Testimony of

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Chairman Markey, Ranking Member Sensenbrenner, and Members of the Committee, thank you for this opportunity to testify today regarding climate science. I am the Alexander Agassiz Professor of Biological Oceanography, at Harvard University, where I teach courses on ocean and climate science. The ocean covers seventy percent of the Earth's surface and it is an integral part of Earth's climate system. I will attempt to address the four questions raised in the Chairman's letter of invitation through the lens of ocean science

For the past three decades my research has delved into many aspects of climate science. In addition, I have been involved in the planning and implementation of several climate science research programs and assessments of climate science. From 1997 to 2001, I co-chaired Working Group II of the Intergovernmental Panel on Climate Change (IPCC), which had responsibilities for assessing impacts of and vulnerabilities to global climate change in the Third IPCC Assessment. I was also an author on the 2005 Arctic Climate Impact Assessment, the 2007 Northeast Climate Impact Assessment, and the 2009 U.S. government report on Global Climate Change Impacts in the United States. I am Past President of the American Association for the Advancement of Science, and currently the Chair of the Board of the Union of Concerned Scientists.

My research has taken me to all the oceans to study how plankton production is affected by physical processes, in order to better understand the ocean's carbon and nitrogen cycles. I have been particularly interested in regions where seasonal climate processes result in strong mixing events. This includes the high North Atlantic, the Southern Ocean surrounding Antarctica, and the monsoonal system in the western Indian Ocean. I have also studied areas where episodic climate cycles strongly affect ocean processes, such the upwelling regions off the coasts of California, Peru, and Ecuador, and the central Pacific Ocean each of which is influenced by the El Niño – Southern Oscillation cycle. At times I have also conducted research in areas that show less seasonal and interannual variability, such the Sargasso Sea and the Caribbean Sea.

The atmosphere, land and surface ocean are heated by energy from the sun. The amount of energy reaching the surface at the Equator is greater than at the Poles, and circulation in both the atmosphere and ocean transport heat from the warmer low latitudes to the cooler high latitudes. But, surface ocean temperature is also strongly influenced by mixing, partly driven by winds, that brings deeper, cooler, water to the surface, a process known as upwelling. This is what causes surface waters to be cooler in the western Indian Ocean during the SW monsoon, along the Equator in the Eastern Pacific Ocean, and in certain regions along the western sides of continents, such as the coasts of California and Oregon during spring. Documenting significant change in surface ocean temperatures requires full knowledge of this natural variability

I. Observed Changes in Ocean Climate and Chemistry

A. Ocean Temperature

In the early 1980s land surface data in some regions were beginning to indicate unusual warming. A trend in warming or cooling of the surface ocean would, however, be much harder to detect due to the aforementioned effects of winds and Earth's rotational forces on ocean currents and vertical mixing.

In 1986, I took a leave from Harvard to start a new scientific journal and a new international research program. I had the good fortune to be hosted during that year at the National Center for Atmospheric Research in Boulder, CO. I vividly recall a day when a colleague walked into my office with a new graph showing surface ocean temperature over the past several decades, and said, "Jim, it looks like the oceans are warming". It was during this same year that Antarctic ice core data were first published showing that the cycle of atmospheric CO_2 content varies in concert with temperature over the hundred thousand year glacial – interglacial cycle. Books on the marine carbon cycle had to be rewritten. We could never again look at climate, with its manifestations in atmospheric and ocean physics, and the ocean carbon cycle, as being independent in any significant way. They are inextricably linked, and each is highly sensitive to perturbations in the other.

So, while it had long been known that variation on seasonal and interannual time scales plays out in upper-ocean physical and biogeochemical processes, and that these cycles are highly coupled, it has only been in the past few decades that we have fully appreciated the coupling of these processes on time scales of hundreds of thousands of years. From this fact flows the realization that a significant change in atmospheric temperature or greenhouse gas concentrations can cause reverberations throughout the entire climate system.

