tons, with over 60% being CO_2 emissions (in terms of equivalent tons of carbon dioxide, or CO_2e, based on the global warming potentials of GHGs with a 100-year time horizon). Furthermore, North American countries, including the U.S., contributed the largest amount of GHG emissions per capita in 2019 as well as cumulative carbon dioxide emissions since 1850 (IPCC WGIII, 2022).

The U.S. emitted over 5.1 billion metric tons of GHGs in 2020 (EPA, n.d.). Of these, carbon dioxide accounted for 79% of the GHG emissions in the U.S., with methane accounting for the second most emissions at 11%. In the U.S., the transportation, electricity, and industry sectors each accounted for about a quarter of the total GHG emissions, while the commercial, residential, and agriculture sectors combined to form the other quarter of the total GHG emissions in 2020, as shown in Figure 2 (EPA, n.d.). Notably, in its lifecycle, oil and gas is part of almost all the above activities; however, GHG emissions that directly result from BOEM-authorized activities on the OCS are part of the Industry sector (24% of total emissions or 1,476 MMT CO_2e in 2020). More specifically, one of the largest contributors to the Industry sector is Natural Gas and Petroleum Systems, which includes both onshore and offshore activities, totaling 278 MMT CO_2e and making up 19.5% of this sector. Other contributors include the uncategorized fossil fuel combustion in the industrial sector (51% or 727 MMT CO_2e), emissions from other industrial categories (9.7% or 139 MMT CO_2e), chemical industry (5% or 72 MMT CO_2e), mineral industry (4.5% or 64 MMT CO_2e), coal mining (3.4% or 49 MMT CO_2e), and others (EIA, 2022).

It is worth noting that 2020 U.S. GHG emissions decreased by 21% compared to 2005 emissions. Some of these reductions for 2020 were attributed to large-scale effects of the global COVID-19 pandemic (EPA, n.d.), and early estimates for 2021 show a growth in GHG emissions compared to 2020 in the U.S., but still less than 2005 emissions (Rivero, et al., 2022).

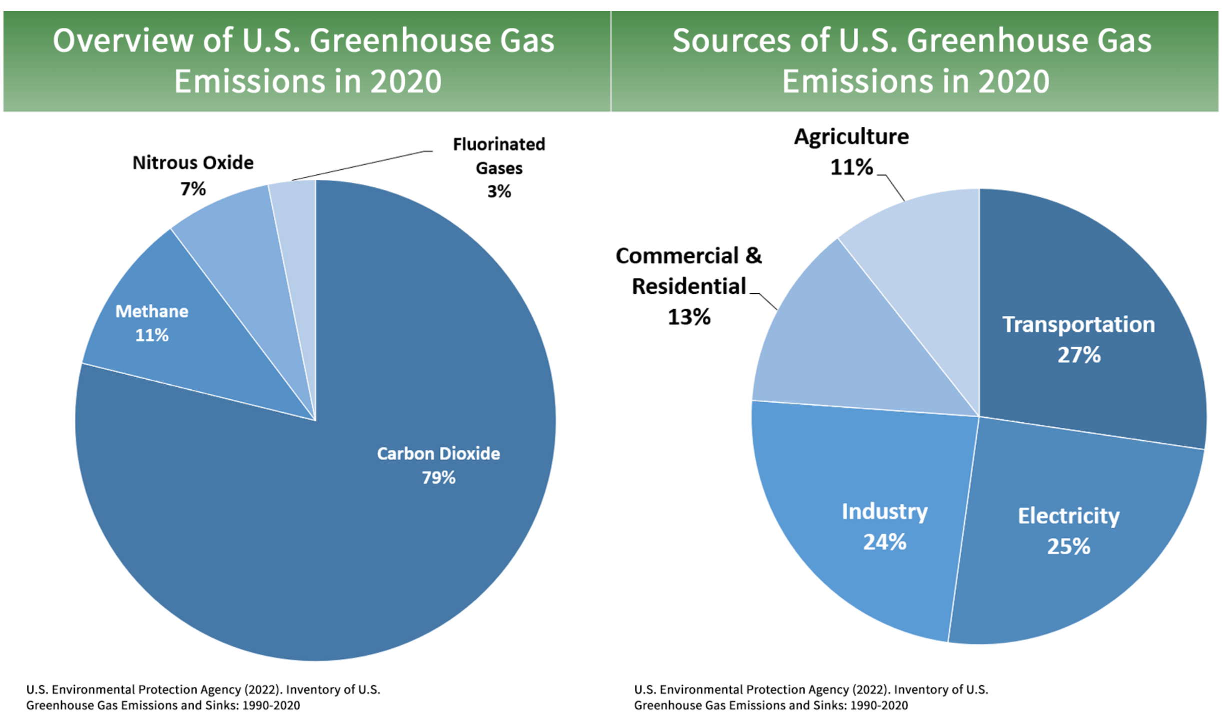

Figure 2: Estimates of U.S. GHG emissions (left) and sources of these emissions (right) for 2020 from the EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020 (EPA, n.d.)

2.1 Share of GHG Emissions from BOEM-Authorized Sources

GHG emissions from BOEM-authorized sources constitute a small fraction of the overall U.S. emissions that have resulted in harms discussed in this report. BOEM's *Year 2017 Emissions Inventory Study* estimated over 25 million tons (or ~23 million metric tons) in CO_2e, on the entire U.S. Gulf of Mexico, of which almost 15 million tons (or 13.5 million metric tons) of CO_2e emissions are attributed directly to BOEM-authorized oil and gas activities, such as production and drilling facilities attached to the seabed, support and supply vessels, pipe laying vessels, survey vessels and helicopters (Wilson, et al., 2019).[1]

Though it remains impossible to quantify the impact of any individual GHG emission source—including from BOEM-authorized activities—on coastal and marine environments, the collective sum over time of all emissions, including those from oil and gas, renewables, and marine minerals activities on the OCS, and globally have resulted in increases in the atmospheric concentration of GHGs. These increasing GHG concentrations have harmed and continue to harm the OCS and nearby coastal areas (Pershing, et al., 2018). The impacts of these GHG concentrations will continue after emissions are reduced (or even in the event of a sudden halt of emissions) due to the long residence times of GHGs like carbon dioxide, and any additional emissions will further increase GHG concentrations in the coming years (Archer & Brovkin, 2008). Thus, reducing and, where possible, eliminating GHG emissions broadly, including those from BOEM-regulated sources, is critical to mitigating the impact of GHG emissions in U.S. marine and coastal environments.

2.2 Observed Effects of GHG Emissions

Scientists have documented the connection between GHG emissions and rising global temperatures, which are increasing at a rate unprecedented in at least the last 2,000 years (Gulev, et al., 2021). The annual mean surface temperature of the contiguous U.S. was 1.2°F warmer for the period of 1986–2016 compared to 1901–1960, with the largest warming trend occurring in the western half of the country. U.S. surface temperature projections for 2071–2100 suggest 5.0°F of warming compared to 1901–1960 for a mid-range future emissions scenario and 8.7°F for a high emissions scenario (Vose, et al., 2017). While global surface ocean temperatures have warmed by about 1.3°F since 1900 (Cheng, et al., 2017), U.S. coastal waters have warmed by about 0.7°F. Coastal waters off the Northeast U.S. have warmed the fastest (1.2°C rise in North Atlantic Ocean over 2010–2019 versus 0.85 ± 0.12°C overall rise (Bates & Johnson, 2020)), and models project that this region of the Atlantic will continue this trend (Saba, et al., 2016).

2.2.1 GHG Effects on Earth's Energy Budget

The Earth's energy budget describes balance between the amount of solar energy absorbed by the Earth and the amount of energy emitted to space. GHG emissions affect the Earth's energy budget by absorbing longwave radiation emitted by the Earth and re-emitting it back into the atmosphere. This process essentially traps heat in the atmosphere like a greenhouse. Increasing concentrations of GHGs in the atmosphere caused by human activity (as well as other factors) have resulted in the accumulation of heat in Earth's climate system and the recent rising trends in global land and ocean temperatures. This extra energy from heat amounts to about 0.65 W/m (Forster, et al., 2021). In contrast, the amount of solar radiation received by Earth at the top of the atmosphere (known as total solar irradiance) has changed

[1] Although the guideline for the Gulfwide Offshore Activities Data System (GOADS) reporting in 2017 (through Notice to Lessees [NTL] No. 2016-N03) was to include emissions from production facilities and drilling facilities attached to the seabed, support and supply vessels, pipe-laying vessels, survey vessels, and helicopters, BOEM's regulatory authority extends to production platforms and drilling facilities, and does not include vessels or helicopters.

little since 1900 and therefore has altered Earth's energy budget by less than 0.1 W/m (Goodwin, et al., 2015; Matthes, et al., 2017). The observed increasing GHG concentrations are critical to explain the observed change in Earth's energy budget (Anderson, et al., 2012).

2.2.2 Emission Scopes

With the broad discussion of the nexus between GHG emissions and climate change in place, this section will now delve deeper to define the types of emission sources that are a part of BOEM's mandate. The easiest way to do so is to adopt the EPA's emissions scope definition convention: Scope 1, Scope 2, and Scope 3, as shown in Figure 3, with a few necessary modifications as explained below (EPA, 2022).

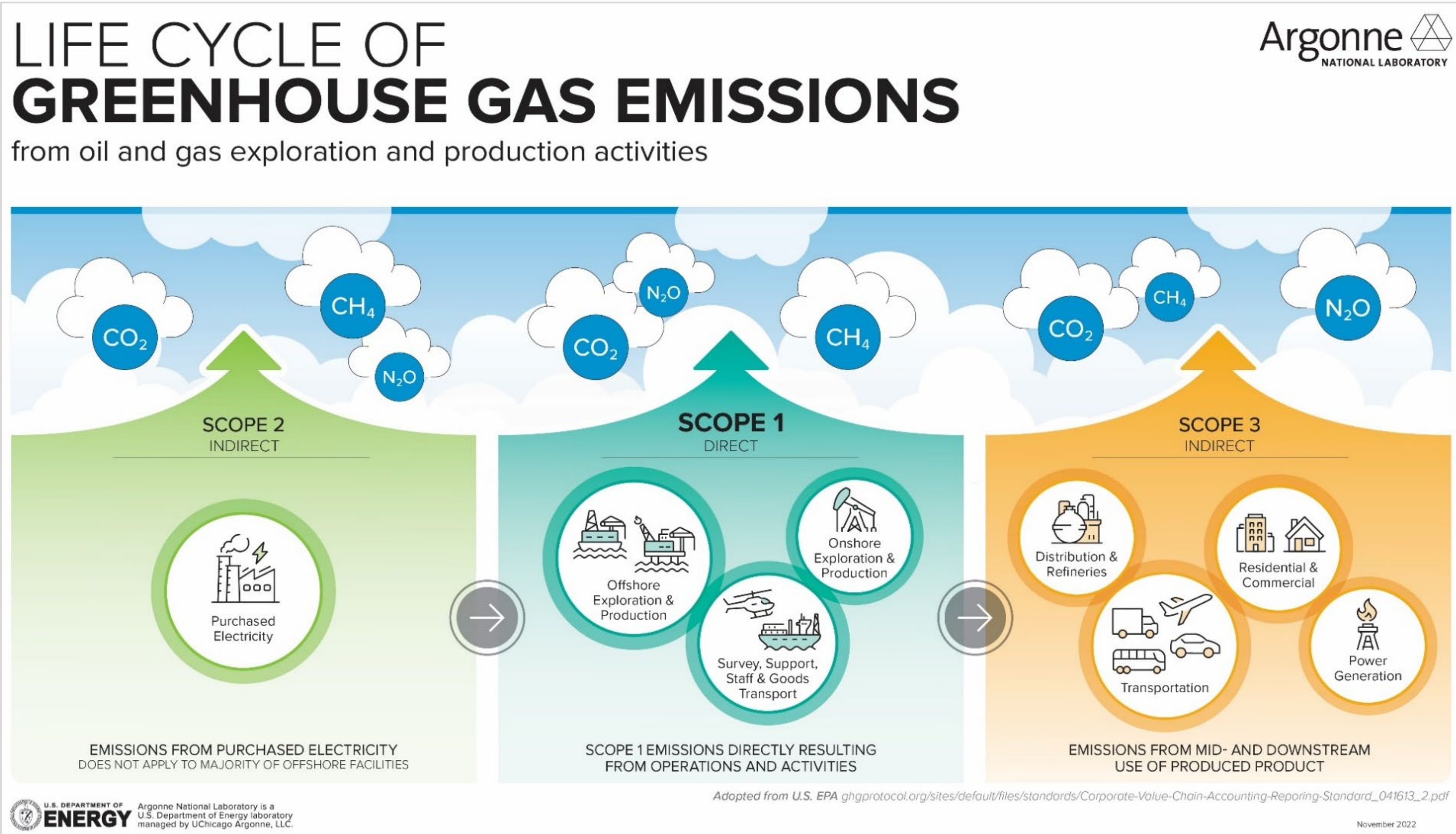

Figure 3: Definition of Scope 1, Scope 2, and Scope 3 emissions for oil and gas exploration and production activities

Scope 1, in this report, refers to GHG emissions directly related to processes at the facilities and associated equipment. These emissions are reported in BOEM's Outer Continental Shelf Air Quality System (OCS AQS) database for facilities.

Scope 2, in turn, would normally refer to emissions from energy generation activities upstream of the operations captured in Scope 1. However, this study makes important clarifications:

- Scope 2 emissions from BOEM-authorized production facilities and equipment cannot be distinguished from Scope 1, since the power is generated onsite and, most often, uses locally produced associated gas (sometimes called "lease gas"). Therefore, this study disregards Scope 2 emissions for production facilities.
- Scope 2 emissions from BOEM-authorized drilling facilities and operations are accounted for by Scope 3 emissions to avoid double-counting the latter, since the fuel (most commonly, diesel) purchased to power drilling facilities or equipment comes from the same pool to which produced crude oil and natural gas contribute.

Finally, **Scope 3** emissions are those from the unavoidable mid- or downstream loss of the produced crude oil and gas and their combustion in uses, such as energy generation, transportation, heating, and other residential and commercial applications.

This scoping convention is different from BOEM's classical definition of upstream, midstream, and downstream emissions, where "upstream" refers to emissions from exploration, development, production, and transportation to shore; "midstream" refers to emissions from refining, processing, storage, and distribution; and "downstream" refers to emissions from consumption by the customer (BOEM, n.d.). However, the authors chose to use the Scope 1, Scope 2, and Scope 3 convention for the purposes of this study to better align with intergovernmental and global policies and considerations with respect to GHG emissions.

Scope 3 emissions constitute the largest share of all emissions related to offshore oil and gas production. However, this report focuses on Scope 1 emissions, as they are a direct consequence of BOEM-authorized activities on the OCS.

2.2.3 Definition of GHGs and Their Relative Effects

Further clarification should be made with respect to the definition of greenhouse gases. Since there are three major greenhouse gas emissions from activities on the OCS that carry varying effects and that are of particular concern (CH_4, N_2O, and CO_2), this report, as well as BOEM's OCS AQS reporting tool and GHG emissions inventory, uses CO_2e Global Warming Potential (GWP) factors as follows:

- CO_2:CO_2 = 1
- CH_4:CO_2 = 25
- N_2O:CO_2 = 298

These equivalents are reported as 100-year GWP effects in the IPCC's Fourth Assessment Report, or AR4 (IPCC, 2007). Although newer Assessment Reports, such as AR5 and AR6, have been published reporting higher equivalence factors, adoption of AR4 complies with international standards for reporting GHG emissions and is also used by other U.S. Federal agencies, such as the EPA (EPA, 2022).

As summarized in subsequent chapters, studies show how, through their GWP, GHG emissions, regardless of their origin or Scope, contribute to the well-tracked effects of climate change. Further sections in this report discuss the details of emissions sources from BOEM-authorized activities.

3 BOEM's Role: Emissions from Authorized Activities on the OCS

The Outer Continental Shelf Lands Act (OCSLA) gives BOEM the unique charge of balancing the responsible development of mineral resources in support of domestic energy security with environmental protection. BOEM's role as the regulator is to manage "the responsible development of America's offshore energy and mineral resources. BOEM promotes energy independence, environmental protection, and economic development through responsible, science-based management of energy and mineral resources on the U.S. Outer Continental Shelf" (BOEM, 2022a).

BOEM has the regulatory authority over Federal waters adjacent to the U.S. contiguous states, as well as Hawaii, Alaska, and U.S. territories, as shown in Figure 4.

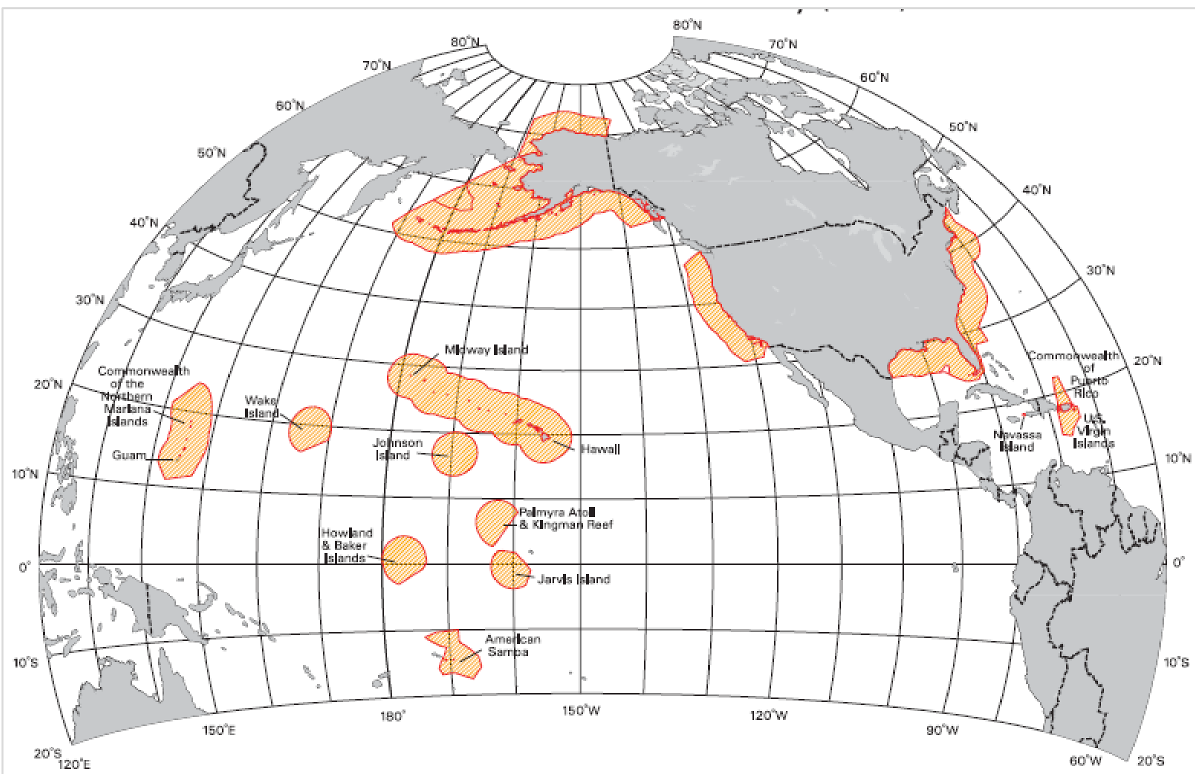

Figure 4: Map of BOEM-authorized areas
Figure reused with permission from BOEM.

