"Projected and Past Effects of Climate Change: A Focus on Marine and Terrestrial"
Global Climate Change Hearing
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An Overview of Past and Projected Consequences for Marine and Terrestrial Systems

A Statement
by
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Introduction

Mr. Chairman, Members of the Sub-Committee, and all gathered here today, I thank you for the opportunity to participate in today's hearing on the *"Projected and Past Effects of Climate Change: A Focus on Marine and Terrestrial*." I am honored to join you to explain the science that underpins understanding of the past and projected effects of climate change, especially in terms of the impacts on marine and terrestrial systems in North America, across the Arctic region, and around the world.

In offering these perspectives, I will be drawing primarily from the findings of major scientific assessments, a number of which I have been involved with, because these assessments very thoughtfully draw together the collective findings of the scientific community. These assessments deserve very high and special consideration because their credibility has been well established as a result of their extensive open review processes, which have helped to carefully hone their findings.

At the national level, I will be drawing upon the results of the US National Assessment that was completed five years ago.[2] In my role from 1990-99 as chair of the Subcommittee on Global Change Research that directed the US Global Change Research Program, I was instrumental in the organization of this assessment, and after I left government service I served on the National Assessment Synthesis Team that summarized the assessment's findings. In describing potential consequences for the Arctic, I will be drawing mainly from the results of the Arctic Climate

[1] Prepared in cooperation with Dr. Michael MacCracken, chief scientist for climate change programs at the Climate Institute, Washington DC, and Dr. Rosina Bierbaum, Dean of the School of Natural Resources and Environment at the University of Michigan in Ann Arbor.
[2] National Assessment Synthesis Team, 2000: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change: Overview Report,* U. S. Global Change Research Program, Cambridge University Press, Cambridge UK, 154 pp. [Also see *Foundation Report*, U. S. Global Change Research Program, Cambridge University Press, Cambridge UK, 612 pp. published in 2001]. The most significant results of the National Assessment were summarized in the *U. S. Climate Action Report—2002*, which was submitted to the UN under the Framework Convention on Climate Change as the Third National Communication of the United States of America (thus representing the official position of the U.S. Government in a document formally approved by all of the involved agencies and departments); this document is available from the U.S. Government Printing Office Web site at http://bookstore.gpo.gov and is posted at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsUSClimateActionReport.html.

Impact Assessment (ACIA), which was completed in 2004,[3] having been established and charged to conduct the assessment by the Arctic Council[4] and the International Arctic Sciences Committee.[5] For ACIA, I served as chair, leading an international team of over 300 scientists, other experts, and elders and other insightful indigenous residents of the Arctic region in preparing a comprehensive analysis of the impacts and consequences of climate variability and changes across the Arctic region. At the international level, I will be drawing mainly from the results of the Intergovernmental Panel on Climate Change (IPCC), which I was instrumental in helping to conceive in the late 1980s in my role as Assistant Director for Geosciences at the National Science Foundation (NSF) from 1987-1999. The IPCC's members are the nations of the world and the periodic assessments that they commission represent the collective evaluation of scientific understanding by the international scientific community. That the IPCC's assessments of 1990, 1995, and 2001 have been *unanimously* accepted by the world's community of nations gives a strong indication of the widespread agreement that exists regarding the major finding that human-induced climate change is already influencing the climate and the environment and that much larger changes lie ahead.[6] For more detailed information and scientific citations on most of my points, reference should be made to the cited assessments. In areas where the pace of research has been especially rapid or significant in recent years, however, I will also be drawing upon the results of more recent scientific articles, which I will specifically reference.

Context for Today's Hearing

The IPCC's Third Assessment Report[7] summarized the peer-reviewed scientific evidence that human activities, in particular the ongoing emissions of carbon dioxide (CO_2) and other greenhouse gases to the atmosphere resulting primarily from the combustion of coal, oil, and natural gas, are causing the Earth's climate to warm more rapidly and persistently than at any time since the beginning of civilization. While some of the fluctuations are likely a result of natural factors (e.g., variations in solar irradiance and major volcanic eruptions), the IPCC evaluation concluded that the strength and patterns of these change makes clear that human influences are responsible for most of the roughly 0.6ºC (1ºF) warming during the 20th century. In particular, despite the cooling influence of the 20th century's largest volcanic eruption in 1991, the fifteen warmest years in the instrumental temperature record available since 1860 have all occurred in the last 25 years,[8] and comparison with paleoclimatic reconstructions[9] of

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[3] Arctic Climate Impact Assessment (ACIA), 2004: *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*, Cambridge University Press, 140 pp. [Also see ACIA, 2005, Cambridge University Press, 1042 pp.]