Just how much change in the ocean would a scientist expect to see over the course of a career in ocean science? Until a few decades ago, the guess would have been – not very much. The oceans are vast, with an average depth of more than 12,000 feet. It takes about a thousand years for ocean currents to fully mix the oceans, and because of strong density gradients most of the deep ocean is influenced only very slowly by what happens in the surface ocean or the atmosphere. But more significantly, we had decades, and in some cases more than a century, of data indicating relative constancy in deep ocean conditions. If you told a skilled hydrographer the depth, salt content, and temperature of a seawater sample, the hydrographer could tell you where the sample was collected. Relationships between depth, salt content, and temperature that had been established over many decades defined a climatology for the ocean. This climatology is now changing more rapidly than could have been imagined when I began my career as an oceanographer.

Levitus et al. (2000) was one of the first to assemble a data set documenting the global extent of changes in ocean temperature to depths of 2000 feet across all ocean basins. We now know from ocean temperature data that since the 1960s the ocean has absorbed more than 90% of the heat trapped by greenhouse gasses that have accumulated in Earth's atmosphere due to human activity over the past century. Confidence in these findings is further validated as instrumented ocean buoys profile the ocean to depths of 6000 feet every ten days, and report their data via satellite to shore stations. Fig. 1 shows the locations of the 3255 Argo floats deployed in February 2010, and the shared international commitment to this effort.

B. Sea level rise

As heat from a warming atmosphere is transferred to the ocean, ocean volume increases and sea level rises. A warming atmosphere also causes land ice to melt, and if this water reaches the ocean, it too contributes to sea level rise. On this subject we have learned a great deal in the last decade as changes in ice and sea level have sped up.

In 2001, the IPCC could not identify any body of science that pointed to the likelihood of a large reduction in Greenland ice during the present century (Anisimov et al. 2001). Since then, several outlet glaciers along the perimeter of Greenland have begun retreating and thinning at unusual rates. The increasing frequency of "icequakes" correlated with glacier movement indicates that an acceleration of ice loss is now under way (Ekström et al. 2006). Satellite studies demonstrate that extensive thinning has expanded to even the highest latitudes on the northwest perimeter of Greenland (Pritchard et al. 2009). Records of numbers of summer melting days on the surface of the Greenland ice sheet continue to be broken. The trend in the total area of melt during 1979– 2008 is an increase of approximately 6000 square miles per year. To put the ice on Greenland in perspective, it is equivalent to a layer of ice 1000 ft thick extending across the contiguous United States.

In 2001, the IPCC also reported that "[w]ithin present uncertainties, observations and models are both consistent with a lack of significant acceleration of sea level rise during the 20th century" (IPCC 2001). But a new study by Rahmstorf *et al.* (2007) has now demonstrated that sea-level rise has accelerated since 1990. This observed rate of increase is at the upper end of what was projected from the early IPCC scenarios (Fig. 2).

The more recent 2007 IPCC report projected 12 – 24 inches of sea-level rise by 2100. These estimates do not preclude higher rates of rise due to increased rates of ice loss on Greenland and Antarctica. Although the IPCC authors were aware of publications relating to recent changes in Greenland and Antarctic ice, they lacked confidence that they could extrapolate meaningfully from these data to future sea-level rise. Rahmstorf (2007) used a semi-empirical relationship from 20th-century temperature and sea-level changes to project future sea-level rise from the IPCC scenarios for warming and derived an estimate of sea-level rise of about 2 – 4.5 feet for 2100 relative to the 1990 level. Using current outlet glacier discharge rates for Greenland to improve on the IPCC 2007 projections, Pfeffer *et al.* (2008) estimated a sea level rise between 2.5 and 6.5 feet. The practical consequence of these studies is that coastal planners should plan for sea level rise that could reach 3 or more feet this century. A summary graphic showing IPCC (2007) and more recent sea level projections is shown in Fig. 3.