BOEM manages almost 2.5 billion acres of seabed adjacent to the continental U.S. and Hawaii, which is similar in size to the land acreage of the U.S., in addition to the recently acquired jurisdiction extending to 200 nautical miles offshore the U.S. territories. In 2022, BOEM has reported a total of 2,013 active leases on the OCS, of which 549 are in producing status, accounting for 15% of domestic oil production and 2% of domestic natural gas production (BOEM, 2022b).

A key part of BOEM's mandate is to lead the development of the *National OCS Oil and Gas Leasing Program* through a five-year plan detailing oil and gas lease sales. The Department of the Interior announced the 2023–2028 proposed plan in July 2022 and the public comment process, which allows for stakeholder input to create the plan.

BOEM tracks emissions from its authorized sources, including greenhouse gas emissions, through OCS AQS.[2] OCS AQS is a self-reporting tool, where the operators are required to report facility emissions from a number of sources,[3] such as emissions from turbines and engines, flaring or venting of methane, fugitive emissions, and others as defined in 30 CFR § 550.302. BOEM later processes these reported emissions and creates an emissions inventory for that year. These emissions inventories are estimates based on activity throughput data provided by the operator. This reporting is required to take place every 3 years.

According to BOEM's 2017 inventory, total single-year oil and gas-related emissions on the OCS, expressed in CO_2e, are 14.9 million tons (13.5 million metric tons). These emissions can be broken down by source as shown in Figure 5 and consist of primarily CO_2, CH_4, and N_2O emissions.

As the chart shows, some of the most significant reported emission sources in 2017 emitted large quantities of CO_2 and a small proportion of N_2O from combustion cycles in natural gas turbines and natural gas engines that provide power to production facilities, as well as CO_2 emissions from diesel combustion engines on drilling facilities and support vessels. Among the other highest emitting sources are CO_2 emissions from flaring, CH_4 emissions from venting, fugitive CH_4 emissions, and the release of CH_4 from pneumatic pumps and controllers.

It is important to note, however, that several studies claim emissions under-reporting in OCS AQS as well as other national and global GHG inventories (e.g., Ayasse, et al., 2022, Brandt, et al., 2016; Gorchov Negron, et al., 2020; and Zavala-Araiza, et al., 2017). For example, aerial methane-verification studies using flyovers in January 2018 and completing several flyovers in spring and fall of 2021 detected several higher-than-average methane emissions (Ayasse, et al., 2022; Gorchov Negron, et al., 2020). Based on flux determinations, the studies suggest a disproportionate level of methane emissions released in certain shallow water areas or from facilities in Federal waters, just beyond the state jurisdiction, in the Gulf of Mexico. The studies hypothesize cold venting and fugitive emissions to be the main drivers of these disproportionate methane emissions compared to the average reported emissions and other observed emissions from the same study, and dubs such methane emissions sources and facilities as "super-emitters." Another study further defines super-emitters as those above a certain threshold and categorizes emissions sources into intentional and unintentional, claiming that unintentional methane releases caused by process upsets may contribute to high volume emissions (Zavala-Araiza, et al., 2017).

[2] This data was previously tracked in GOADS. OCS AQS will be the new mechanism for reporting 2020 and onward emissions, and it also contains historical data. GOADS and OCS AQS data include emissions from activities in the Gulf of Mexico and Alaska Regions.

[3] Further information on emissions reporting is provided in BOEM's OCS AQS Frequently Asked Questions (FAQ) document (https://www.boem.gov/sites/default/files/documents/OCS%20AQS%20FAQs.pdf).

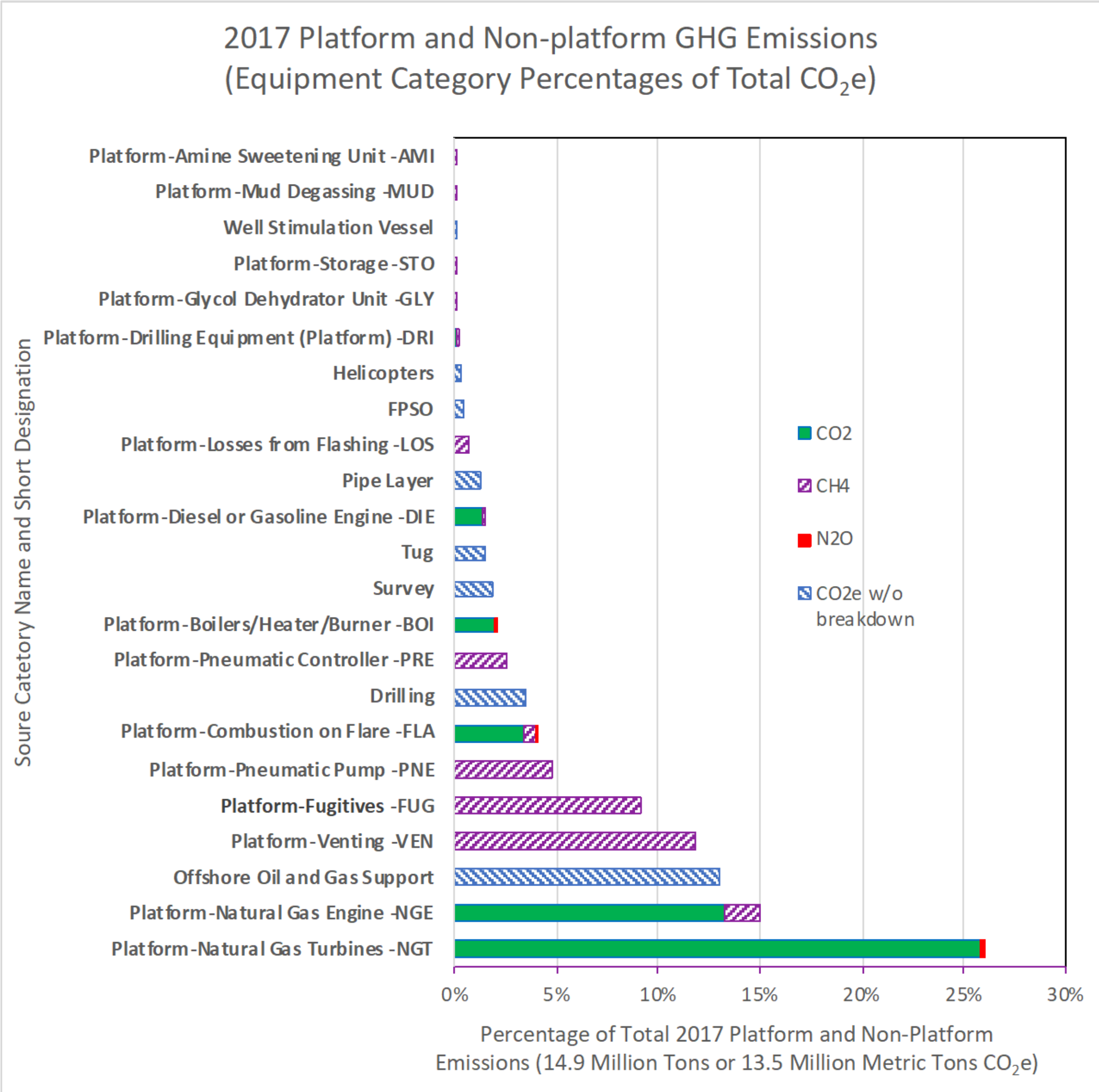

Figure 5: Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide equivalent (CO_2e w/o breakdown) emissions by emissions source reported in OCS AQS in 2017

Because the chart combines BOEM's 2017 inventory data that is otherwise divided into platform and non-platform emissions, the labels for emission quantities for sources reported in OCS AQS's Platform database start with the word "Platform." Data for non-platform activities include drilling and support activities that mostly constitute emissions from power generation or combustion cycle related CO_2 emissions. Non-platform emissions are shown here the way they are reported in BOEM's inventory as CO_2e, without a GHG type distinction (hence the "CO_2e w/o breakdown" category).

Existing regulations at 30 CFR Part 550 contain extensive provisions to regulate criteria pollutants that can cause immediate damage to human health and the environment. In contrast, GHG emissions are those that contribute to the greenhouse effect by accumulating in the oceans and atmosphere and are main drivers of harmful effects, together referred to as "climate change." These harms are summarized in the sections directly below and discussed in more detail in Appendices A through F of this report.

Legislation and Executive Orders could provide the mandate for BOEM's efforts towards a potential role in GHG regulation and newer policies and legislation, such as the Inflation Reduction Act (IRA), may have the potential to shift BOEM's focus. BOEM may be called upon to institute additional monitoring of Scope 1 GHG emissions and/or regulation as part of its responsibility for protecting the environment and, specifically, marine and coastal environments that fall under BOEM's purview (Figure 4).

4 Summary of Observed Changes and Their Effects on the OCS

Climate change threatens the U.S. oceans and coastlines through SLR, more intense and frequent storms, and decreased water quality due to acidification and hypoxia. These changes negatively impact both marine and terrestrial ecosystems, which in turn lead to declines in fishery productivity and biodiversity, as well as increases in flooding and shoreline erosion. Ultimately, climate change, caused by anthropogenic emissions of greenhouse gases, disrupts coastal communities and economies through declines in commercially valuable fish stocks and recreational opportunities, and increased damage to essential infrastructure. Although the effects of climate change on marine and coastal regions are extensive and interconnected, those relevant for the purposes of this document can be broken down into six broad categories, as shown below. Sections 4.1 through 4.9 contain summaries of key harms, and Appendices A through F contain more detailed summaries pertinent to Sections 4.1–4.9.

4.1 Effects of SLR on Shoreline Degradation and Erosion

As ice sheets and glaciers melt and ocean water thermally expands due to increasing temperature, the global sea level continues to rise (Wigley & Raper, 1987). Due to SLR, high tides in certain coastal cities are causing damaging flooding regularly, even on completely sunny days with no storms (Moftakhari, et al., 2015). These higher tides increase rates of shoreline erosion, threatening destruction of personal property, businesses, and important infrastructure such as roads, bridges, tunnels, pipelines, and ports. Damage to these structures not only impacts local economies but also the economy and productivity of the entire country (Gordon, 2014). SLR also degrades coastal wetlands, mainly through saltwater intrusion and subsequent deaths of trees and other stabilizing flora (Dahl & Stedman, 2013). As wetland habitat dies and erodes away, its natural ability to sequester carbon depreciates, leaving more CO_2 in the atmosphere to warm the planet; the loss of habitat also leaves human structures more vulnerable to high tides, rough waves, and storm surges (Davis, et al., 2015). As graphic photographs in Appendix A demonstrate, the detrimental effects of SLR on U.S. coasts are evident through examples, such as eroded coastlines on Nantucket Island, MA, and in Isla Vista, CA.

4.2 Damages Caused by Increased Severe Weather Effects

As ocean temperatures warm due to climate change, there is more energy available for hurricanes to draw from. While this will not likely raise the number of hurricanes that form each year, the hurricanes that do form are expected to be more intense and produce more rain, which will increase the damage when they move over or nearby land (Knutson, et al., 2010). SLR is increasing the levels of storm surge during hurricane landfalls (Tebaldi, et al., 2012) and, in combination with heavier rainfall, will worsen flooding, erosion, and shoreline degradation during these events (Wahl, et al., 2015; Moftakhari, et al., 2017). Amplified damages cost more and take longer to repair, thus intensifying the negative impacts on the local economy and communities. As Appendix B discusses in more detail, the potential damage to natural and built environments has been revealed in recent years, as some of the costliest hurricanes in U.S. history have struck the East and Gulf Coasts (NOAA, 2022). More severe storms can also increase the amount of polluted runoff flowing into marine ecosystems, which causes harmful algal blooms and deoxygenation of the water (Rabalais, et al., 2007).

4.3 Ocean Acidification Effects from Emissions of Greenhouse Gases

The ocean is constantly absorbing carbon dioxide from the atmosphere, which makes the ocean more acidic. As the water becomes more acidic, it becomes harder for some marine organisms to build and maintain their calcium carbonate shells (Orr, et al., 2005). The stress caused by the acidified waters makes the organisms more vulnerable to other sub-optimal conditions, such as marine heat waves and hypoxia, that are also caused by human activities (Cai, et al., 2011; Bednaršek, et al., 2016). Ocean acidification can reduce the productivity of bivalve aquaculture and alter food webs when species at the base of the webs, such as plankton or krill, cannot source enough calcium carbonate and die nor move to another location. Changes to the abundance of any species has a ripple effect throughout the ecosystem, which can often impact any services that the ecosystem provides to humans (Kohlbach, et al., 2016). A case study for the northern Gulf of Mexico shows that man-made structures that have served as artificial reefs, ranging in locations from Texas to the Florida west coast, perform significantly well as hosts of marine life, adding multi-million-dollar economic benefit to southwest Florida alone (Schulze, et al., 2020). However, it is still unclear how the life in the artificial reefs, including those in the U.S. Gulf of Mexico, will react to the changing water pH in terms of predator and prey balances with respect to metabolism, feeding activity, and behavior. Additional examples and discussion regarding ocean acidification are summarized in Appendix C.

4.4 Effects of Climate Change on the Health of the Environment

The most apparent changes to marine environments driven by climate change are occurring in tropical and polar ecosystems, where ocean warming is having the largest impacts. In cold climates, declines in sea ice reduce available habitats for species like polar bears and ringed seals (Kovacs, et al., 2011) and alter the locations and timing of seasonal algal blooms that occur on the edges of sea ice and are essential to the local food webs (Post, 2017). In the tropical marine environment, the combination of ocean warming and acidification causes coral bleaching, which results in the weakening and deterioration of the calcium carbonate reef structures (Hughes, et al., 2018). When the reefs deteriorate beyond a certain degree, the whole ecosystem that relies on them is lost. This impact is a direct threat to ocean biodiversity, as well as the services that reefs provide such as storm surge protection, a source of food, and tourism income (Rogers, et al., 2014). Future projections of climate change suggest sea ice area will continue to decline and coral reefs will experience more frequent environments conducive to bleaching (Ricke, et al., 2013). This topic is expanded upon further in Appendix D.

4.5 Extent of Climate Change Impacts on the Formation of Hypoxic Zones

Low levels of oxygen concentrations in the ocean, known as hypoxia, typically occur near coastlines where fertilizers runoff the land into the ocean and stimulate algal blooms. These algae then die, and the process of decomposition lowers the oxygen levels in that area (CENR, 2000). Hypoxia is worsened by ocean warming, since oxygen is less soluble in warmer water (Schmidtko, et al., 2017). Additionally, the warming of the ocean surface often causes increased vertical stratification, which limits the amount of oxygen that gets mixed upwards from deeper waters and can extend hypoxic conditions for longer. Hypoxic areas, sometimes called “dead zones,” can be deadly for marine life, especially immobile organisms that cannot move out of the low oxygen zone. This condition can have a big impact on fisheries that operate near the coasts (Purcell, et al., 2017). Areas of hypoxia and acidification often happen in the same locations, and the combination of these conditions is more harmful than either one individually (Gobler & Baumann, 2016). As Figure E-1 in Appendix E shows, the 2021 dead zone in the northern Gulf of Mexico was approximately 6,334 square miles, making approximately 4 million acres of habitat potentially unavailable to marine species (NOAA, 2021).

4.6 Climate Change Effects on Marine Life and Fisheries

The physical and chemical conditions of the ocean greatly impact marine life, and though some organisms can adapt to changing oceanic conditions caused by climate change, others cannot (Gunderson, et al., 2016). Changes in the abundance of any species impacts the whole ecosystem, as species rely on others for food, shelter, or other services. If organisms are forced to move to new locations because of changing conditions in their usual habitats, they may encounter predators, competitors, or diseases they have not evolved to deal with (Nagelkerken & Connell, 2015). As ocean temperatures warm, many species are moving poleward to remain in the temperature conditions they are adapted to. Depending on the species and location, this shift can have large impacts on the productivity of fisheries, thus greatly impacting the economies and communities that rely on these fisheries. Changes in distributions of commercially valuable fish and invertebrates are straining those who manage the fisheries, as fishing port locations, regulations, and national borders do not necessarily follow the movements of the target marine species (Haynie & Pfeiffer, 2012; Pinsky & Mantua, 2014). As discussed further in Appendix F, in the U.S., some of the largest affected species are lobsters in the Gulf of Maine and the New England area cod (Mills, et al., 2013; Le Bris, et al., 2018).

4.7 Heritage Impacts

Observing and protecting coastal heritage sites against the impacts of climate change has been the subject of discussion and significant effort in the U.S. and worldwide (e.g., (Rowland, 1992; Westley, et al., 2011; Daire, et al., 2012; Rowland & Ulm, 2012; Hambrecht & Rockman, 2017)). The majority of the impacts to coastal heritage is caused by SLR, coastal erosion, and severe hurricanes and typhoons capable of causing catastrophic loss to a site in a matter of days or hours or contributing to slow degradation over decades (Dawson, et al., 2020). Most recently, effects of the 2017 Hurricanes Irma and Maria were devastating to the southern U.S. and Caribbean islands, including Barbuda and Puerto Rico, where heritage sites, along with houses and infrastructure, suffered catastrophic damages (Rivera-Collazo, 2020). Additionally, strong winds that can move coastal sands and increase the concentration of salt on the coast can damage archaeological remains, standing structures, and buried remains, which may have historical significance to the Indigenous peoples (Sesana, et al., 2021).