[4] The **Arctic Council** was established on September 19th, 1996 in Ottawa, Canada. The Arctic Council is a high-level intergovernmental forum that provides a mechanism to address the common concerns and challenges faced by the Arctic governments and the people of the Arctic as a means of improving the economic, social and cultural well being of the north. The national members of the Council are Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States of America; the Association of Indigenous Minorities of the North, Siberia and the Far East of the Russian Federation, the Inuit Circumpolar Conference, the Saami Council, the Aleutian International Association, Arctic Athabaskan Council and Gwich'in Council International are Permanent Participants in the Council. Many additional entities participate through a provision that provides for non-arctic states, inter-governmental and inter-parliamentary organizations and non-governmental organizations to become involved as Official Observers.

[5] The **International Arctic Sciences Committee** (IASC) was founded 28 August 1990 by national science organizations representing all of the arctic countries. It provides the major venue for national science organizations, mostly academies of science, to facilitate and foster cooperation in all fields of arctic research. IASC currently has participation by scientists from Canada, China, Denmark, Finland, France, Germany, Iceland, Italy, Japan, The Netherlands, Norway, Poland, Republic of Korea, Russia, Sweden, Switzerland, United Kingdom, and the United States.

[6] The IPCC's assessments are all published by Cambridge University Press, and are also available over the Internet at http://www.ipcc.ch. IPCC's Fourth Impact Assessment Report is due to be completed in 2007.

[7] IPCC, 2001: *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., Cambridge University Press, 881 pp., see also http://www.ipcc.ch.

[8] For example, see http://data.giss.nasa.gov/gistemp/2005/. Results of other centers give similar results.

temperatures over the last two thousand years indicates that recent warmth is unprecedented, at least for the Northern Hemisphere where paleoclimatic data are most available.[10] In addition to the warming of the surface, which has been particularly strong in the Arctic,[11] warming is also evident in ocean temperatures (causing some of the sea level rise), below ground temperatures, and temperatures well up in the troposphere.[12] Other evidence of climate change includes diminishing sea ice and snow cover in the Northern Hemisphere, melting back of mountain glaciers in the tropics and in most other locations around the world, and an increasing tendency for precipitation to occur in relatively heavy amounts.

For the future, IPCC projects that significantly greater warming lies ahead. Considering a wide range of possible scenarios for how human activities (e.g., changes in population, technological development, energy use and supply, economic development, and international cooperation) are likely to alter atmospheric composition during the 21st century, the IPCC projects a further increase in average annual surface air temperature around the globe of roughly 1-2ºC (1.8-3.6ºF) from 1990 to 2050 and a further 1-2.5ºC (1.8-4.5ºF) by 2100, bringing the projection for total human influence from the start of the Industrial Revolution to 2100 to roughly 2.5-5ºC (about 4.5-9ºF).[13] As is the case for the warming over the 20th century, future changes are expected to be greater over land than over the ocean, greater in mid- to high latitudes than in low latitudes, and, except where regions really dry out, greater during the winter than during the summer and greater during nighttime than daytime. As will be explained more fully in discussing likely impacts, many other aspects of the world's weather and climate will also be affected.

That such changes in the climate will occur as a result of human activities is no longer scientifically controversial. During the rest of my testimony, I will discuss what the likely consequences of the changes in atmospheric composition and climate are likely to be for the environment, focusing on three specific domains:

- Oceans and marine systems;
- The terrestrial biosphere; and
- The interface between the marine and terrestrial environments.

My discussion will focus on the links between climate change and these systems. It is important to recognize, however, that a number of additional stresses are affecting each of these

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[9] Such reconstructions estimate past values of surface temperature using tree-rings, coral growth patterns, changes in vegetation indicated by changes in pollen preserved in lake sediments, etc.

[10] For example, see Mann, M. E., and P. D. Jones, 2003: Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**, 1820-1824, doi. 10.1029/2003 GL017814. Controversies over the findings reported in this initial paper have largely been addressed over the years since it was published.