C. Ocean Chemistry

When Svante Arrhenius made calculations in the 1890s regarding the influence of fossil fuel combustion on climate he included estimates for the fraction of the released CO_2 that would be absorbed by the oceans. But it was a century later, in the 1990s, that scientists had the first inventory of CO_2 in the oceans, and could *begin* to document changes in ocean chemistry. We now know that the oceans have absorbed about a third of the CO_2 released with the combustion of fossil fuel since the industrial revolution. When CO_2 is added to water it forms carbonic acid. However, an excess of carbonate and bicarbonate ions in seawater help to buffer ocean waters against large changes in the acid/base balance, and historically have tended to keep the seawater basic with a pH (the measure of acid/base balance) of about 8.2. (The neutral point of this scale is 7, with < 7 being acidic and >7 being basic.) Carbonate buffering in the ocean provides favorable conditions for the formation and maintenance of calcium carbonate skeletal material, common in plant and animal plankton, mollusks, corals, etc. Under acid conditions calcium carbonate shells dissolve. Carbonate buffering in the ocean helps to explain why organisms with calcium carbonate shells are far more successful in marine than in freshwater environments.

As theory and laboratory experiments would predict, trends of declining ocean pH are now evident, and are certain to continue as CO_2 rises. Organisms in the ocean evolved over hundreds of thousands and millions of years, and CO_2 in the atmosphere is now higher than it has likely been any time in the last several million years. Thus in the genome of today's marine species there is no recent "memory" of conditions similar to those that these organisms are now experiencing.

An important report on this topic was released by The Royal Society in 2005, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*. More than a dozen models of the ocean carbon cycle were used to examine the effects of future emissions of carbon dioxide on marine organisms. The high latitude oceans around Antarctica and in the north, especially the subarctic Pacific, are areas where this effect will occur sooner for organisms that make shells of the aragonite mineral form of calcium carbonate. Early effects, such as thin and fragile shells in these high-latitude ecosystems will likely be evident within decades (Orr et al., 2005). Small aragonite shelled mollusks in the plankton, known as Pteropods, are of particular concern, as they are an important component of the diet of salmon.

II. Evidence for Attribution to Human Activities

Barnett et al. (2005) demonstrated that the observed changes in ocean heat-content since the 1960s are consistent with what would be expected from the accumulation of greenhouse gases from human activities, and that these patterns in warming cannot be solely explained by natural cycles, solar cycles or volcanic activity. Vast numbers of studies have corroborated these analyses, and there is no credible challenge to their validity.

Multiple paths of research provide consistent and irrefutable evidence that the CO_2 increase in the atmosphere since the early 1800s is arising from human activities. Initially land use caused much of the change - forest clearing and soil tilling practices facilitate the conversion of living and dead organic material to CO_2, and its release to the atmosphere. With a growing population and its needs for energy for heating, manufacturing, and lighting and increasing dependence on the internal combustion engine, fossil fuel combustion became the dominant, human-caused source of CO_2 release to the atmosphere. Stable and radioactive isotopes of carbon provide unambiguous evidence that the CO_2 accumulating in the atmosphere is due to human activities.

III. Impacts of Ocean Warming

A. Species Distributions

Many marine species, plant and animal plankton, migratory fish, bottom fish, shell fish, etc. show high sensitivity to temperature in their distributions. Species that depend on coldwater or predicable temperatures will be greatly affected. For species that live primarily on the bottom, or are dependent on resources that do, the cool bottom waters can be critical in defining a suitable habitat. Some shoals, such as Georges Bank, just east of Cape Cod provide a unique habitat for certain species – such as the Atlantic cod. The depth of the Bank and the ocean currents that swirl around it provide an environment that nourishes young cod very successfully. But the success and survival rates for cod are highly sensitive to temperature. Atlantic cod populations are generally not found where bottom temperatures exceed 54°F.

Moreover, where average annual bottom temperatures are above 47°F there is diminished and survival of young fish. Over the past few decades the cod populations have moved northward as ocean waters have warmed. Projections of warming for high global warming emissions indicate that both the 47°F and the 54°F thresholds in the vicinity of Georges Bank will be met or exceeded in this century.

The American lobster, another commercially important species in New England waters, is also known to be sensitive to temperature. It is especially susceptible to disease at the southern (higher temperature) extent of its range. With warming the center of production for lobster would likely move further north, in the Gulf of Maine and waters off the Maritime Provinces, but overall its stock may not decline significantly (Frumhoff et al. 2007). These are but two examples of what can be expected with continued warming of waters all along the coasts of the US.