At the same time, there is a gap in research and knowledge of potential impacts of climate change on underwater sites of historical significance, such as shipwrecks. While more inter-disciplinary work is needed, researchers recognize that specific climate-related events can affect maritime heritage, as discussed below.

Increased ocean temperature, acidification, and deoxygenation are hypothesized to have effects on the iron and wood that make up most sunken, historically significant maritime vessels (Gregory, et al., 2022). Specifically, increased ocean temperature under the IPCC worst-case scenario (which is over 2°C) may possibly accelerate corrosion rates in the iron components of shipwrecks. Temperature increase may also lead to an increased spread in wood-degrading organisms.

Effects of ocean acidification may include potentially accelerated corrosion rates of metal shipwreck sites. Indirectly, lower pH levels affect a wide range of biological processes associated with the growth, reproduction, and survival of organisms that can both colonize and degrade underwater cultural heritage.

Interestingly, deoxygenation may potentially have a positive influence on both corrosion rates and the spread of wood-boring organisms. Hypoxia may limit the growth of wood-boring organisms and decrease metal corrosion rates.

4.8 Other Broader Effects

Harms associated with climate change enhanced by GHG emissions can already be identified in the Gulf of Mexico and other U.S. coastal areas, as discussed above; however, developments related to changes in the large-scale atmospheric circulation could lead to further degradation in physical and economic assets in areas both within and outside BOEM's purview. One such set of changes relates to the Hadley cell circulation, in which warmed, generally moisture-laden tropical air rises from ecosystems near the equator, travels poleward high in the troposphere (15–20 km) until encountering cooler atmospheric conditions in the subtropics and lower temperate zones, and subsides toward the surface, where it joins circulation back to the equator to begin the cycle again. Both the trade winds and the equatorial doldrums are the product of the Hadley cell and related circulations. It is of concern that, owing to greenhouse warming in the mid-latitudes, the subsidence edge of the Hadley Cell may be expanding poleward. Because subsiding air limits the formation of precipitation in the troposphere, latitude bands now enjoying reliable water supply and favorable growing conditions may become increasingly arid and suffer prolonged drought stress to already threatened ecosystems. Some analyses have associated at least some of the long-term persistence of drought conditions in the southwestern U.S. with Hadley cell expansion (Lu, et al., 2007; Fu, et al., 2006).

Other developments are flashing major warning signs in more northerly latitudes. Climate change-related warming in the Arctic and Antarctic has accelerated the melting rate of ice sheets and terrestrial glaciers (especially on Greenland and West Antarctica), portending a dramatic rise in sea level much sooner than was originally anticipated (Marshall, 2019). Two significant sources of currently sequestered carbon dioxide and methane are the Yedoma permafrost of northern Siberia and Alaska, and solid methane hydrates under the deep ocean. There are indications that temperature rise has begun thawing the permafrost, releasing the trapped gaseous species (Khvorostyanov, et al., 2008). A large reservoir of solid-state methane hydrates largely sequestered under ocean floors in poleward latitudes can be mobilized by increased temperature in deep ocean waters, potentially releasing significant quantities of methane and nitrous oxide to the shallower ocean layer and eventually to the atmosphere (Archer, et al., 2009). Although the El Niño ocean circulation (El Niño Southern Oscillation) regime occurs largely in the equatorial region, if one part of the regime becomes more dominant due to climate change, it would have long-term effects in the northern hemisphere.

4.9 Longer Term and Future Effects

The impacts of climate change explained in the sections directly above are likely to worsen, and new impacts will arise if GHG emissions continue to rise at the current rates. A diverse set of academics and industry officials are studying the economic and environmental costs associated with climate change and highlight a host of data points on a future that is not tenable. For example, due to SLR, it is likely that between $66 billion and $106 billion of coastal real estate will be below sea level by 2050 (and between $238 billion and $507 billion by 2100), under a high emissions climate change scenario[4] (Houser, et al., 2015). All this real estate will be much more vulnerable to high-tide flooding, storm surges, and erosion and potentially will be unsellable (Sweet, et al., 2017). Though projections about the future frequency of hurricane landfalls in the U.S. are uncertain, hurricane rainfall rates are expected to increase by about 7% for every 1°C of global warming, and rising sea levels will certainly intensify the impacts of storm surge

[4] This definition refers to IPCC's climate change scenarios, https://www.ipcc.ch/site/assets/uploads/2018/03/sres-en.pdf

(Knutson, et al., 2020). Considering the U.S. population living below the high-tide line in coastal areas is expected to increase 435% from the 2020 number to about 1.2 million in 2100 (Hauer, et al., 2021), more people will be at risk of flooding, which will likely burden the capacity and budget of emergency response teams.

Marine ecosystems will have to adapt to changing ocean conditions in order to survive. For example, one modeling study found that by 2050, under a high emissions climate scenario, 86% of marine ecosystems will experience a combination of high temperature and water acidity that has never before been experienced by modern species (Henson, et al., 2017), which will stress many species including seagrasses, warm water corals, pteropods, bivalves, and krill (Gattuso, et al., 2015). Ocean acidification by the end of the century is expected to hinder the growth of all coral reefs in U.S. waters (Ricke, et al., 2013), and the loss of recreational benefits from these coral reefs is projected to total about $140 billion by 2100 (EPA, 2017). Long durations of warmer-than-average ocean temperatures, known as marine heat waves, are expected to increase in frequency about 20 times off the East Coast and 15 times off the Pacific Northwest coast under 2°C of climate warming (Frölicher & Laufkötter, 2018). Worsening ocean acidification, marine heat waves, and hypoxic events will negatively impact important marine fisheries, such as declines in abundance of American lobsters (Le Bris, et al., 2018) and Atlantic sea scallops (Cooley, et al., 2015).

5 Mitigation and Adaptation Pathways

Although findings in the existing research and published literature paint a worrisome picture of the future, research shows that there are pathways that can help us to reduce the chances for a climate crisis for future generations. Mitigation and adaptation are sometimes characterized as two sides to the same coin; mitigation is defined as activities to reduce and stabilize the levels of heat trapping GHGs, and adaptation activities focus on helping communities deal with current impacts of climate change (NASA, n.d.). When looking at the oil and gas industry, it is possible to characterize mitigation and adaptation on a continuum. One way to look at GHG reduction is to first consider avoiding emissions through operational improvements and improving the efficiency of current processes. Investments in new technologies and developing carbon offsets are other parts of the emissions mitigation and adaptation spectrum (Belletti & Schelble, 2022).

This section begins with a discussion of some of the top GHG reduction strategies that directly relate to BOEM's mandate and then moves onto a larger discussion of mitigation and adaptation pathways, which include the strategies discussed in the webinar and those distilled from the literature review and recent policy announcements.

5.1 Scope 1 GHG Mitigation and Management Pathways for OCS Facilities

As mentioned in prior sections, in parallel to this study, the authors also have conducted a deeper-level overview of the emission sources from BOEM's authorized activities and worked to identify opportunities to reduce emissions from these sources. To summarize the findings of this parallel study, the authors hypothesize that technological- and policy-based (or procedure-based), facility- and component-level emission reductions may contribute to overall Scope 1 emissions reductions in the upcoming several decades. The parallel study is done in support of determining ways in which BOEM may meet respective 2030 and 2050 goals of 50% and net-zero carbon emission reductions from its authorized activities, as mandated by the Executive Orders referenced in the Introduction section of this report. As the authors hypothesize, Scope 1 emissions from BOEM sources may be reduced through implementing a combination of opportunities. Section 5.1.1 summarizes key findings with regard to

Scope 1 GHG emissions reduction opportunities, and Sections 5.1.2 through 5.1.6 discuss observed potential gaps in current emissions reporting and data and, where possible, suggest areas of potential improvement.

5.1.1 Opportunities to Reduce Scope 1 Emissions from BOEM-Authorized Activities

In many ways, Argonne's study report titled *Pathways to Reduce Greenhouse Gas Emissions on the U.S. Outer Continental Shelf* (or "Pathways Report", currently in production) agrees with the conclusions from other published literature pointing to high methane emissions sources (such as cold venting, fugitives, pneumatic pumps and controllers, and others) as a priority in terms of potential GHG mitigation opportunities. The study further recommends prioritization of methane emissions reduction due to methane's higher GWP. In addition, the authors attempt to quantify potential CO_2 emissions reductions from hypothetical improvements in combustion-heavy processes, such as drilling activities, or natural gas engines and turbines. As the study concludes, to meet the currently projected domestic and global energy demand assuming unchanging projections in exploration and development and production levels on the OCS (primarily in the Gulf of Mexico), potential Scope 1 GHG emission reductions on BOEM's authorized facilities are possible through facility-level implementation of reduction techniques (also referred to as "opportunities"). The study recognized over 30 potential emissions reduction opportunities that target primarily reductions from the highest emission sources shown in Figure 5. Many of the recognized opportunities are well-developed and have high levels of technology readiness ("high TRL"), while others are recognized as nascent.

The details of these opportunities are available in the aforementioned parallel Pathways Report and include their description, projected costs, and GHG reduction capacities. In sum, these Scope 1 reduction opportunities can be generally categorized into three pathways:

1. Improving process efficiency, which may have additional benefits of improved safety and lead to reduced carbon dioxide emissions and methane waste. Examples include the following:

    - Replacing existing incandescent or halogen lighting bulbs and/or fixtures with light-emitting diode (LED) type lights, which can lead to lower power demand from diesel generators, natural gas turbines, and natural gas engines, translating into reduced CO_2 emissions

    - Maximizing the use of fuel additives to optimize the combustion cycle in diesel generators, leading to further CO_2 emission reductions

    Any such additions would need to include an environmental review of potential negative effects from these technological changes, such as impacts to wildlife.

2. Maximizing the recovery of fugitive and vented methane and routing it to the sales line or repurposing it to power onsite equipment, which may lead to a reduction in natural resource waste and prevention of further climate change harms by translating Scope 1 methane emissions into Scope 3 CO_2 emissions.[5]

    - Employing the use of LDAR to target and routinely remove fugitive emission sources appears as an important facility-level part of optimized methane recovery.

[5] A maximized benefit assumes minimum leaks in the methane transmission pipelines and efficient combustion of the methane in downstream uses, effectively reducing methane's GW).

3. Introducing technologies and processes to recover and sequester carbon dioxide from the onsite combustion processes, where the cost as well as the carbon footprint of the additional engine, compression, and other required processes must be significantly lower than the benefit and the amount of carbon dioxide prevented from otherwise entering the atmosphere or being absorbed in the water.

To help manage carbon emission reductions, BOEM may employ its regulatory tools, such as the following:

- Changes in regulation to require new technology or processes, as long as these changes are in line with the statutory authority under OCSLA
- Issuance of notices to lessees (NTL) to provide guidance regarding new technology or processes leading to GHG emission reductions, if BOEM determines that the current regulations already cover BOEM's authority to regulate carbon emissions and prevention of mineral resource waste
- Collaboration and coordination with other parts of the U.S. Government, including other regulating agencies, such as the EPA, to standardize the GHG emission reduction mandates and provide the industry incentives to implement new technology or processes[6]

The authors recognize that in an industry that is as fast-evolving and well-developed as oil and gas exploration and production on the OCS, it is difficult, if not impossible, to issue blanket regulations requiring the implementation of a particular kind of technology on all facilities. Some of the specific challenges include the following:

- There are virtually no two platforms or drilling rigs on the OCS whose processes and technology are identical, and although the technical components in the drilling or production processes serve similar roles, they come in different designs and sizes and have evolved over time.
- Some facilities have less physical space available than others to install additional equipment. Most facilities are also subject to weight limitations, possibly precluding significant technological changes.
- Although it is recognized that the largest production share on the OCS comprises large companies (often publicly traded, with high market capitalization, and that could likely tolerate additional capital costs of these improvements), many facilities belong to smaller private companies for whom the capital and maintenance costs of these improvements may represent an unexpected significant financial burden.

For the reasons stated above, as well as others, a potentially more viable approach would be to adopt a policy driven by prioritizing the implementation of GHG emission reduction opportunities on a facility-by-facility basis, considering factors such as addressing disproportionately high emission sources, facility limitations, costs, and others.

Importantly, the analyzed opportunities hypothetically could be implemented in a way that the 2030 goal of reducing overall GHG emissions levels by half compared to 2005 would be achieved. However, many of the opportunities are exceedingly costly and may require incentives for the industry to implement these technological changes and meet the goal. Additionally, the 2050 goal of net-zero emissions will require a

[6] As of the writing of this report, the IRA, which has been newly signed into law, has allocated an incentive fund specifically targeting Scope 1 emissions reductions from oil and gas activities. However, it remains to be seen how activities on the OCS will be affected.

heavy reliance on carbon offsets—a hotly discussed topic in the current energy community, but whose effectiveness and full potential is in its very early stages of being understood. While some may suggest slowing activities on the OCS as another measure, a likely unchanging demand in energy may possibly lead to a net increase in emissions through imports of oil and gas from countries that may host potentially more carbon-intensive oil and gas exploration, drilling, and production activities.

Carbon offsets to achieve net-zero emissions may be a viable way of achieving these goals, but, as discussed in Section 5.2.2, it too will need scrutiny to ensure the purported effectiveness of this approach.

5.1.2 Accounting for Potential Inaccuracies in Past Emissions Data

BOEM's 2005 emissions inventory data used as the point of comparison for 2030 and 2050 reduction goals in this study potentially may be flawed, possibly leading to uncertainties in quantifying relative GHG emissions reductions. BOEM's 2014 Emissions Inventory Study included a trends analysis for BOEM inventories prepared for the years 2000 through 2014. Overall, as the study indicates, emission analyses are affected by three main factors: activity and production levels, changes in inventory methodologies, and improvements in the emission factors used to estimate emissions. However, as the study contends,

> *Changes in emission factors, models, and activity data sources have created artificial trends in the data (i.e., emission decreases or increases are seen due to improved method and activity quantification). For example, the increased resolution in the marine vessel identification and better quantification of activity makes it appear as if emissions from BOEM sources have decreased recently. In reality, the revisions to the methods, primarily the improved data sources, are better at identifying vessel categories and quantifying their propulsion operations.* (Wilson, et al., 2017)

The authors of this report projected emissions changes based on BOEM's projected platform and non-platform activity levels from 2017 through 2050 and believe these projections to be consistent. However, a survey into the possibility of reconciling emissions reports in past inventories (e.g., through applying the same emission factors and GWP equivalents) may help BOEM to determine whether relative 2030 and 2050 emission level goals can be stated more accurately. An alternative approach may be to adjust BOEM's goals understanding that the reported 2005 OCS emission levels, which the White House mandates as the point of comparison, may be inaccurate.

5.1.3 Revision to GHG Data Reporting Frequency

As stated in prior chapters, BOEM employs the OCS AQS database, where operators are required to report activity levels, which are used to calculate the emissions through emission factors and component counts every three years.[7] A possible improvement that may lead to more accurate reporting may be to require more-frequent emissions reporting (and published emissions inventories), which could be essential to improving understanding and subsequent management of Scope 1 GHG emissions from BOEM's authorized activities.[8] With the improved user-friendly OCS AQS interface, emissions reporting has become arguably easier, and a transition from every 3 years to every year may not cause a significant increase in effort on the industry. Further, this approach may effect an improvement in the reporting

[7] There was a delay in reporting the 2020 emissions inventory due to a delay in BOEM's transition to adopting the new OCS AQS tool to replace GOADS, and, as a one-time exception, BOEM instead required reports in 2021. Future reporting will resume the three-year frequency with the next inventory comprising 2023 emissions data.

[8] This determination potentially would have to be made by the Government in order to avoid possible Paperwork Reduction Act of 1995 (44 USC §3501—3520) violations.

requirements under EPA's Greenhouse Gas Reporting Program per regulations in 40 CFR § 98.230, where reported offshore facility emissions match those reported to BOEM on inventory years and are adjusted by activity levels for non-inventory years.

Another potential benefit of more-frequent reporting lies in providing the industry an opportunity to report and track the annual outcomes of the GHG emission reduction-related improvements that they may implement on their facilities over a given year. This feedback may allow them to take advantage of any potential benefits of demonstrated reductions or avoid possible penalties in a scenario where a GHG emissions reduction regulation is implemented, as a potential cause for penalty may arise from untracked reductions and not by an absence in actual reduction.

5.1.4 Importance of Top-Down Emissions Verification

Many independent studies suggest that self-reported inventories may have led to an underrepresentation of some of the emission quantities, going as far as pointing out certain facilities or sources as "super-emitters." Aerial or satellite-based verification may lead to improvements in emissions data quality. Such checks are often referred to as "top-down verification" (National Academies Press, 2018). The accuracy and sensitivity of detectors present on-board aircraft or satellites, as well as the software that helps interpret the detected fluid concentrations, has vastly improved over time, providing researchers the ability to more accurately characterize emissions and pinpoint their possible origins. Together with technological improvement, climate change research has shown that a significant portion of GHG emissions released or absorbed by the water mostly stays in the water, precluding them from being captured via aerial detectors, meaning detected emissions likely come from anthropogenic processes present on man-made facilities above the sea level (USGS, 2017). Still, these checks are prone to further possible errors, which researchers often recognize and acknowledge by reporting their findings with error bars (e.g., (Gorchov Negron, et al., 2020)).

However, further improvements can be made in the emissions reporting and inventory verification work. For example, current aerial and satellite reported checks are based on one-time or short-term snapshots, often leading to assumptions that the detected higher-than-normal emissions are present all year (e.g., (Gorchov Negron, et al., 2020, p. 5117)) or could miss intermittent high emissions. Temporal variability is another variable that needs to be adjusted for to avoid misrepresentation of emissions (Vaughn, et al., 2018). More frequent top-down verification, covering greater geographical areas, as well as accounting for temporal variability, may lead to more accurate verification results. Recognizing that these checks require a significant effort, making funding available to support such studies will likely lead to improved clarity.

5.1.5 Cross-Verification of OCS AQS with Oil and Gas Operations Report (OGOR) Data

Similar to the above point, some of the parameters to calculate emissions are required to be reported to both OCS AQS and BSEE's OGOR databases (BSEE, n.d.). It may be worthwhile for BOEM to verify the parameters to calculate emissions for items tracked in both OCS AQS and OGOR, such as volume vented, with OGOR reports for a given facility. While OGOR B (one of the OGOR databases) data is reported by well or by lease, other data tables present in BOEM and BSEE's data center can enable a cross-reference to the facility.