[11] See Attachment 1 for an overview by the authors of ACIA's chapter on past climate change regarding the unprecedented patterns of modern warming and reconciling this finding with the analyses of supposed similarly warm conditions in the early to mid-20th century.

[12] The near final draft of a tightly focused assessment by the US Climate Change Science Program (see http://www.climatescience.gov/Library/sap/sap1-1/third-draft/default.htm) of trends in surface and upper troposphere temperatures indicates that previous criticisms that warming rates have been significantly different are not valid. This focused assessment reports near resolution of this issue as a result of studies that have identified corrections needed in satellite and balloon records as a result of instrument and observational factors.

[13] These estimates allow for uncertainties in projections of future energy-related emissions. However, two other factors can also introduce uncertainties. First, present models have only a limited treatment of the processes that govern how rapidly CO_2 will be taken up by the land and ocean carbon reservoirs; preliminary studies by Cox et al. (Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, 2000: Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model, *Nature*, **408**, 184-187) and Fung et al. (Fung, I., S.C. Doney, K. Lindsay, and J. John, 2005: Evolution of carbon sinks in a changing climate, *Proceedings of the National Academy of Sciences* (USA), **102**, 11201-11206, doi:10.1073/pnas.0504949102) indicate that current models are overestimating the amount of carbon that can be taken up, thus leading to small underestimates of the rate of warming. Second, limits in our estimates of how the climate will respond to changing atmospheric composition are estimated to have the potential to increase or decrease the temperature changes in 2050 by about 0.3ºC (roughly 0.5ºF) and in 2100 by about twice this amount, with the likelihood (as a result of recent studies of the likely effects of sulfate aerosols) that the change could be greater than estimated more likely than that these are overestimates.

environments, including air pollution, nitrogen deposition, toxics such as mercury, unsustainable extraction of resources, over-fishing, nutrient-induced eutrophication, depletion of stratospheric ozone and UV enhancement, etc. Climate change is thus only one aspect of global environmental change, although a continuously accumulating one that over time will have very large impacts, and for a full evaluation of likely environmental consequences for both marine and terrestrial environments, comprehensive research and assessment efforts are essential.

Interactions and Impacts Linking Climate Change and the Ocean and Marine Environment

Oceans cover about 70% of the Earth's surface. Because of their large heat capacity, the oceans moderate climatic swings by supplying heat to the atmosphere and adjacent continents during the winter and, because they warm relatively slowly during the summer, are the source of cooling sea breezes during times of peak solar radiation. Much of the heat absorbed by the oceans goes into evaporating water, providing the moisture that supplies vital precipitation for land areas via the monsoons and tropical and extratropical storms. These rains and associated geochemical interactions help to cleanse the atmosphere of pollution. In addition, oceans support a wide diversity of biological life that supplies fish, birds, marine mammals and other species higher in the food chain, and supports the fisheries that in turn provide substantial food for humans.

While the oceans seem so large that it is hard to imagine that human activities could affect them, records over geological time and observations of recent changes make clear that both the physical and biological systems in the ocean are quite sensitive to changes, and, indeed, are being affected. The very human activities that are causing the climate to change are becoming the major influence on the oceans.

First, the oceans affect atmospheric chemistry. In their natural state, cold waters forced to the surface by wind patterns in low latitudes release large amounts of CO_2 to the atmosphere as they warm. Before humans started altering the carbon cycle, roughly the same amount was taken up in mid- to high latitude ocean areas as the ocean waters cooled and marine organisms grew, died and sank to the ocean depths. With this balance, which was modified somewhat during glacial periods when the oceans were colder, the atmospheric CO_2 concentration has been held in the range of about 180 to 300 ppmv[14] for the past several million years. As human activities began to emit large amounts of CO_2 as a result of combustion of coal, oil, and natural gas, the atmospheric concentration has been driven higher because the oceans and living biosphere cannot absorb it all. On time scales of years to centuries, the oceans take up about a third of the emitted amount, limiting the atmospheric buildup and thus moderating the pace of climate change.