B. Sea Level Rise

A sea-level rise of 2.5 to 6.5 feet during this century would be of enormous consequence for lives, livelihoods, and property in coastal regions across the globe. Major cities, large portions of nations, indeed entire island nations will become uninhabitable. With additional tropical storm intensity, damage from any rise in sea level becomes intensified.

Changes in sea level experienced at a particular location along the coast depend not only on the increase in the global average sea level, but also on changes in regional currents and winds, proximity to the mass of melting ice sheets, and on the vertical movements of the land due to geological processes. Thus regional variations in relative sea-level rise are to be expected in the future. For example, assuming historical geological movement continues, a 2-foot rise in global sea level by the end of this century would result in a relative sea-level rise of 2.3 feet at New York City, 2.9 feet at Hampton Roads, Virginia, 3.5 feet at Galveston, Texas, and 1 foot at Neah Bay in Washington state.(Karl et al. 2009)

As population continues to increase in coastal regions at a greater rate than the overall population increase, and with an expectation that this trend will continue, the combined effects of future climate change and socioeconomic development means that coastal storm damage will be that much greater for coastal populations and infrastructure. (Karl et al. 2009)

A significant fraction of America's energy infrastructure is located near the coasts, from power plants, to oil refineries, to facilities that receive oil and gas deliveries. One-third of the national refining and processing capacity lies on coastal plains adjacent to the Gulf of Mexico. Several thousand offshore drilling platforms, dozens of refineries, and thousands of miles of pipelines are vulnerable to damage and disruption due to sea-level rise and the high winds and storm surge associated with hurricanes and other tropical storms. In the Gulf Coast area alone, an estimated 2,400 miles of major roadway and 246 miles of freight rail lines are at risk of permanent flooding within 50 to 100 years as global warming and land subsidence (sinking). Seven of the 10 largest ports (by tons of traffic) are located on the Gulf Coast.(Karl et al. 2009)

A summary statement in the U.S Climate Change Research Program (2009) report on sea level rise describes well the urgency of new work on this topic:
The prospect of accelerated sea-level rise and increased vulnerability in coastal regions underscores the immediate need for improving our scientific understanding of and ability to predict the effects of sea-level rise on natural systems and society. These actions, combined with development of decision support tools for taking adaptive actions and an effective public education program, can lessen the economic and environmental impacts of sea level rise.

C. Declining Ocean pH aka Ocean Acidification

A report released by NOAA in 2008, points to concerns about ecosystem implications for many species, notably those of economic importance with commercial and recreational harvests of fish and shellfish and associated tourism. There may also be ecosystem implications of a declining ocean pH for animals that do not have shells. From laboratory studies it is known that many physiological processes, such as the oxygen binding capacity in squid blood, are to sensitive to changes in pH. We have no idea as to how far-reaching the effects of reduced pH in the ocean might be on these processes. But given that the CO_2 captured by the ocean today will be retained for thousands of years, this is not an experiment that we should welcome on our planet. There is no known practical way to reverse the current trend towards lower ocean pH. But we can hope to slow and ultimately arrest this trend with substantial reductions in CO_2 emissions before the consequences for important marine species become grave.

IV. Public Understanding of Climate Change

Scientific knowledge is always evolving. Science progresses because scientists constantly question every aspect of scientific understanding. New findings, seemingly credible, and perspectives that prevailed for decades are sometimes proven to be wrong. The process of science is one of always questioning and challenging both the new and the well-established findings.

A scientist is always asking these questions: Does evidence adequately support the prevailing view as to how a particular process works? Is there a contradictory body of evidence? Is there an alternative explanation that is also, or perhaps even more, consistent with the highest quality evidence?

All good scientists ask these questions about everything they have either been taught or have discovered themselves. We train our students to go beyond what we can teach them – to use newer methods for gathering evidence, to subject their data to ever more sophisticated analyses, to always keep their mind open to other views in order to advance, in the most genuine sense of the word, the science. The very best students will discover errors and inadequacies in what their mentors thought to be the best understanding of the natural world.