5.1.6 Using Detection Mechanisms for Fugitive Emissions

Lastly, current fugitive reporting is done through component count and EPA emissions factors. A more precise detection mechanism, such as using equipment as part of LDAR programs, may lead to a clearer picture of the true nature of fugitive emissions from process equipment.

5.2 Overarching Mitigation and Adaptation Strategies

While the previous section addressed strategies directly related to BOEM activities, this section raises additional pathways to reduce environmental harms associated with GHG emissions.

5.2.1 Near-Term Activities Addressing Existing Damage

Although various measures to halt or reverse some of the damage associated with SLR and erosion were raised at the webinar and in the literature review, these should be considered short-term fixes and potentially costly from a financial standpoint (Fagherazzi, 2014). Suggested strategies include edging and restoring vegetation, and protection of mangroves. Mangroves are a part of the "blue carbon" ecosystem, and the tidal marshes and seagrass meadows that make up the mangroves along the U.S. Gulf of Mexico help in reduction of GHGs. In addition to sequestering carbon, mangroves play a key role in stabilizing the shoreline, protect the ecosystem and prevent erosion. This plays a role for both the ocean environment and helps to protect infrastructure on land due to the ability to absorb storm surges.

Other adaptation strategies from the webinar focused on the need to protect reefs, highlighting the need for a better understanding of the micro-environments and ways to offset harms from acidified waters. Though lower water temperature is an essential factor in the long term, there are direct human interventions that can enhance the health of reefs, which may both improve water quality and decrease overfishing of reefs. Man-made solutions include netting overlays, which are thought to be one option to promote sustainability but will be of limited utility if average ocean water temperature continues to rise.

5.2.2 Carbon Sequestration and Carbon Offsets

Another distinct line of investment is in new technologies to mitigate environmental impact of existing GHGs in the atmosphere. Industry is investing in GHG removal technologies that include direct air capture in a pilot phase, with heavy investment from the oil and gas industry to move from startup to full operations. As energy companies have recognized that their future depends on reducing harms to the environment, there has been increased investment in these technologies (Krauss, 2019).

While the discussions during the webinar and BOEM's focus leads one to first think of the role of oceans in carbon sequestration, industry is now looking to onshore nature-based solutions to offset Scope 1–3 emissions. Carbon offsets, which are also referred to as carbon credits, are a basic concept to understand. The approach is that GHG emissions can be reduced or neutralized by certain activities, and if an entity emits a certain amount of GHGs in a year, it is possible to offset these emissions with carbon-sequestering activities, such as planting trees or certain cover crops (Liu, 2022). Although the overarching concept is simple, developing markets with validated data are still at an evolving stage.

Academic studies and advocacy reporting raise concern that these projects may not be as effective as promised and supposed benefits have been overstated (Jacobson, 2019). Although the concept of offsets is commonly accepted, the available information regarding the readiness of this solution to offset the GHGs is still vague in many cases. If industry continues to feature offsets to mitigate emissions, it is important to gain a greater ability to verify that the natural sinks are as effective and abundant as claimed. This verification is particularly important as the U.S. Securities and Exchange Commission (SEC) is taking a closer look at companies that purport to have environmental policies to reach net-zero GHG emissions but perhaps do not have the data or disclosure processes in place to substantiate those claims. We can anticipate greater regulation from the SEC in the months to come, and carbon offsets will most likely be a part of that scrutiny to ensure that investors have access to verifiable data and not mere greenwashing when making a financial investment in a publicly held company.

Various trends indicate that additional investment on mitigation and adaptation are on the horizon. From a U.S. policy perspective, the current administration's legislation and global commitments to methane reduction both signal a commitment but also provide financial incentives ("carrots") to those who make investments and taxes or penalties ("sticks") to those who continue to emit.

5.2.3 Considering Global Energy Needs

Although it is important to reduce emissions through operational improvements, it is also important to consider the possibility of reduction of demand for hydrocarbons. One school of thought is that the most cost-effective intervention to reduce GHG emissions is to reduce consumption of hydrocarbons, but global economic growth and population growth are a significant obstacle to any sort of reduction in demand, at least in the near term. Though reduction in demand for energy is not likely, at least in the near future, a future energy mix that features a greater percentage of low carbon energy generation, paired with carbon offset activities, is one of the scenarios envisioned both domestically and at international environmental summits.

As the international community seeks to transition from hydrocarbon-based energy economy, many stakeholders highlight that there is no "one size fits all" solution to create a high energy future while simultaneously reducing dependence on hydrocarbons. Although there are differences in opinion on the best way to create a high energy future while simultaneously reducing the negative impact of GHG emissions, there is a consensus under the United Nations Sustainable Development Goal 7 that the international community needs reliable, affordable, and sustainable sources of energy for both economic and human development, and that tensions can cause price shocks and shortages (United Nations, n.d.).

In addition to mitigation strategies to directly address Scope 1 emissions, a wide, larger effort must be integrated to combat the harmful effects of all emissions. All efforts might be successful in helping reduce Scope 1 emissions that are a key part of BOEM's mandate, but it is other mitigation efforts related to Scope 3 emissions (i.e., those from combustion of produced oil and gas) that will play an even more critical role in reducing the long-term climate implications.

6 Conclusions

From the information gathered in this report, the documented impacts of continued increases in GHG emissions on U.S. marine and coastal environments are becoming more evident. These impacts manifest in rising sea levels along U.S. coasts, which have led to coastal erosion and losses. In addition, severe coastal storms, such as hurricanes with increased severity of storm rainfall linked to increasing sea surface temperatures, further impact coastal flooding and lead to economic and environmental harms. The resulting increases in ocean temperatures and ocean acidification from GHG emissions are also damaging ecosystems that support biodiversity, such as coral reefs, and directly altering the lives of marine organisms more broadly. Increasing ocean temperatures and changes in salinity can lead to changes in hypoxia events, which can damage marine organisms and habitats and directly diminish coastal fisheries. These impacts have direct consequences for the U.S. by stressing OCS natural resources, coastal infrastructure, food systems, and recreation.

As the studies referenced throughout this report point out, emitted GHGs, regardless of their scope or origin, accumulate in the atmosphere and in the ocean and are projected to continue impacting the environments, including the OCS, for hundreds of years. Therefore, incremental changes, including the reduction of Scope 1 emissions from BOEM-authorized sources, are an important step in achieving the overall goal of slowing the ill-effects of climate change through slowing the contribution to the anthropogenic GHG emissions.

Finally, consideration and understanding of the domestic and global energy demand will be an even more important aspect of GHG emissions policy adoption. Although policies that effectively incentivize a slowing in activities on OCS may lead to Scope 1 emissions reductions, they may have little effect on net GHG emissions as imported substitutions to meet the demand may come from countries with potentially more carbon-intensive oil and gas activities. Furthermore, ongoing and possible future global hostilities by significant oil-exporter countries may require a revised posture of the U.S. as a producer and net-exporter of energy. To support the sustainability of growth in this scenario, further requirements and incentives for cleaner operations on the OCS may carry significant global benefits. BOEM devotes significant effort to examining and projecting demand as part their Five-Year National OCS Oil and Gas Leasing Program planning. With added focus on GHG emissions, this effort appears more essential than ever.

7 Recommendations

Presented below is a summary of potential actions in the near-, mid-, and long-term timeframes and their possible outcomes, which the authors recommend BOEM consider while working to meet the GHG emissions reduction mandate on the OCS. Although the list below was compiled in an attempt to summarize generally positive and likely helpful actions, it is important to also note any potential drawbacks in each case. In general, any new program, activity, or initiative comes at a cost and typically requires significant initial resources and commitments. Given these variables and challenges, specific actions and their potential benefits or impacts are described below.

- A review of GHG emission reduction activities already undertaken by the offshore energy industry on a voluntary basis may help BOEM to determine which of these efforts or activities to support. Such a review may provide guidance on the technological and process improvements that may be ripe for relatively straightforward adoption on the OCS.
- An interagency collaboration among relevant Federal agencies—such as BLM, EPA, DOT/PMHSA, and possibly the Department of Energy—may be beneficial to streamlining regulatory practices for controlling GHG emissions. Specifically, regarding potential taxes on methane as a possible result of the IRA, the benefit of interagency coordination may be a signal to industry on the future of such a tax. However, this tax will probably require a statute, which is outside of BOEM's (or any other agency's) control, possibly posing an obstacle to a coordinated tax scheme.
- BOEM and BSEE independently maintain emission inventories (i.e., BOEM's OCS AQS reporting tool) and venting and flaring reports (i.e., BSEE's OGOR data), and a first beneficial step in understanding the state of the current bottom-up reporting may be to compare the consistency of same-year OCS AQS and OGOR data for like sources (such as venting and flaring). This comparison could potentially help to reveal areas of data inconsistency. An outcome of this knowledge, in turn, may contribute to improvements in data collection through possible revised bottom-up reporting practices, placing a focus on areas with identified gaps.

- BOEM may consider additional focus on methane emissions, as they are the focal point of many studies suggesting underestimated reporting, and identify verifiable data sources from producers, the research community, and tools like LDAR and remote sensing or top-down verification. As several studies suggest, methane emissions from certain facilities or sources (i.e., "super-emitters") are significantly higher than previously reported and understood, which may merit additional investigation by BOEM. More frequent top-down verification, covering greater geographical areas, as well as accounting for temporal variability and other potential causes of imprecision, may lead to more accurate verification results. Although additional investigations require significant effort, funding such studies will likely lead to improved clarity with regard to Scope 1 emissions on the OCS.

- A possibly overlooked additional benefit of instrumentation-based sensing, such as LDAR or remote aircraft or satellite sensing, may be to aid BOEM and the industry in detecting unexpected releases (e.g., those caused by system upsets in unmanned infrastructure). For that reason, BOEM may consider supporting a top-down verification strategy to detect and verify these unexpected releases, which could decrease the volume of undetected GHG releases by alerting the appropriate stakeholder and enabling a faster response. At the same time, there is currently a gap in the sensitivity and precision of offshore technology applications. Further assessment and standardization of these instruments likely would be required before their adoption as an industry standard.

- BOEM may consider supporting any existing or future research efforts focused on evaluating the effectiveness of carbon offset projects. As studies cited in this report suggest, there is currently a gap in understanding the extent to which carbon offsets can help achieve national net-zero emissions goals. Although individual companies' statements related to offsets likely will be scrutinized by other regulators (such as the SEC), taking a closer look at how offset programs in general function now, and ways in which they might be optimized, may help guide emission related policies for BOEM-regulated activities.

8 References

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APPENDIX A. Effects of Sea Level Rise on Shoreline Degradation and Erosion

Sea level rise (SLR) occurs when large land-bound ice masses (sheets, glaciers) become unstable, undermined by melting due to increased atmospheric temperature, and eventually collapse, thus sliding or draining into oceans. This phenomenon increases the volume of water in ocean basins and raises the water level at ocean rims (Sweet, et al., 2022) Additionally, thermal expansion of seawater as a result of a warmer temperature also contributes to SLR (Wigley, et al., 1987). The impact on littoral lands vary depending on the nature of the shoreline (Temmerman, et al., 2013). Sea cliffs and palisades are undercut and may collapse. As a result, real estate and other valued resources in these areas are lost (Athanasiou, et al., 2019). An example from Isla Vista, CA, appears in Figure A-1.

Figure A-1: Effects of shoreline erosion in Isla Vista, CA. Image source: U.S. Geological Survey

Of particular concern is the erosion and loss of so-called buffer areas and the flora that inhabit them as they serve effectively to protect inshore lands from storm damage (FitzGerald, et al., 2008). A case in point is Breton Island, part of an archipelago of barrier islands east of the Mississippi delta in Louisiana, where buffer land that also serves as a habitat for brown pelicans has been severely reduced in area over the past 100 years (Terrano, et al., 2016). As discussed subsequently, both loss of land and reduction of species in the lower food chain disrupt avian and terrestrial mammal habitat.

Marsh bird habitat loss due to shrinkage of marsh acreage is a significant concern. The Gulf of Mexico contains about 22% of the world's non-arctic tidal marsh, representing about 62% of tidal marsh habitat in North America (Woodrey, et al., 2012). About 10 species of tidal marsh birds occupy Gulf of Mexico marshlands year-round, and 10 more species are seasonal occupants. These species include grebes, rails, bitterns, coots, wrens, moorhens, sparrows, and grackles. Strategies to manage or conserve these populations must account for possible changes to bird habitat as tidal marshes are increasingly affected by climate change. Further, the impact of these changes on coastal marshes will likely vary spatially, requiring an understanding of ways different wetland ecosystems respond to climate change at local and regional scales.

Description of Harm

The type of harm produced by SLR in the coastal areas of the U.S. varies with coastal slope and ecosystem. Like much of the Gulf of Mexico and Atlantic Coasts, shallow slope regimes will see a coastal retreat from sand erosion. The sand scoured from beaches is redeposited on the continental shelf floor, thus raising the sea bottom and further leveling its slope. The sea then moves in to occupy the area of littoral sand loss (Athanasiou, et al., 2019; FitzGerald, et al., 2008). As storm severity becomes more intense as the climate warms, scouring and erosion intensify with each storm. Pertinent examples are shown in the photos in Figure A-2, where the loss of buffer marshlands and mangrove stands in the coastal areas of the Mississippi River delta result in salinization of formerly freshwater areas and loss of vegetation.

Figure A-2: Examples of mangrove erosion (two images on the left) and marshland erosion (two images on the right)

Locations of the images are as follows: top left: marsh boundary of Virginia Coast Reserve; bottom left: Everglades National Park, FL; top right: Plum Island Sound, MA; bottom right: Virginia Coast Reserve.

Figure A-3 further shows effects of salinization. In recent years, long-term average loss rates of Louisiana coastland approximate an American football field's worth of coastal wetlands within 34 minutes when losses are rapid, to within 100 minutes at more recent, slower rates (Couvillion, et al., 2017). This situation prompted the Governor of Louisiana in 2017 to issue a state of emergency, which empowered all governmental divisions and agencies within the state to "undertake any activity authorized by law ... to expedite implementation of integrated coastal protection ... [and] cooperate in actions the State may take in response to the effects of this coastal crisis and to assist in expeditiously implementing integrated coastal protection in the State."[9]

Steeper slope regimes such as much of the U.S. Pacific coast become increasingly susceptible to wave and storm impacts and eventually experience the cleaving of elevated coastal lands, plunging natural and built infrastructure into the sea, as shown in Figure A-4 and the right photo in Figure A-1.

[9] Proclamation no. 43 JBE 2017, 18 April 2017.

Figure A-1: Salinization resulting in dead mangroves in Everglades National Park, FL
Photo courtesy S. Fagherazzi

Figure A-2: Erosion damage at Wainwright, on Alaska North Slope
Image source: U.S. Geological Survey

As sea level continues to rise at an accelerated rate, the intensive development and infrastructure along California's coastline is under an increasing threat. Whether affecting construction on coastal bluffs or cliffs, or along low-lying shoreline areas, higher sea levels combined with storm waves and high tides will lead to increased rates of cliff and bluff retreat and more frequent coastal flooding. A study of the West Cliff Drive coastline at Santa Cruz, CA, showed a total coastal retreat over 65 years ranging from 0.3 to 32 m, and a maximum cliff retreat rate of 0.5 m/year (Griggs, et al., 2019). Moreover, along stretches of Alaska's Beaufort Sea North Slope, average annual erosion rates doubled from historical levels of about 20 feet per year between the mid-1950s and late-1970s to 45 feet per year between 2002 and 2007, leading to the disappearance of cultural and historical sites of native populations (Pacific Coastal and Marine Science Center, 2022).

With higher sea levels, even moderate but frequent storms can accelerate salinization. The higher salinity of groundwater near the shoreline poisons the roots of tree stands, killing trees and other buffer flora, as shown in Figure A-3.

Loss of Marshland

When barrier and buffer zones erode through SLR, marshlands behind the barriers decline through erosion as tide heights increase (Fagherazzi, et al., 2019). Over time, the marsh retreats to a fringe or disappears altogether, losing a vital ecosystem. Mangrove stands, which occupy marsh and bayou regions in the littoral zones, are critical in sequestering carbon due to their ability to store orders of magnitudes' more carbon than the forests found on land. Mangroves can store and stockpile carbon from the atmosphere during their growing period from 50 metric tons to as much as 220 metric tons per acre (Nyanga, 2020).

The term for carbon absorbed by the world's vegetated coastal ecosystems, such as mangroves, salt marshes, and seagrass beds, is called "blue carbon" because of the longevity of the carbon sequestration in their sinks (up to 10 times longer than that of tropical rainforests and boreal and temperate forests) (Mcleod, et al., 2011). After the uptake of carbon ceases due to the loss of these efficient carbon sinks, the rest of the marsh ecosystem deteriorates and becomes subject to erosional depletion. Inshore groundwater becomes more saline from seawater intrusion, because mangroves are highly efficient at converting saline water uptake to fresh water. Figure A-5 shows the effectiveness of marsh plants as carbon sequestrator. These blue carbon uptake resources exist in virtually all coastal areas in the U.S. and globally (see more at thebluecarboninitiative.org), and the U.S. continues to promote their development (NOAA, n.d.). These resources have been vital in total carbon sequestration, and the U.S. is the first country to include blue carbon into its national greenhouse gas inventory (NOAA, n.d.).

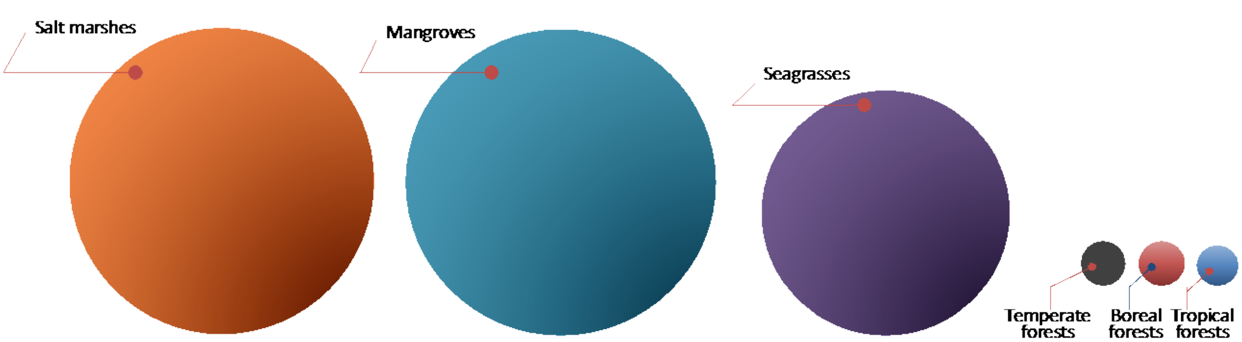

Figure A-5: A visualization of proportions of carbon sequestration by forest type
The size of each circle represents mean sequestration rates of carbon per square meter per year in soils in terrestrial forests and sediments in vegetated coastal ecosystems. Modified from Mcleod, et al., 2011.