There are many examples of dramatic shifts in prevailing views in science. In my scientific lifetime examples that come readily to mind are the discovery of plate tectonics in the 1960s, the linking of an asteroid impact to extinctions at the Cretaceous–Tertiary boundary (65 million years ago) in the early 1980s, and the role of chloroflurocarbons in the depletion of ozone in the Antarctic stratosphere in the late 1980s. In each of these cases even though a consensus among experts emerged within a few years of the finding of key evidence, it is noteworthy that a small number of experts, some very senior and distinguished, remained unconvinced for the rest of their lives that the new mainstream view was correct.

For many of us in ocean science the compelling evidence for human-caused climate change came with the observations of deep ocean warming, the ice core data linking Earth's past temperature and atmospheric greenhouse gas content, the acceleration in sea level rise, the abrupt melting of land ice and ice shelves that had been in place for many thousands of years, and an ocean-wide decline in pH. All of these are linked, and can only be consistently explained by an unusual rate of greenhouse gas release to the atmosphere.

The idea that greenhouse gases from fossil fuel combustion affect climate, which was studied by Arrhenius a century ago and developed further by Calendar a half century later, is correct. Interestingly, Arrhenius did not anticipate the explosive growth in human population and our increasing demands for energy - he thought that it would take 3 millennia rather than a just a century to double the pre-industrial atmospheric CO_2 concentration.

State of the art fully coupled climate models can now simulate the natural processes that affect climate (solar cycles, volcanoes, and internal cycles such as the El Niño –

Southern Oscillation) and the human-caused processes that affect climate (greenhouse gases and aerosols) to show the relative importance of each of these components in the climate of the past and present. Using assumptions about trends in population, type of energy used, etc. these same models can make projections about future climate. One very clear finding from these studies is that one of the largest uncertainties about future climate relates to the choices that we and our children will make regarding energy use. The more energy we use and the more dependent we are on CO_2-emitting sources of energy, the more climate will change.

In the public media there is a lot of misinformation and, unfortunately even disinformation, about climate. Many myths about climate change are exposed for what they are in publications like the Royal Society's 2007 *Climate Controversies, a Simple Guide*. Most National Academies and professional societies have issued statements about climate science. The American Meteorological Society, for example, in a 2007 two-page statement says:

Despite the uncertainties noted above, there is adequate evidence from observations and interpretations of climate simulations to conclude that the atmosphere, ocean, and land surface are warming; that humans have significantly contributed to this change; and that further climate change will continue to have important impacts on human societies, on economies, on ecosystems, and on wildlife through the 21st century and beyond.

Last October scientific organizations in the United States issued a common statement that says in part:

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver…. If we are to avoid the most severe impacts of climate change, emissions of greenhouse gases must be dramatically reduced.
(Appendix 1)

To this point in my testimony I have dealt with climate science - now I offer an opinion. Climate scientists have a responsibility to use every opportunity we have to share our understanding of climate science with the public and with policy makers across the land. Some of us have such opportunities as professional educators, and all of us need to be receptive to invitations to talk to non-scientists in business organizations, religious groups, etc. This is what brings me here today. Thank you for this opportunity.