Mitigating Measures

Mitigating measures have been developed over time to halt or reverse some of this damage, but these are often expensive to implement and short term in their effectiveness. Constructing edging and sills of restored vegetation can reduce wave energy in low wave energy environments.

At the same time, built structures such as breakwaters, revetments and bulkheads can stabilize and hold sills in place when applied in conjunction with existing hardened shoreline structures, as shown in Figure A-6 (Fagherazzi, 2014). Louisiana has constructed projects in at least 20 parishes since 2007, constructing 60 miles of barrier islands and berms and building or improving about 315 miles of levees, claiming a benefit to over 46,000 acres of coastal habitat (Coastal Protection and Restoration Authority, 2013). Since the 1940s, more than 3,800 planned public artificial reefs have been placed in state and Federal waters off Florida's coast (Florida Fish and Wildlife Commission, 2022). Artificial reefs are beneficial for multiple reasons including:

- Mitigation reefs to replace hard bottom habitat lost through activities such as beach re-nourishment and repair of damage caused by vessel groundings
- Oyster reef regeneration
- Shoreline protection

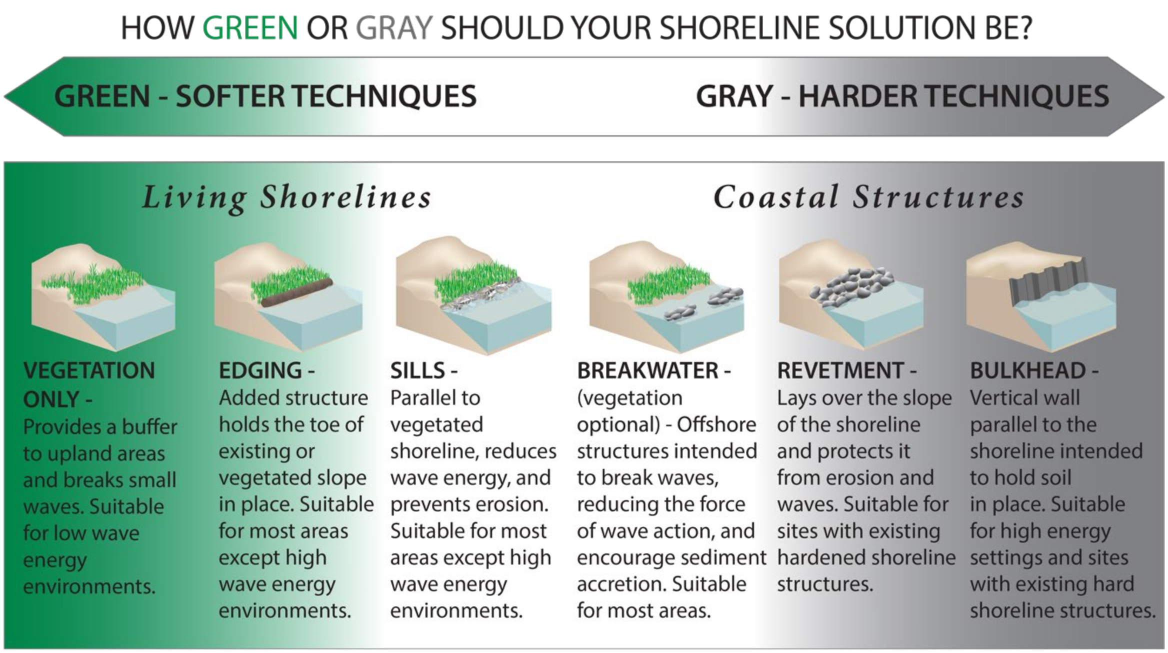

Figure A-6: Mitigation techniques against coastal erosion
Image source: NOAA, n.d. a

In Alaska, most of the measures that have been employed in coastal villages and other infrastructure locations are hard structures such as revetments, bulkheads, seawalls, groins, and offshore berms. In general, revetments usually require maintenance throughout their service life as they can be easily displaced and destroyed during storm events or by sea ice floes. Despite this limitation, revetments are preferred over seawalls, bulkheads, and other offshore structures due to the low costs and easy construction, inspection, and decommissioning. Soft structures such as beach nourishment and dynamically stable beaches have also been implemented at northern high-latitudes. However, beach nourishment requires continual sources of sand and is effective only when there are existing sources of sand adjacent to the sites (Min Liew. et al., 2020).

In California, as of 2018, hard shoreline armoring structures reached 13.9% of the entire state's coastline, a 5.5-fold increase since 1971. However, studies have concluded that none of the past or present efforts to protect shoreline development and infrastructure from coastal storm damage and shoreline erosion will be effective over the long term with continuously rising sea levels (Griggs & Patsch, 2019).

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APPENDIX B. Damages Caused by Increased Severe Weather Effects

As ocean surface temperatures rise due to climate change, more heat energy becomes available to naturally forming storms in the tropical and subtropical latitudes that will increase their intensity. The dynamics of storm formation favor the creation of strong vertical motion fueled by evaporation and heat transfer from the upper ocean. When combined with the helical action of Coriolis forces due to Earth's rotation, these dynamics can produce over tropical waters the powerful and often broad-spread cyclonic storms called hurricanes and typhoons (Knutson et al., 2020). When these storms make landfall or occur near the coastline (including the OCS), their threats to life and property are significant (Figure B-1).

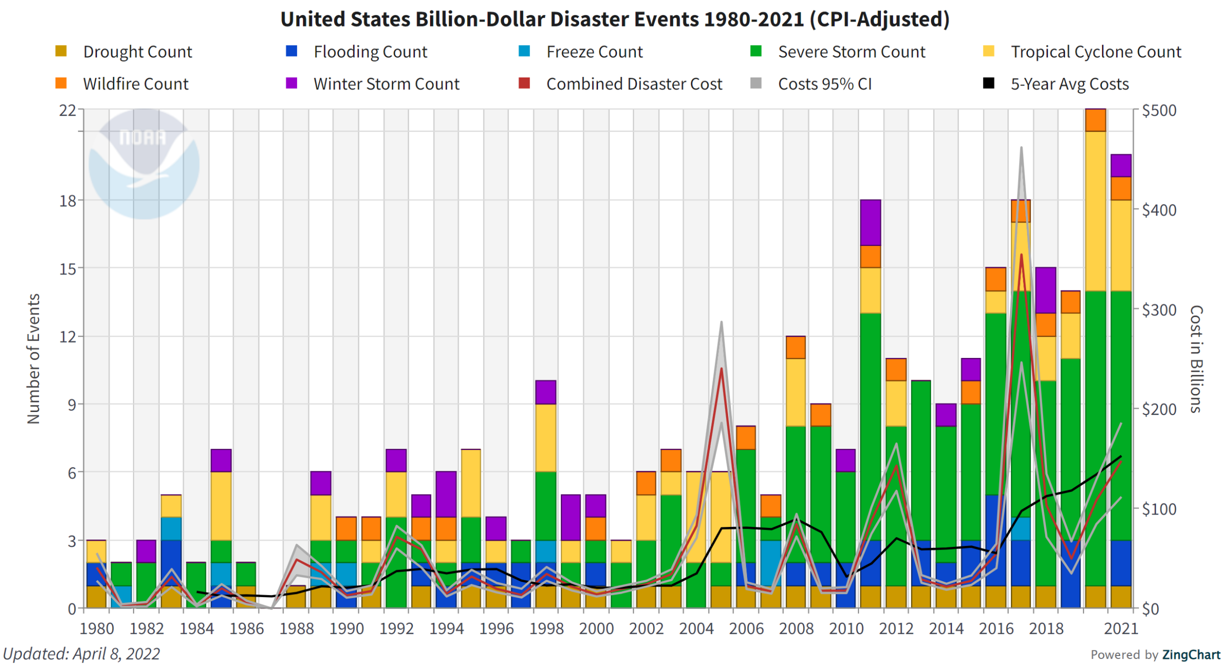

Figure B-1: Weather and climate disaster events with damages totaling a billion U.S. dollars or more in the U.S., 1980–2021

Graph demonstrates how the increasing trend in observed events coincides with the increase in temperature anomalies shown in Figure B-2. Image source: NOAA, 2022

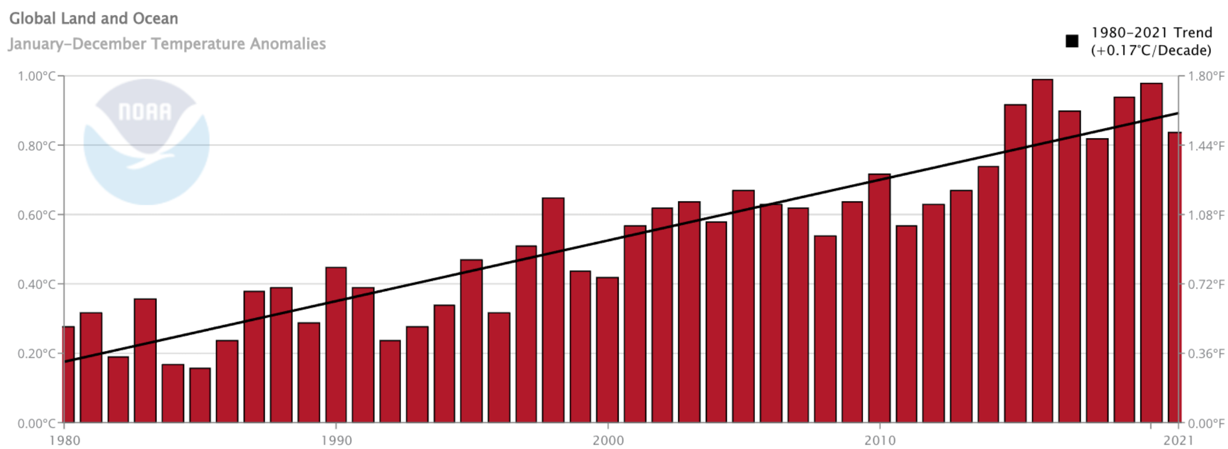

Figure B-2: Observed global land and ocean surface temperature anomalies with respect to the 20th century average

The red bars show the observed anomalies for each year and the black solid line shows the trend. Image source: NOAA National Centers for Environmental information, 2022.

Description of Harm

Recent studies have established that warmer ocean temperatures provide increasing energy to tropical cyclones, which will decrease the frequency of cyclonic storm development. This decrease is related to increased atmospheric stability that leads to less vertical motion and cumulonimbus cloud formation that precedes storms—and therefore their creation. However, developed cyclones are able to pull in more heat energy and water vapor as they travel over open water. Upon landfall, more moisture is available to precipitate as rain (Stansfield et al., 2020a). This suggests wetter hurricanes with more intense rainfall making landfall may occur in the future. The potential damage to natural and built environments has been revealed in recent years, as some of the costliest hurricanes in U.S. history have struck the East and Gulf Coasts, as shown in Figure B-2 and Figure B-3 (NOAA, 2022). Furthermore, hurricanes can direct environmental impacts on coastal ecosystems, changes in estuary salinity due to storm surge and freshwater input (Liu et al., 2020), and the formation of harmful algal blooms due to enhanced runoff, which can increase nutrient loading (Phlips et al., 2020). Finally, high hurricane rainfall amounts and storm surge in combination with sea level rise (SLR) can lead to compounding economic and environmental damages.

What Climate Models Tell Us

Climate models such as the Community Atmosphere Model, v. 5 (CAM5), and the Atmospheric Model Intercomparison Project (AMIP) have been in development at the National Center for Atmospheric Research for decades. CAM5 physics using AMIP protocols can replicate and project atmospheric processes at a high level of three-dimensional precision using numerical modeling (Wehner et al., 2014).

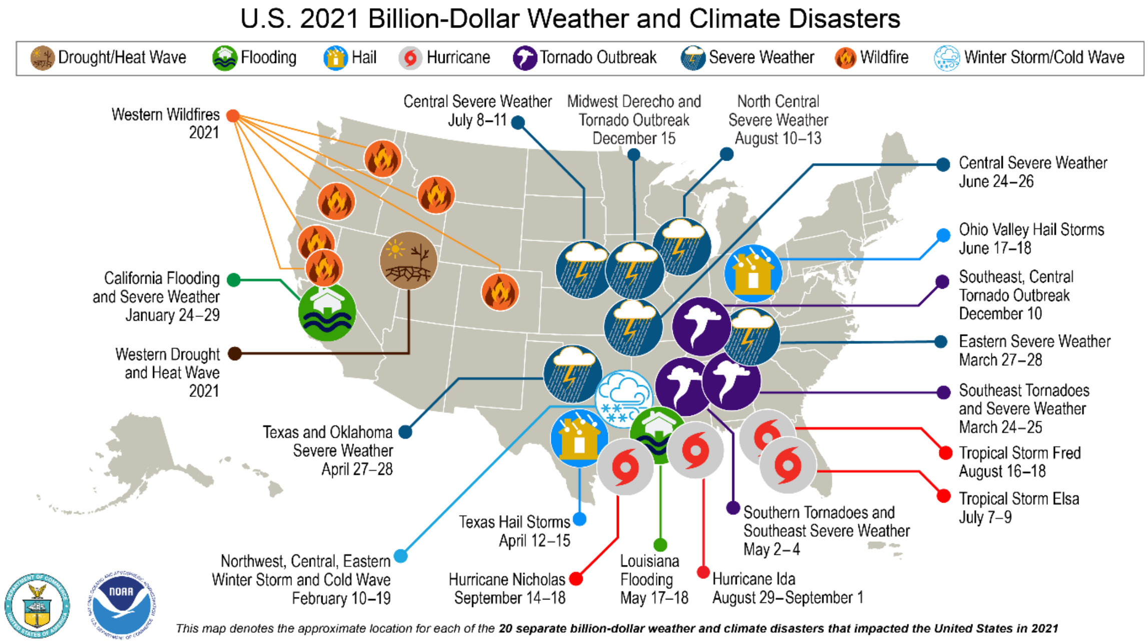

Figure B-3: Extreme weather and climate disasters in the U.S., 2021
Image source: NOAA, 2022a

Advanced modeling techniques have also employed a method called "hindcasting," which seeks not only to replicate the initial conditions that led to significant storm event formulation but also to calculate what would have transpired if the conditions were to reflect those of a previous base year(s) and not include observed ocean surface and atmospheric warming effects that has occurred since then. Figure B-4 illustrates an application of this method for Hurricane Florence, a severe storm that hit the North Carolina coast and traveled inland in 2018. As shown, observed total rainfall amounts (Figure B-4, left) in comparison with actual forecast amounts (Figure B-4, center) from Hurricane Florence were well predicted. However, according to the hindcast projection, if average ocean surface temperature had remained consistent from 1980 to 2018, less total rainfall would have occurred (Figure B-4, right) (Stansfield et al., 2020b; Reed, et al., 2020). This analysis suggests that decreasing GHG emissions could aid in preventing increases in average tropical cyclone rainfall.

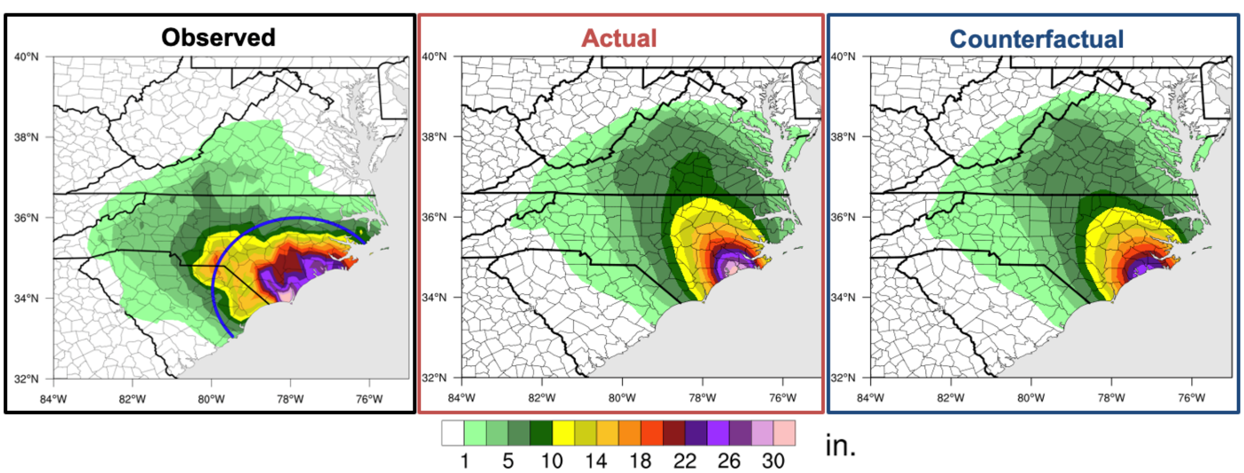

Figure B-4: Observed (left), actual forecast (center), and counterfactual forecast (right) rainfall totals from Hurricane Florence
The blue line in the left panel shows the radius 200 km around storm's landfall location as a reference of spatial scale of the extreme rainfall.

Anticipated Future Developments

Historical data reveal an inverse relationship between tropical cyclonic storm frequency and rising average global temperature, but not between rainfall intensity and temperature (Bacmeister, et al., 2018). As shown in Figure B-5, global storm counts are projected to decrease from currently-observed counts as global temperature rises, as modeled by the tools earlier described in this section.