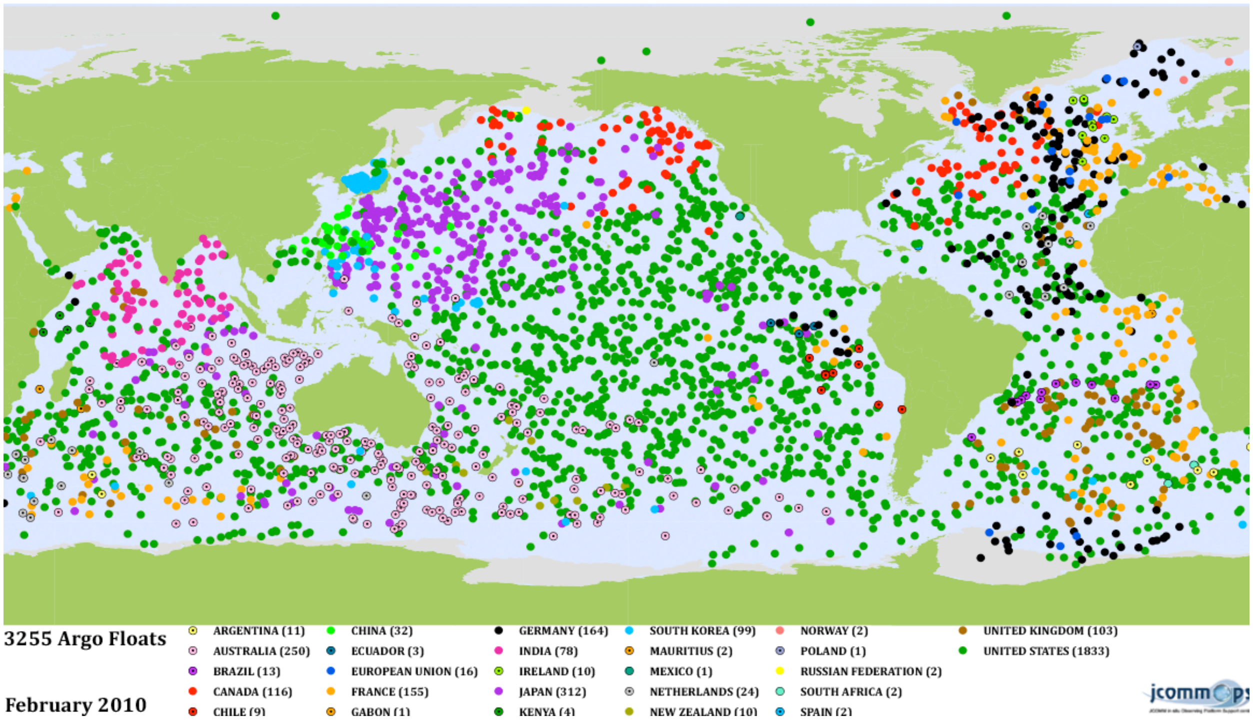

Fig. 1. The global distribution of Argo floats in February 2010. They profile the ocean to 6000 ft. every ten days and relay their data to shore stations. (http://www.argo.ucsd.edu/)

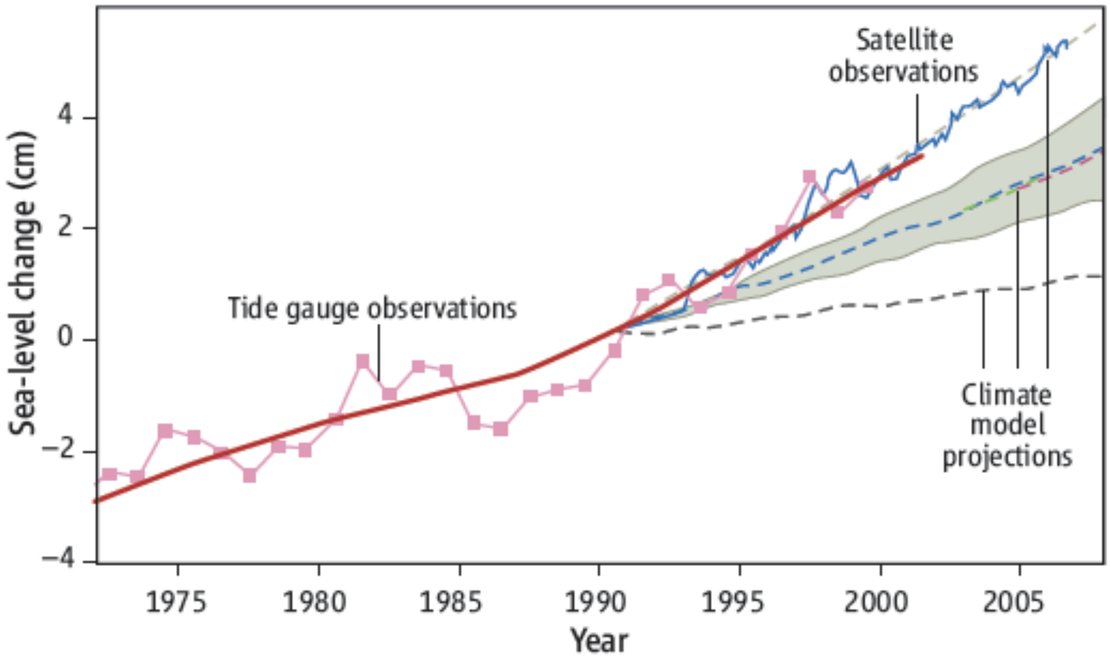

Fig. 2. Sea level Rise. Sea-level data based on tide gauges (annual, red) and satellite altimeter measurements (3-month data spacing, blue, up to mid-2006), and their trends. McCarthy (2009, adapted from Pfeffer et al. 2008)