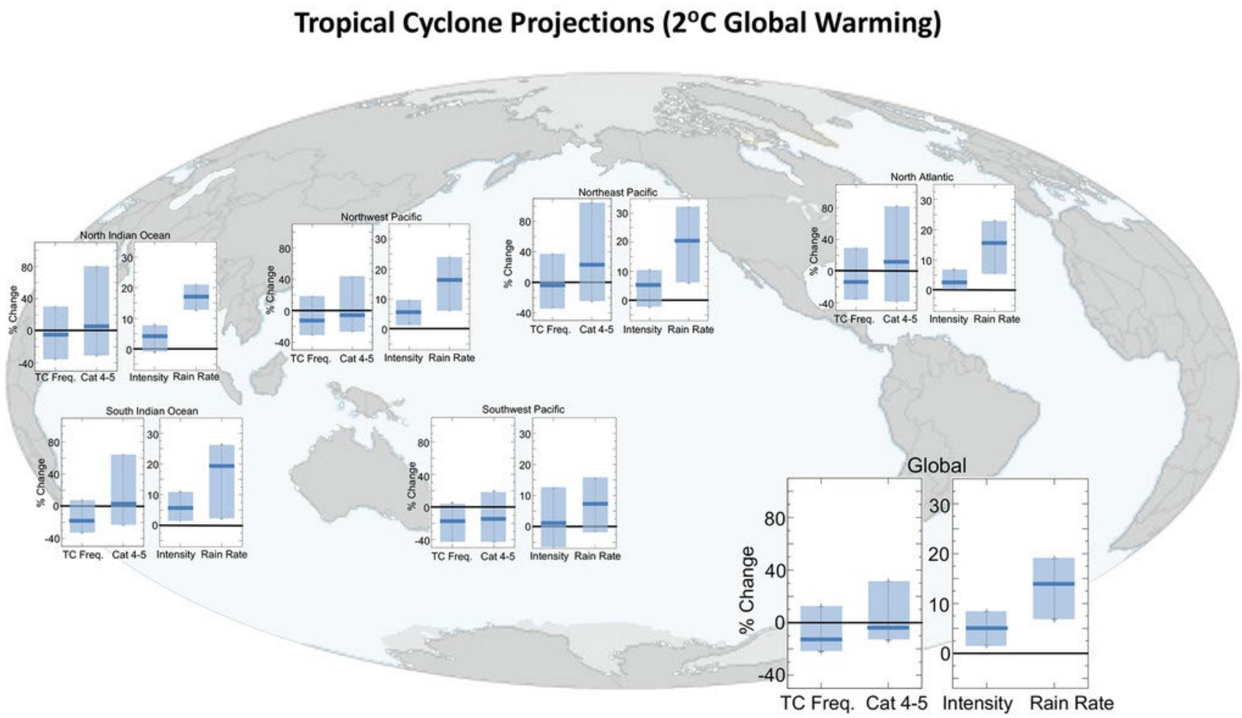

Figure B-5: Future climate scenarios—global statistics

The number of hurricanes is projected to decrease, while the proportion of hurricanes that are major is expected to increase with the increase in anticipated global mean temperatures. Image source: Knutson, et al., 2020.

The amount of time onshore areas experience tropical storms and hurricanes will also decrease as storm frequency decreases. However, rainfall accumulation and intensity, especially near coasts, will rise for those storms that develop and make landfall (Stansfield, et al., 2020b). This will possibly increase rain rates from these systems by as much as 20 percent (Knutson, et al., 2020). As sea surface temperature warms, both mean precipitation and extreme precipitation increase; the magnitude of extreme precipitation can increase at more significant rates. Analysis of the 2020 hurricane season in the Atlantic and Gulf of Mexico demonstrated that human-induced climate change increased the extreme 3-hourly precipitation rates and total accumulations by 5–11% for the entire season (Reed, et al., 2022). This trend shows no current indication of abating.

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APPENDIX C. Ocean Acidification Effects from Emissions of Greenhouse Gases

Coral reefs, other marine species, and ecosystems experience endangerment from the debilitating effects of ocean acidification. Among the impacted species are marine annelid worms (or polychaetes), credited with converting organic debris in the ocean to nutrients for plant plankton that release oxygen; sand dollars (*arachnoides placenta*), which are key components of the ocean's lower food chain; and sea urchins (*heliocidaris tuberculata*), which evolved in the more neutral to alkaline seawater of earlier eras and now undergo stress as the pH of their habitat decreases.

Description of Harm

Average seawater acidity in tropical and temperate zones has been changing from slightly alkaline to neutral to slightly acidic, which is expected to accelerate (see Figure C-1, from Gattuso, et al., 2015).

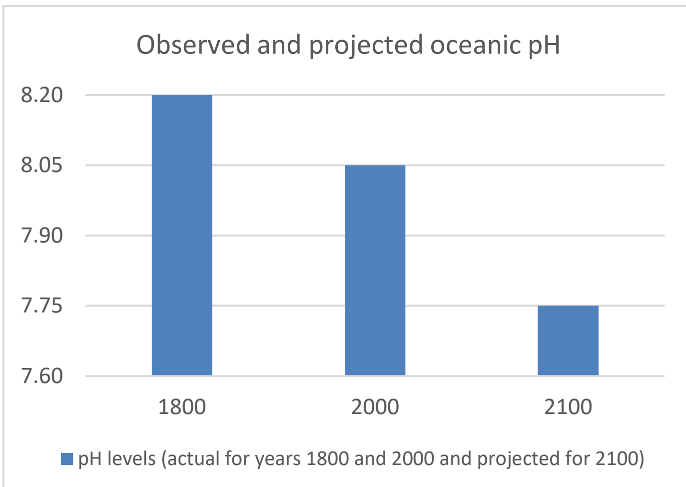

Figure C-1: Rate and effect of ocean acidification
Data from Gattuso, et al., 2015

The uptake of atmospheric carbon dioxide by surface seawater alters carbonate chemistry, producing hydrogen and carbonate ions from carbonic acid that damages the structural integrity of the shells of marine organisms, as shown in Figure C-2.

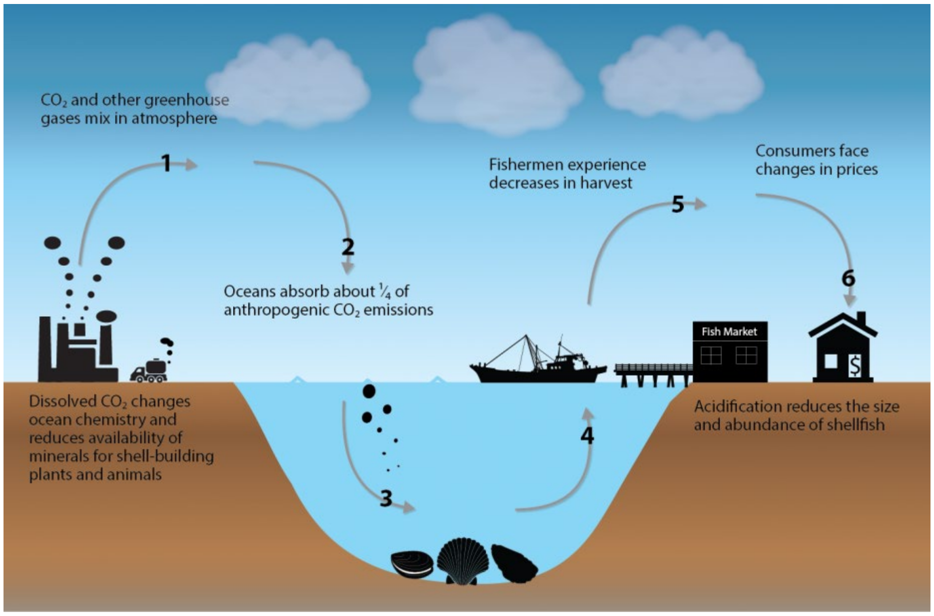

Figure C-2: CO_2 interaction with ocean life
Image source: EPA, 2015

Early life stages of calciferous organisms are especially vulnerable to acidification, which retards calcification, slows growth, and increases mortality (Dupont and Thorndyke, 2009), as shown in Figure C-3).

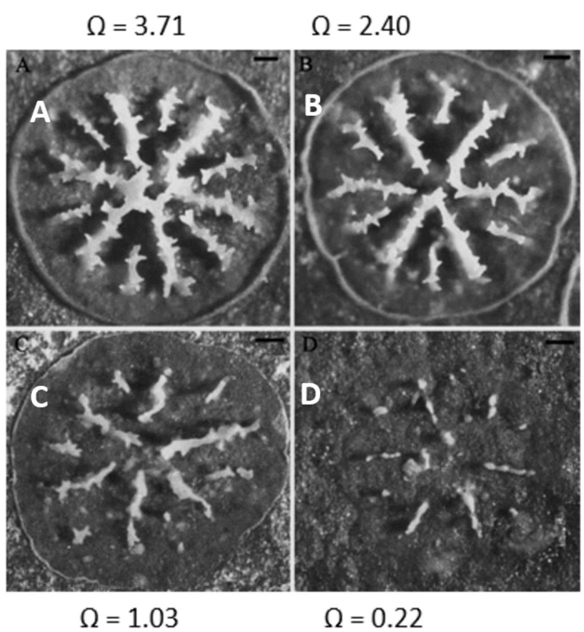

Figure C-3: Impact of acidification on coral recruits in a simulated environment
The simulated environment was created using seawater acidified with HCl, where omega (Ω) represents the calcium saturation rate. It should be noted that other experiments have shown the new recruit calcification response effects of adding HCl to seawater to be similar to dissolving CO_2 in seawater. From Cohen, et al., 2009; electron microscopy photographs used with permission.

Yet, multiple factors are at play in the determination of the viability of a species' ecosystem: ocean temperature (higher solubility), infusion of riverine waters that can be more alkaline (e.g., nitrogen fertilizer runoff into the Lower Mississippi), eutrophication (which fosters the dominant proliferation of algae and other oxygen-suppressing plant species), and hypoxia, among others. Although species—such as Neptune grass (*Posidonia oceanica*) and other sea grasses (epiphytes)—that may assist by forming mobile barriers in the protection of coastlines do not appear to be negatively impacted overall by acidification, with no reduced abundance (Cox, et al., 2015 and 2016), they compete with calciferous species and can eventually supplant them where they occupy joint habitats.

Case Study from the Northern Gulf of Mexico

Two species of seagrass are prominent in the northern Gulf of Mexico—*Ruppia maritima* (widgeon grass) and *Halodule wrightii* (shoal grass)—and are both characterized by medium to large, thick leaves, large rhizomes (self-propagating plant stems), relatively long lifespans with slow turnover, high biomass content, and rapidly germinating seeds. In a 2017 study, these species were cultivated in side-by-side pairings in an aquarium environment with (a) ambient and (b) elevated carbon dioxide seawater concentration. Ambient conditions were maintained for 18 days before 81 days of acidification (to an average pH of 7.7, down from 8.1). Water temperature increased slightly while salinity declined. Under high carbon dioxide conditions, shoot density for both species generally increased, but individual plant growth generally did not reach prior (ambient condition) levels. The study concluded that ocean acidification does not directly harm, but is unlikely to benefit, seagrass vegetative growth significantly. Plants in the north and northeastern Gulf region are not limited by carbon dioxide because of the interaction of multiple environmental factors (as listed above). Both species studied utilized carbonate ions more efficiently than other sea grasses (Cox, 2022, personal communication). In short, these sea grasses exhibited higher tolerance to climate-driven changes to ambient conditions than that exhibited by calciferous species studied, implying that creatures with hardened structural materials, in failing to adjust, will likely decline.

To offset the loss of hardened natural structures in ocean waters, man-made solutions in the form of artificial reefs fabricated from both new and repurposed structures (former bridges, oil and gas platforms, limestone aggregate, army tanks, concrete culverts, ships, dry-docks, and barges) have been lowered into near-shore Gulf waters in recent years, such that several hundred of these artificial reefs are in place from Texas to the Florida west coast (Schulze, et al., 2020). Results have been impressive: these structures teem with marine life with commercial value and have added $76 million in economic benefit to southwest Florida alone. What has not yet been identified from these artificial reef systems or elsewhere in Gulf waters is how decreasing ocean water pH would affect predator/prey balances among affected species with respect to metabolism, feeding activity, and behavior. In particular, disruptions of balance in the lower food chain will negatively affect marine mammal and avian species reliant on survival of more primitive life forms in their diet.

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APPENDIX D. Effects of Climate Change on the Health of the Environment

Coral reefs are among the most diverse and vital ecosystems on the planet. As coral organisms build the protective environment—called reefs—in which they survive and deter predators, these calcified structures become home to thousands of marine species vital to the oceanic food chain. Over time, a change in the intensity of ocean water acidification resulting from increasing levels of carbon dioxide in the water damages alkaline structures of reefs, causing bleaching (Raven, et al., 2005). Because this change also kills the coral animals themselves, the process of reef construction is halted, and the reef structure deteriorates because it is no longer amplified by coral activity. When such an ecosystem degrades and is ultimately lost, habitats disappear, as do the species they once hosted (Fabry, et al., 2008).

Description of Harm

The form of calcium that accretes in coral reefs is a significant determinant of the reef's durability. With higher temperatures and greater carbon uptake causing increased carbon dioxide in ocean water, the saturation state of reef-adjacent waters tips toward acidic, in which aragonite—the essential calcium compound used for reef-building—is more susceptible to dissolution. Calcite and aragonite are polymorphs of calcium carbonate. The critical difference between calcite and aragonite is that the crystal system of calcite is trigonal, whereas the crystal system of aragonite is orthorhombic. Calcite is more stable than aragonite, but coral does not predominantly build calcite structures.

A critical factor in the health and durability of calcium carbonate structures like aragonite is the solubility product of the solution they reside in; in general, a warmer water environment has a higher solubility potential. Equilibrium saturation for aragonite structures is achieved when the product of calcium and carbonate ions is exactly equal to the solubility product. If the ratio of products is greater than one, aragonite building may occur and manifest as reefs. If it is less than one, with higher solubility and lower levels of calcium, reefs are harmed and eventually bleached (Cornwall, et al., 2021). Figure D-1 shows historical saturation of ocean surface waters between the 1880s and the most recent decade (2006–2015). Almost none of the high temperate and polar waters retain a saturation value favorable to reef preservation and growth (Wolfe & Roff, 2022).

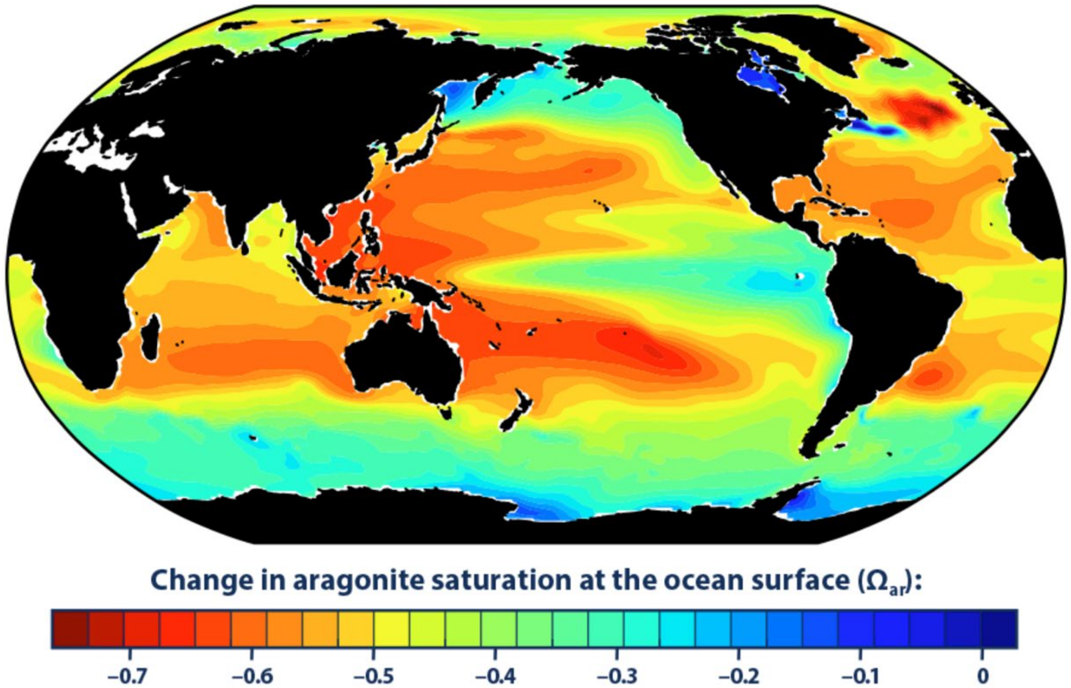

Figure D-1: Aragonite saturation of ocean surface waters between the 1880s and the most recent decade (2006–2015)
Image from: EPA, 2016. Data source: Woods Hole Oceanographic Institution, 2016.

A more graphic illustration of the harm caused by shrinking values of calcium saturation rate in coral recruits with increased seawater acidification was shown previously in Figure C-3. In this figure, coral recruits are nascent reef-building materials that could thrive in high calcium saturation but fail when low (Cohen, et al., 2009).

The Economic Value of Coral Reefs

In addition to their benefits as a habitat, coral reefs make substantial contributions to world economies. As storm buffers, they fend off what could be significant and costly weather events. As tourist attractions and recreational fishery destinations, they bring in $1.6 billion per year in the Florida Keys alone. Coral reef fisheries account for 10 percent of the fish harvest in tropical countries, 25 percent of the fish caught in developing countries, and 90 percent of the proxies consumed by inhabitants of Pacific islands. They are unrivaled as harbors of biodiversity and discovery of interactions among marine species, leading to a greater understanding of marine life at all scales (NOAA Coral Reef Conservation Program, 2013).

Is Reef Destruction Inevitable?

There are areas around the globe where reefs are thriving, and new reefs regularly are being discovered. More needs to be understood about the micro-environments that coral reef builders find accommodating and sufficient to offset the harmful impact of acidified waters. Lower water temperature is an essential factor, but more direct human interventions may enhance the health of reefs. Figure D-2 shows a possible mitigation strategy that can improve water quality and decrease the overfishing of reefs. Large netting structures can overlay reefs and other seabed ecotones, decked with suspended seaweed cultures and limited-capacity fish and invertebrate traps. These structures can provide a sustainable harvest of seafood, protect the natural structures lying below by reducing seawater acidity (through uptake and filtering by seaweed), and reduce the overfishing that can destroy reefs by mechanical harvesting activity. Thus, many endangered reefs can be protected and conserved with careful management (Breitberg, et al., 2015). Still, every increase in average ocean water temperature and acidity creates more barriers to achieving this success.

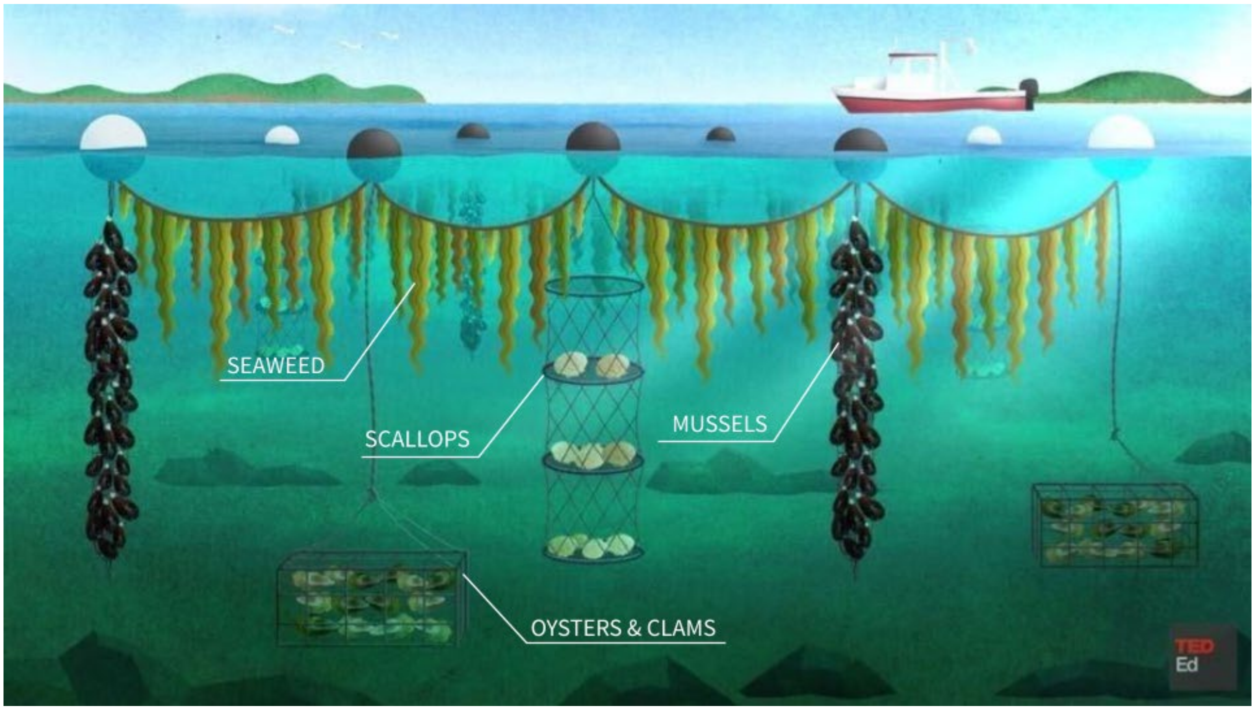

Figure D-2: Model of integrated seafood farm using seaweed suspended from buoys at the ocean's surface

Image from: Greenwave.org, used with permission

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APPENDIX E. Extent of Climate Change Impacts on the Formation of Hypoxic Zones

In the northern Gulf of Mexico, there is an area that experiences oxygen depletion, or hypoxia, every spring or summer at least since the 1950s, affecting resources and biogeochemical processes. The definition of hypoxia (sometimes called oxygen deficiency or deoxygenation) is less than 2 mg of dissolved oxygen per liter (mg/l), which equates to about 30% saturation.

Description of Harm

Depending on the organism's tolerance, the oxygen concentration at which they start experiencing adverse effects is different. A marine hypoxic zone is sometimes called “dead water,” “red water,” or “dead zone.” These areas are increasing globally, primarily driven by anthropogenic activities, farming activities, and nonpoint nutrient loads in watersheds.

One example supporting the above-stated definition of hypoxia is the amount of shrimp catch per unit effort that goes to zero in areas with oxygen less than 2 mg/liter, suggesting that these species move away when this number is surpassed (Leming & Stuntz, 1984).

The effect of oxygen loss in the ocean is a result of warming through a reduction in the saturation of oxygen in the ocean, as well as increased oxygen consumption by bacteria, increased ocean stratification and ventilation changes, and over-enrichment of nutrient loads (N and P) to the coastal zone (IPCC, 2019). One of the primary drivers in the formation of hypoxic zones in the northern Gulf of Mexico is the river inflow from the Mississippi River, which influences the physical stratification of water and nutrient-enriched primary production of phytoplankton in the surface waters. Figure E-1 shows the concentration of bottom-water hypoxic zones in the Gulf of Mexico in 2021.

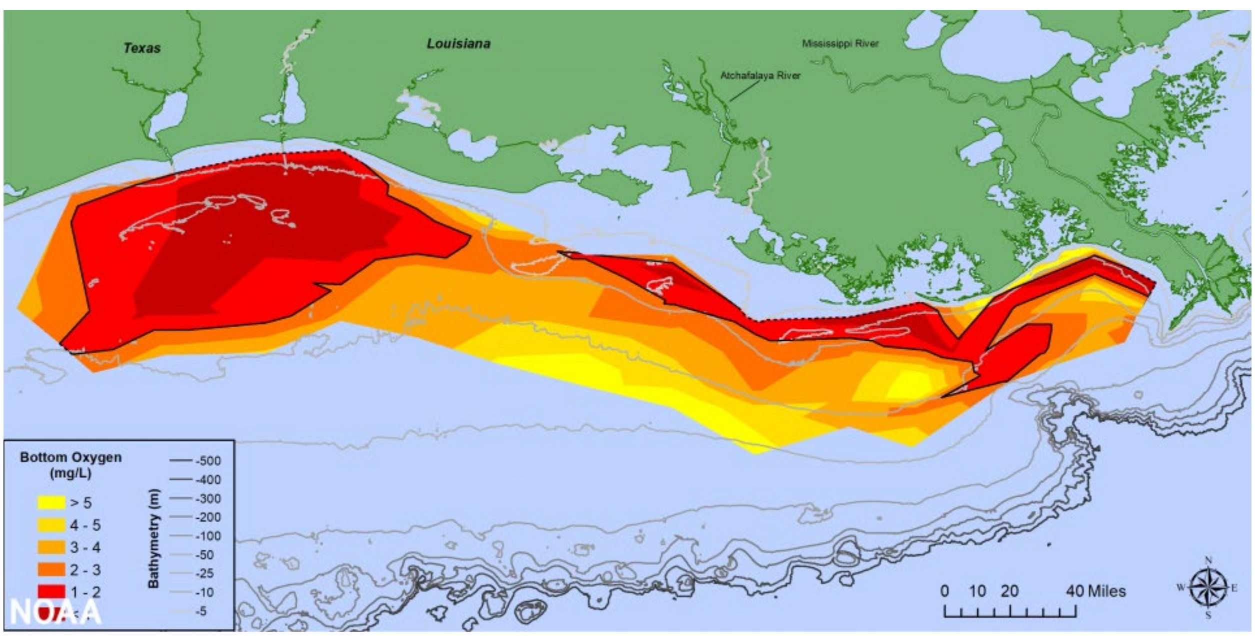

Figure E-1: Hypoxic zones in the Gulf of Mexico

The 2021 Gulf of Mexico's dead zone was approximately 6,334 square miles, equivalent to more than 4 million acres of habitat potentially unavailable to fish and bottom species. Image source: NOAA, 2021. Data source: LUMCON/LSU/NOAA.

River inflow creates a two-layered system with fresh (less saline) water on top and salty water on the bottom. The fresh water is less dense than the sea water and prevents the vertical mixing of oxygen into the deeper areas in the water column. River inflow also affects the proliferation of land-derived nutrients that reach coastal waters. Nutrients support algae production, which are preyed upon by zooplankton, whose fecal matter falls to the seafloor and senesces. Aerobic bacteria decompose this organic matter in the lower water column and seabed sediments. The respiration of these bacteria reduces the oxygen to well below 2mg/l or 1mg/l, sometimes even creating anoxic zones (i.e., no oxygen). This process is depicted in Figure E-2 below.

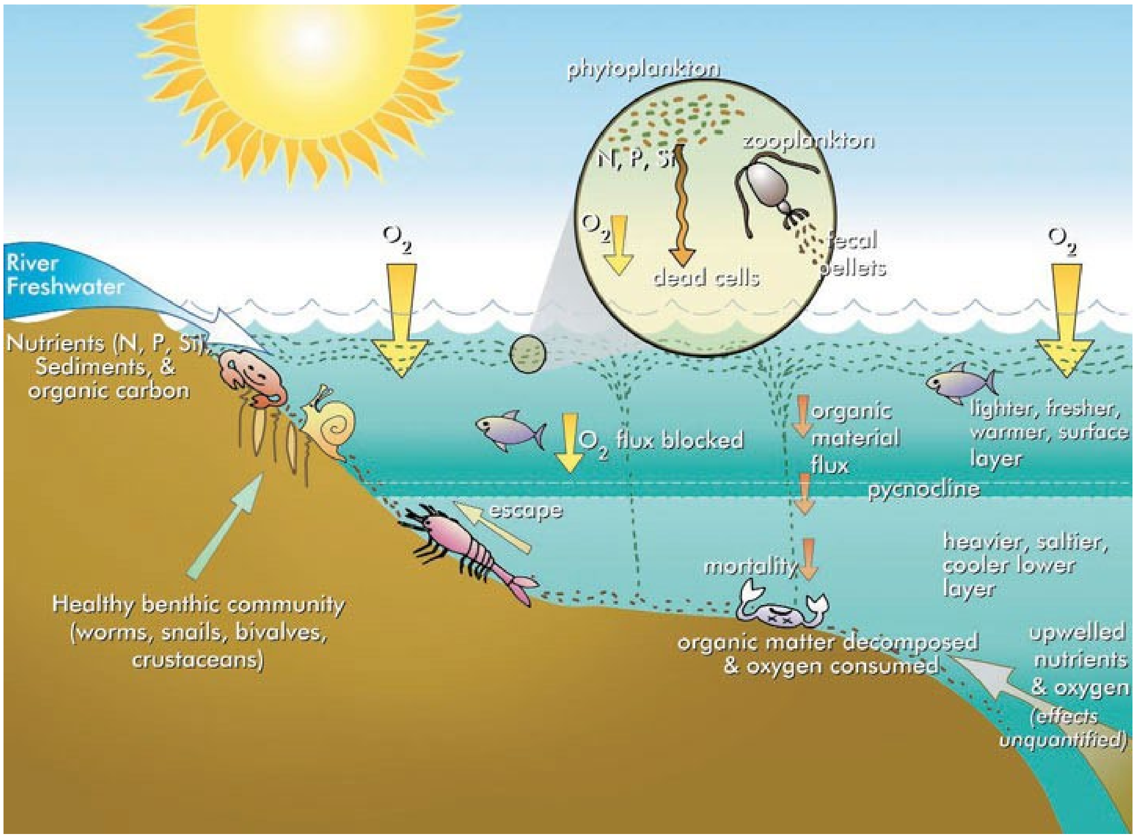

Figure E-2: The process of hypoxic zone formation

The hypoxic zone in the Gulf of Mexico forms every summer due to excess nutrients from the Mississippi/Atchafalaya River and seasonal stratification (layering) of waters in the Gulf. Image source: EPA, 2022.

The increase in anthropogenic inputs, including increased ocean warming from carbon dioxide emissions and nutrients in the river runoffs, has affected the worldwide coastal hypoxia in terms of duration, extent, and intensity, leading to significant damage to marine organisms' habitats. Further, the proliferation of aerobic and anaerobic microbes in low oxygen environments leads, to a small extent, to an additional generation of methane and nitrous oxide in hypoxic waters. Increased warming at the ocean's surface leads to more pronounced stratification of the water, and warmer water holds less oxygen. The inputs of nutrients, such as phosphorus and nitrogen, have been primarily linked to the increased presence of industrial and agricultural products delivered to the ocean waters. Figure E-3 shows the breakdown of phosphorus and nitrogen input sources.

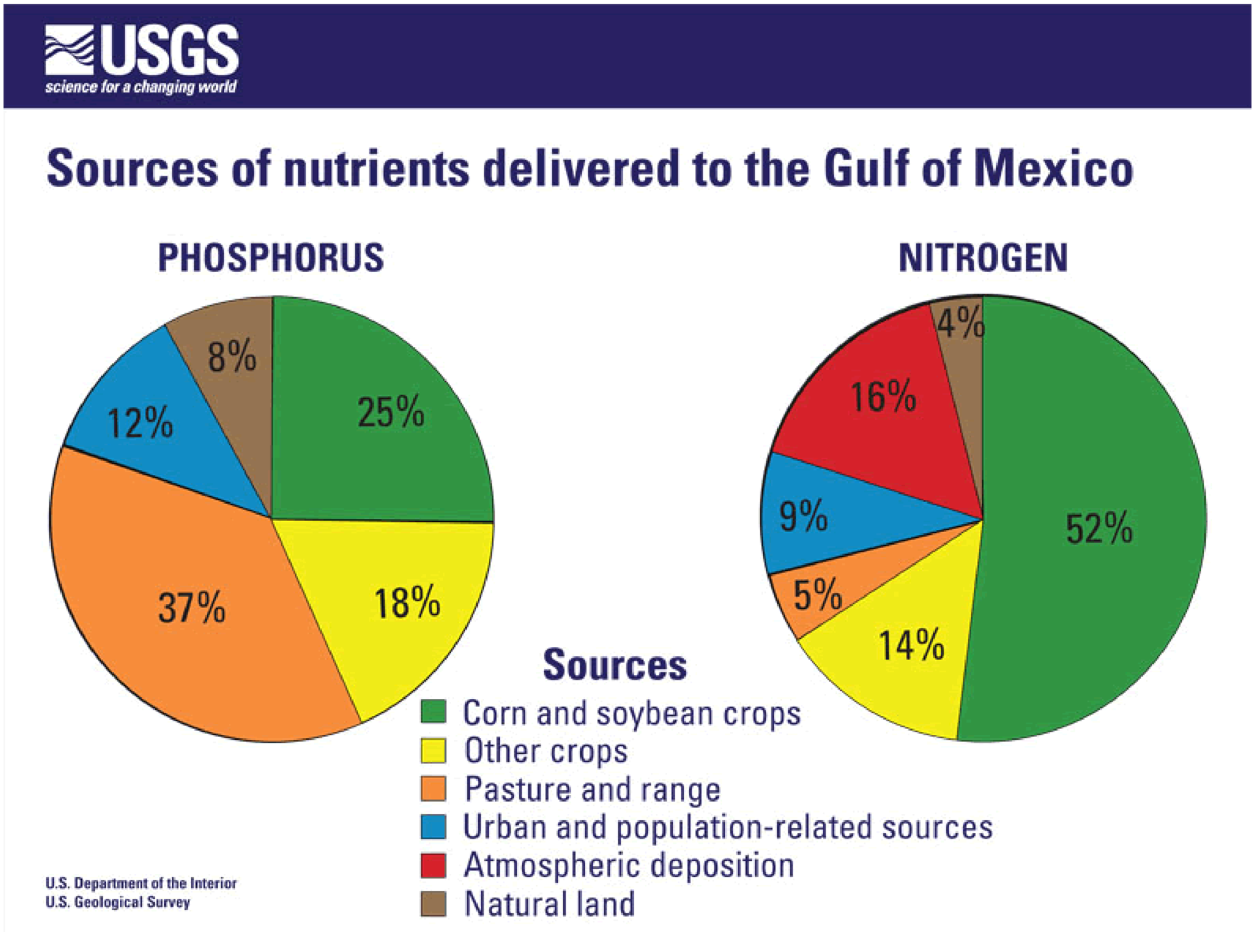

Figure E-3: Proportions of sources of phosphorus and nitrogen in the Gulf of Mexico in 2008
Agricultural sources contribute more than 70 percent of the nitrogen and phosphorus delivered to the Gulf of Mexico. Image source: USGS, 2014, with data from Alexander et al., 2008.

Low oxygen areas can redistribute via currents and wind directions. The low oxygen bottom waters may move closer to shore, or farther offshore. At times, winds from the north push surface waters offshore and allow bottom waters to move inshore, generating low oxygen along the beach, which contributes to conditions called a "jubilee," where stressed fish move close to shore or onto the beach (Rabalais et al. 2002).

Mitigation and Prevention of Marine Hypoxic Zones

As inputs from industrial and agricultural activities are one of the primary anthropogenic drivers of coastal ocean hypoxia, more efficient food consumption and farming practices can reduce nutrient inputs. Additionally, a slowdown in greenhouse gas emissions that leads to warming in the ocean water is likely to decrease the stratification in the ocean water column.

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APPENDIX F. Climate Change Effects on Marine Life and Fisheries

Climate change impacts fisheries, including those of regional commercial value. This effect is evident from studies and observations of how warming has impacted multiple species by altering where they can thrive, leading to shifts towards cooler waters, and thus affecting reproduction and survival.

Description of Harm

In addition to temperature-related changes in ocean circulation patterns, atmospheric carbon-dioxide-driven ocean acidification, resulting in deoxygenation and general ocean warming, is altering fish habitat. As reported in a journal article in Science, many North American fisheries have tracked toward cooler waters (Pinsky, et al., 2013), as shown in Figure F-1. Although water on the West Coast was cooler to the south at the time (2010–2012), current tracking patterns on both coasts are to cooler waters in the north. Similar patterns have been observed for plants, insects, and other animals with latitude and elevation changes.

As an example, in the northwest Atlantic, species such as squid or tuna were able to move considerable distances in a short time to track water temperature changes. However, since lobsters cannot move quickly, their situation is more complex; the Gulf of Maine has become more conducive to their production (more larvae). The populations increased in the Gulf of Maine while populations decreased in the warmer southern New England waters. According to modeling, looking forward and assuming better fisheries management, the southern population may return or improve slightly under modest warming assumptions but decrease with more extreme warming. In the Gulf of Maine, models show modest population declines for the modest warming scenario and a decrease of 75% of current (approximately 400 to 100) for extreme warming scenarios by 2050 (Mills, et al., 2013; LeBris, et al., 2018).

New England area cod is a unique situation and second example of environmental harm. Between about 2000 and 2013, the spawning stock biomass declined by about 75% and has recovered little in the following 7 years. Studies suggest that increasing ocean water temperatures in the Gulf of Maine, which has experienced a more rapid rate of warming compared to the global ocean temperature increases, reduced the number of new cod produced by spawning females (Pershing, et al., 2018).