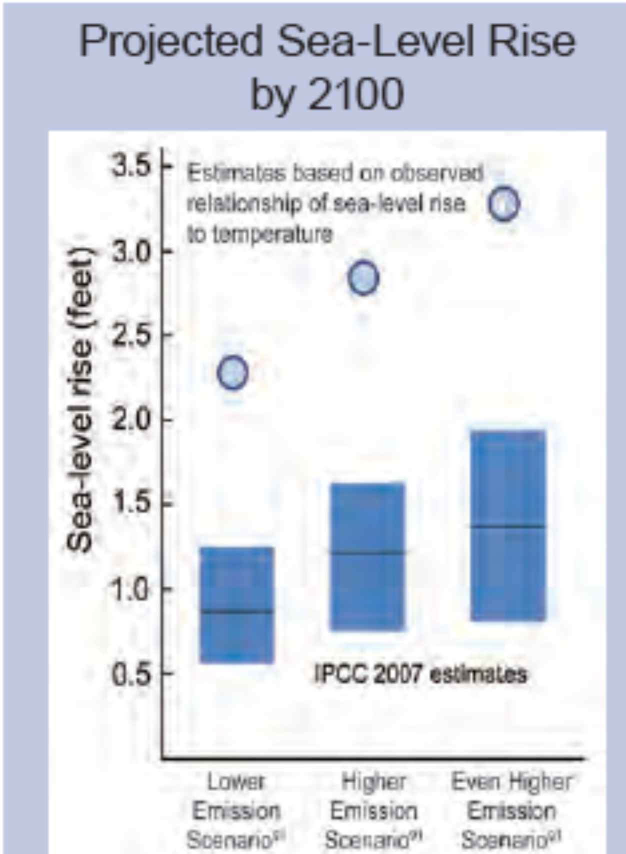

Fig. 3. Estimates of sea-level rise by the end of the century for IPCC 2007 projections excluding changes in ice sheet flow (blue bars), and more recent estimates (blue circles) using the observed relationship of sea-level rise to temperature.

Global Climate Change Impacts in the United States, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson, (eds.), Cambridge University Press, 2009.