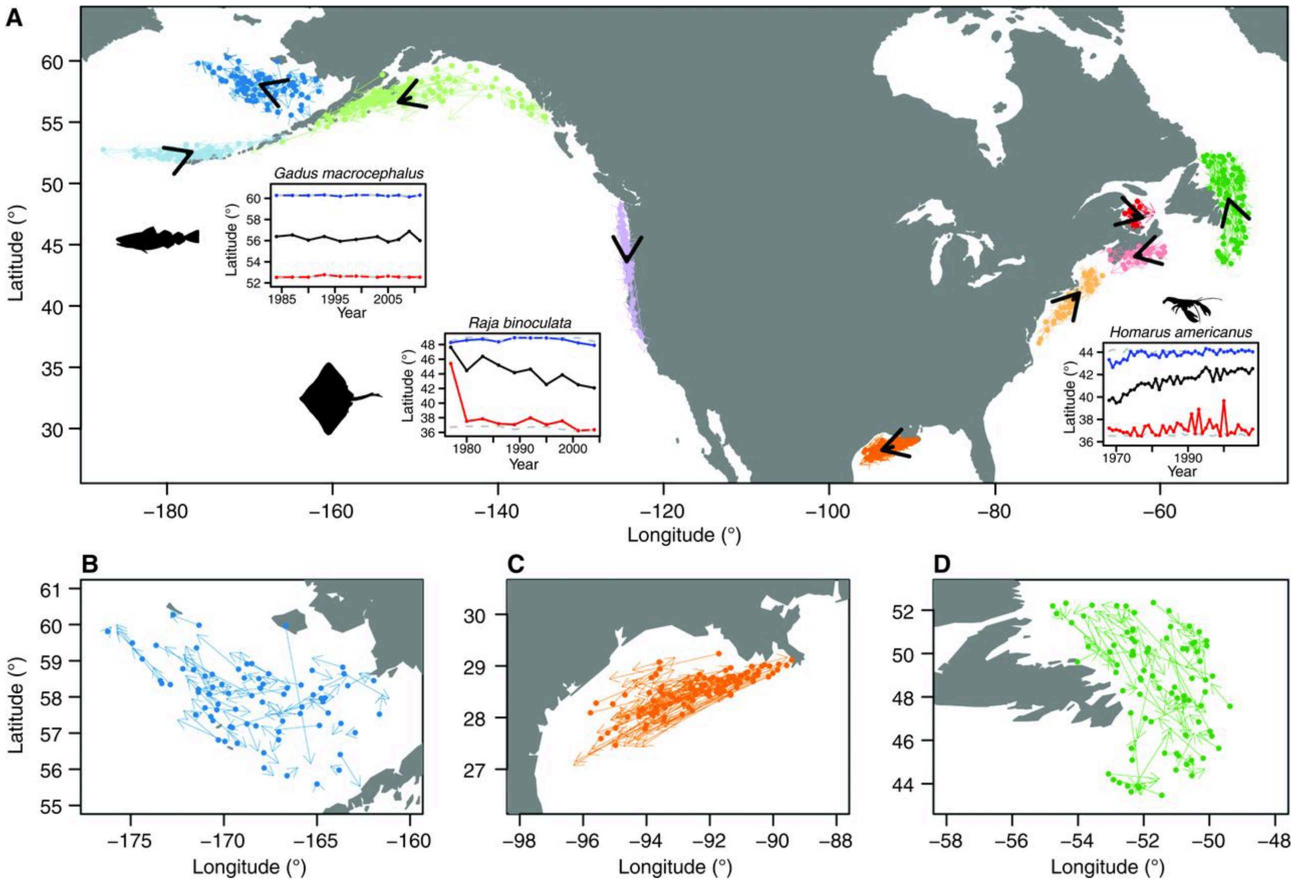


Figure F-1: North American fisheries' migration patterns

The large black arrows in (A) show the average latitudinal and longitudinal movements of each region, and the colors with thin arrows show shifts in each taxon in the regions. Inserted graphs show the mean (black), minimum (red), and maximum (blue) latitudes of detection for Pacific cod in the Gulf of Alaska, big skate on the U.S. West Coast, and American lobster in the Northeast. On the bottom of each, gray dashed lines indicate the range of surveyed latitudes. Additionally (B), (C), and (D) show detailed shifts in the Eastern Bering Sea, the Gulf of Mexico, and Newfoundland, respectively. Figure from Pinsky, et al., 2013. Reprinted with permission from the American Association for the Advancement of Science.

At the same time, the goal of improved fisheries management to offset decades of overfishing (biomass that produces the maximum sustainable yield) had been set at 55,000 metric tons, as shown by the dotted line in Figure F-2 (Pershing, et al., 2015).[10] However, this goal did not consider warming and other changes in the ocean ecosystem. When these factors are considered, feasible adjustments are shown in blue using temperatures from observations and global climate model (GCM) projections. Annual harvests consistent with this improved fisheries management strategy show a recovery could be achieved around 2028 for GCM mean temperature change. Earlier and later recovery dates and higher and lower population levels are expected if the temperature changes are less or more. The outcome for the cod industry is yet to be determined.

[10] Overfishing in the US has declined in the last 40 years (since the Magnuson-Stevens Fishery Conservation and Management Act established our modern fisheries management system). However, this is not true in New England, where many stocks are still considered overfished. This difference is likely a combination of a long history of overfishing (oldest fisheries in the country) and the intensity of the recent warming.

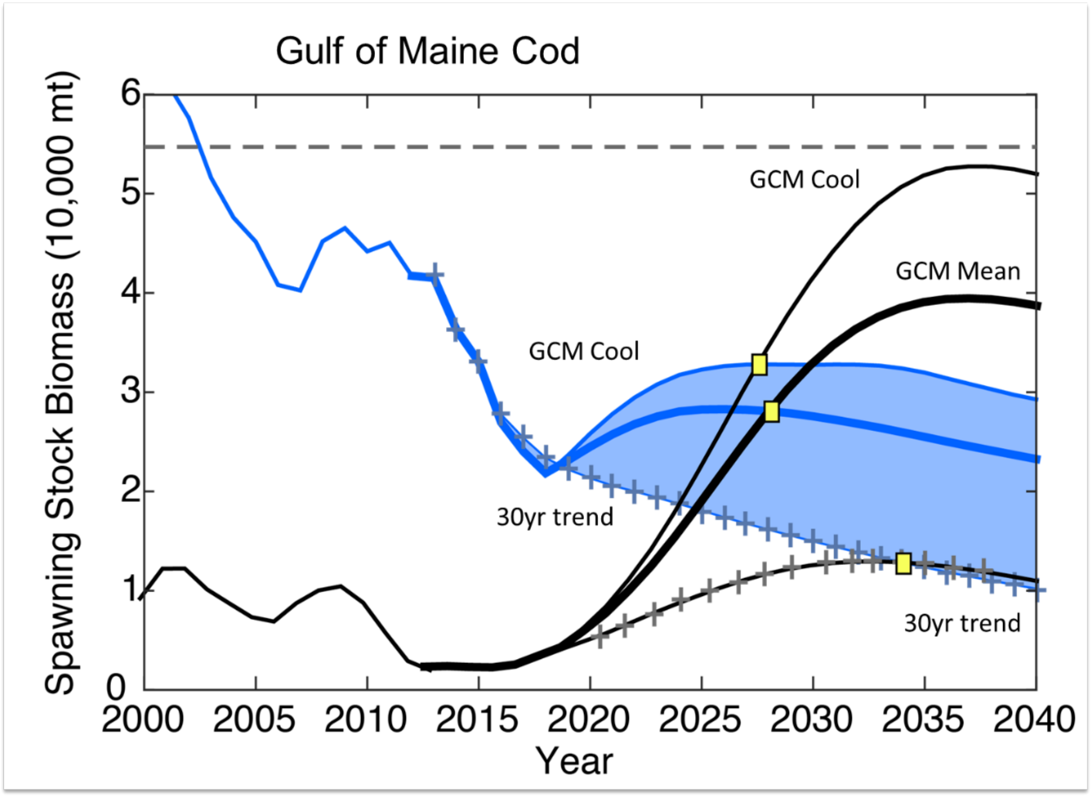
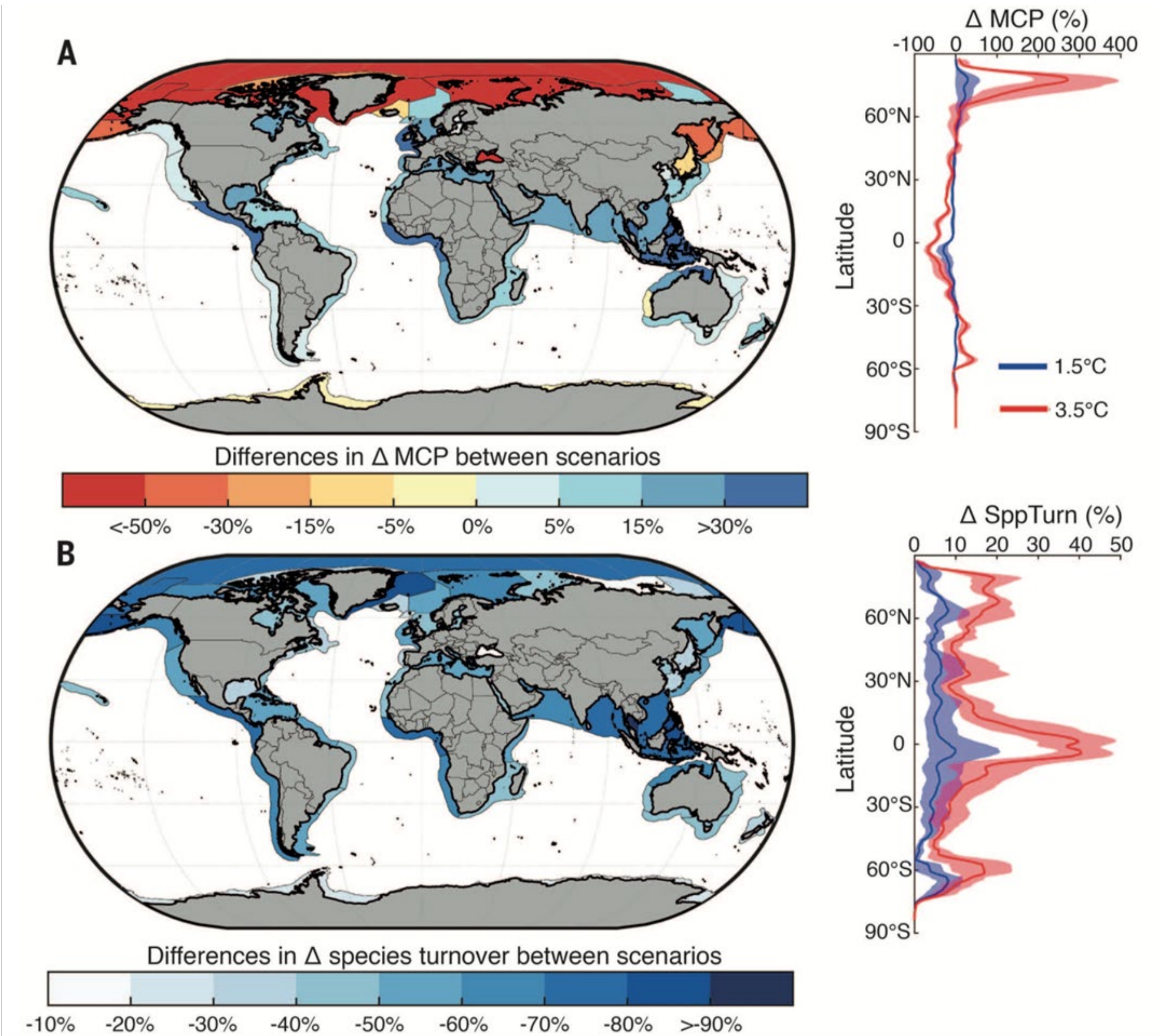


Figure F-2: Maine cod spawning forecast through 2040

Population growing from the 2013 biomass (black curves) was simulated without fishing under three temperature scenarios: a cool scenario (solid line), a warm scenario (heavy line) represented by the climate model ensemble mean, and a hot scenario (plus signs) with warming at the 0.07° year^{-1} rate observed in the summer in the Gulf of Maine since 1982. The yellow boxes indicate when the stock has reached its target biomass (biomass producing the maximum sustainable yield). From Pershing, et al., 2015. Reprinted with permission from the American Association for the Advancement of Science.

Another study (Cheung, et al., 2016) determined maximum catch potential and average species turnover (SppTurn) for different warming levels. As shown in Figure F-3, except for Artic areas, the outcomes are consistently better for 1.5° C change than 3.5° C. There is a clear benefit to reducing emissions and warming.



Cheung et al.(2016) Science. DOI: 10.1126/science.aag2331

Figure F-3: Differences in maximum catch potential (A) and species turnover (B) projections for different levels of warming due to climate change

Panels on the right represent turnover percent by latitude (solid line, bands show maximum and minimum projections) over the large marine ecosystems under the 3.5°C (red) and 1.5°C (blue) warming scenarios. From Cheung, et al. 2016. Reprinted with permission from the American Association for the Advancement of Science.

Extreme Heat Events May Correspond with Whale Entanglement Incidents

The National Oceanographic and Atmospheric Administration compiled large whale entanglement incidents, showing a total of 105 documented entanglement incidents in 2018, of which 92 cases involved live animals and 13 cases involved animals that were dead at the time of reporting (NOAA, 2020). These entanglement incidents are cases when large whales become wrapped in the ropes used in lobster, crab, and gill net fisheries. As shown in Figure F-4, many years with increased whale entanglements occur during extremely warm years (indicated by the thermometer symbol) on both the East and West Coasts. Entanglements are interactions that can occur between where and when whales appear in an area and where, when, and how intense the fishing activity is. It is not clear the degree to which this apparent relationship between entanglements and temperature is driven by changes in whale behavior or changes in the fisheries.

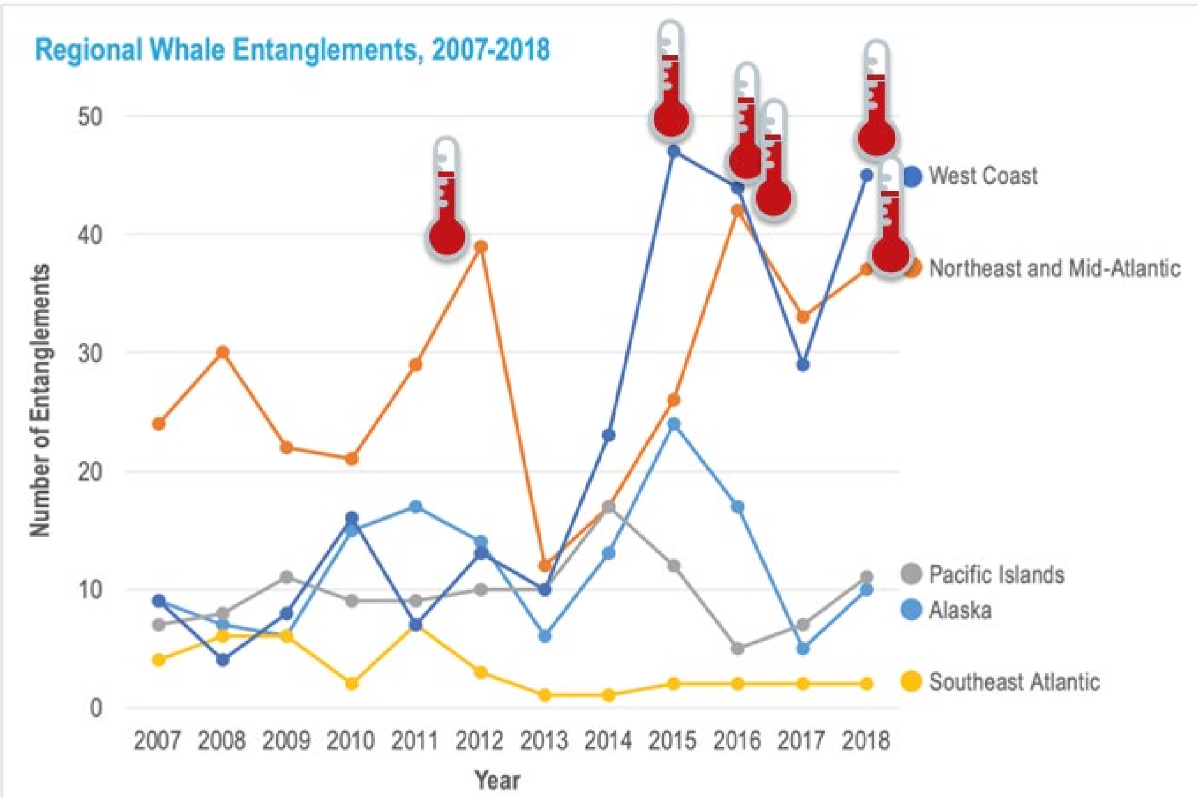


Figure F-4: Numbers of reported regional annual whale entanglements

Added thermometer symbols show years with reported high temperature anomalies. A trend of these anomalies is shown in GMRI, 2022. Figure source from NOAA, 2020.

Examples of reported high temperatures and their consequences for individual years are discussed further in individual studies for the respective years:

- 2012 Northwestern Atlantic: Mills, et al., 2013 reported a sea surface temperature in 2012 of 2°C warmer than the 1982–2011 average, which may be linked to the 2012 heat wave in the Gulf of Maine.
- 2016 Northwestern Atlantic: Pershing, et al., 2018 reported that the temperatures at the start of 2016 had exceeded the record conditions set in 2012 in the Gulf of Maine, and overall, 2016 was documented as the second warmest year in the Gulf of Maine, with the interpolated sea surface temperature recorded as less than 0.5°C below the 2012 levels.
- 2019–2020 Northeast Pacific: Weber et al., 2021 reported marine heatwaves in the Northeast Pacific beginning in the summer of 2019 and summer of 2020, linked to sea surface temperature

anomalies at times exceeding 1°C and coincidental relatively high atmospheric pressure and reduced wind-mixing in the two summers.

Although the noted literature does not conduct rigorous study of correlation of high temperature with an increased number of entanglements, the authors of this report hope that this observation should prompt further research into the area.

Mitigating Measure

For fisheries, the best mitigation is to reduce emissions and resultant warming to the greatest extent possible. This effort would reduce economic losses to fisheries and simplify management decisions, making it easier to achieve national goals around sustainable fisheries and ecosystem health.

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