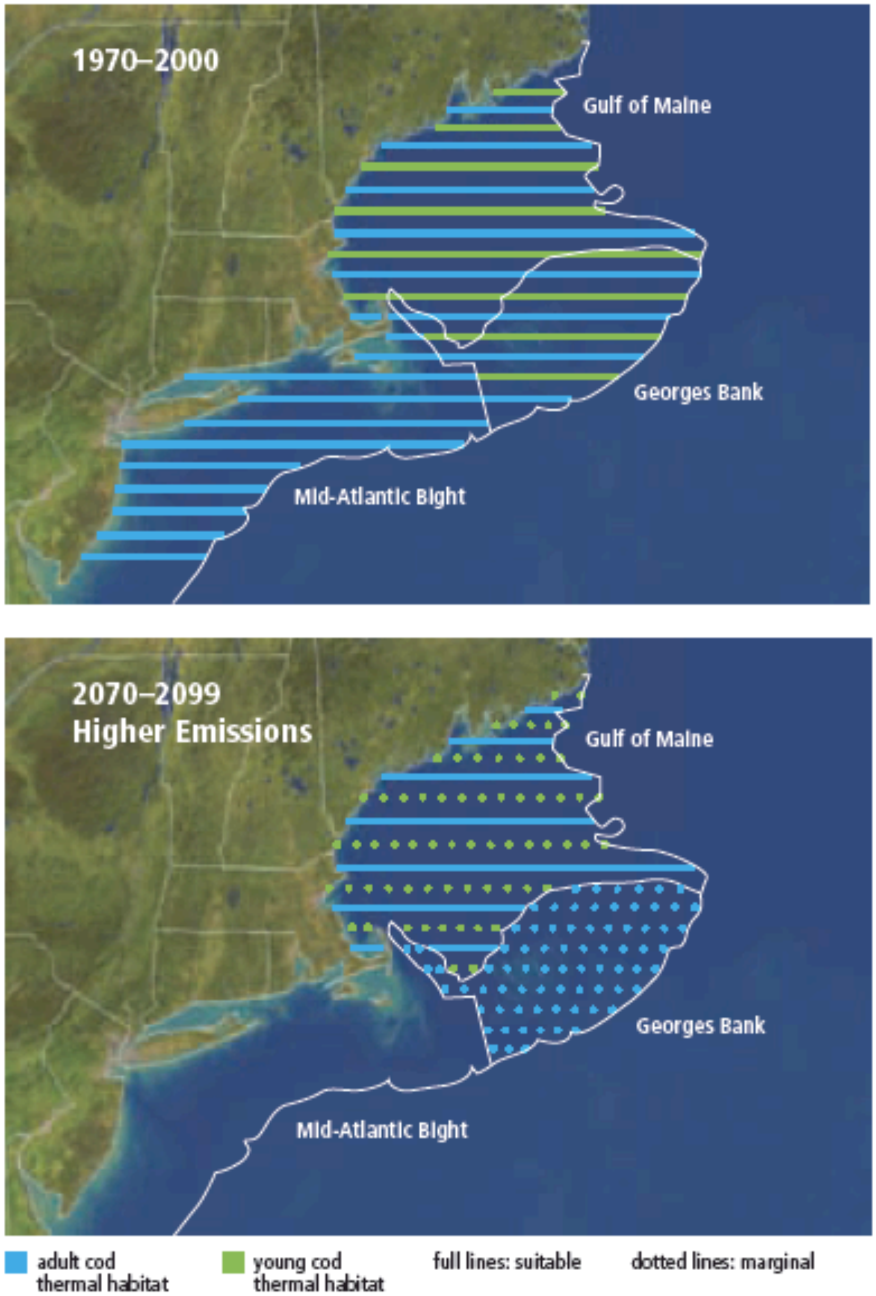

Fig. 4. Present and projected habitats for Atlantic Cod. The Mid-Atlantic Bight is currently too warm for reproductive success, hence young cod are restricted to Georges Bank and the Gulf of Maine. With projected warmer conditions late in this century, young cod will only be viable further north in the Gulf of Maine, and the adult cod habitat on Georges Bank will be marginal. (Frumhoff et al. 2007)

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Appendix I

October 2009 letter from the heads of 18 U.S. science organizations to members of the U.S. Senate regarding climate science (three attached pages).

October 21, 2009

Dear Senator:

As you consider climate change legislation, we, as leaders of scientific organizations, write to state the consensus scientific view.

Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver. These conclusions are based on multiple independent lines of evidence, and contrary assertions are inconsistent with an objective assessment of the vast body of peer-reviewed science. Moreover, there is strong evidence that ongoing climate change will have broad impacts on society, including the global economy and on the environment. For the United States, climate change impacts include sea level rise for coastal states, greater threats of extreme weather events, and increased risk of regional water scarcity, urban heat waves, western wildfires, and the disturbance of biological systems throughout the country. The severity of climate change impacts is expected to increase substantially in the coming decades.[1]

If we are to avoid the most severe impacts of climate change, emissions of greenhouse gases must be dramatically reduced. In addition, adaptation will be necessary to address those impacts that are already unavoidable. Adaptation efforts include improved infrastructure design, more sustainable management of water and other natural resources, modified agricultural practices, and improved emergency responses to storms, floods, fires and heat waves.

We in the scientific community offer our assistance to inform your deliberations as you seek to address the impacts of climate change.

[1] The conclusions in this paragraph reflect the scientific consensus represented by, for example, the Intergovernmental Panel on Climate Change and U.S. Global Change Research Program. Many scientific societies have endorsed these findings in their own statements, including the American Association for the Advancement of Science, American Chemical Society, American Geophysical Union, American Meteorological Society, and American Statistical Association.

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