While the oceans as a whole can hold vast amounts of dissolved CO_2, the oceans are not well mixed vertically, and so most of the added CO_2 builds up in the near surface layer. This has the effect of altering oceanic chemistry, most importantly by making the ocean more acidic.[15] Increasing oceanic acidity has a range of effects, but most important makes it chemically more difficult for marine organisms to form shells. For corals, the rise in the CO_2 concentration from its preindustrial value of about 280 ppmv to its present value of 380 ppmv has already caused a

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[14] ppmv stands for parts per million by volume, or number of CO_2 molecules per million molecules of air.
[15] See Doney, S.C., 2006: The dangers of ocean acidification, *Scientific American*, **294**(3), March 2006, 58-65; and *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*, Royal Society, 2005. Available at http://www.royalsoc.ac.uk/displaypagedoc.asp?id=13314.

significant shrinkage in the regions most favorable for reef-forming, and by 2050, virtually all of the most favorable regions in the world will have disappeared, simply due to the rise in the CO_2 concentration.[16]

Adding in the sensitivity of corals to warmer ocean waters (the "coral bleaching" effect), the prospect for more powerful storms and wave conditions, the increasing threats from coastal runoff and fish-harvesting, and other stresses, the prospects for many of the world's reefs are very problematic. While the potential impacts on coral are of most immediate concern, impacts on other shell-forming organisms are also likely to become significant over coming decades, particularly as the CO_2 level approaches 750 ppmv.[17]

As the rising concentrations of CO_2 and other greenhouse gases have trapped more infrared radiation, making it more difficult for the Earth's surface to cool, most of the additional heat has been taken up by the oceans because they are capable of mixing it through the upper hundred meters (yards) or so of ocean depth. Surveys of ocean temperature give a clear indication that the ocean's upper layers are warming;[18] indeed, the warming that is being observed is in good agreement with climate model simulations of how the oceans are being projected to warm as a results of the changes in atmospheric composition.[19]

This oceanic heating is having a wide range of both physical and biologically important impacts. Because the oceans are able to mix the heat downward, they are able to slow the warming of the atmosphere, which is beneficial, but it also means that we are not experiencing the full extent of warming to which past emissions of CO_2 have committed the world. Experiments with climate models indicate, for example, that the world would be committed to further warming of about 0.5ºC (almost 1ºF) even if global emissions of CO_2 were to be quickly cut to near zero.

Warming of the oceans also makes more energy available to the atmosphere if just the right conditions prevail. For example, warm ocean waters provide the energy needed to intensify tropical cyclones (i.e., hurricanes and typhoons), and indeed, recent studies[20] are finding that increasing sea surface temperatures are leading to an increasing proportion of tropical cyclones to be in the most powerful and destructive categories (more on the consequences of more powerful tropical cyclones in the section dealing with the ocean-land interface). While there has been significant debate recently about whether the available record provides a definitive indication of this linkage, a paper in press in the *Bulletin of the American Meteorological Society*, of which I am a co-author, finds that there are many reasons to suggest that there is indeed a strong linkage and that it may well be limitations in our detective work that are the

[16] See Kleypas, J. A., R. W. Buddemeier, D. Archer, J-P. Gattuso, C. Langdon, and B. N. Opdyke, 1999: Geochemical consequences of increased atmospheric carbon dioxide on coral reefs, *Science*, **284**, 118-120; and Buddemeier, R. W., J. A. Kleypas, and R. B. Aronson, 2004: Coral reefs & global climate change: Potential contributions of climate change to stresses on coral reef ecosystems, Prepared for the Pew Center on Global Climate Change, http://www.pewclimate.org/global-warming-in-depth/all_reports/coral_reefs/index.cfm.

[17] See: Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.-K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on marine calcifying organisms, *Nature*, **437**, 681-686, doi:10.1038/nature04095.

[18] Levitus, S., J. I. Antonov, and T. P. Boyer, 2005: Warming of the world ocean, 1955-2003, *Geophysical Research Letters*, **32** (L02604), doi: 10.1029/2004GL021592. Levitus et al. find that over 90% of the energy trapped by the increasing concentrations of greenhouse gases ends up in the ocean.

[19] Barnett, T. P., D. W. Pierce, K. M. AchutaRao, P. J. Gleckler, B. D. Santer, J. M. Gregory, and W. M. Washington, 2005: Penetration of human-induced warming into the world's oceans, *Science*, **309**, 284-287.

[20] For example, see Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Change, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, **309**, 1844-1846 and Emanuel, K. A., 2005: Increasing destructiveness of hurricane intensity on climate, *Nature*, **326**, 483-485.

problem.[21] If this is indeed the case, and it seems quite likely, then the world faces a situation where the storm season is becoming longer, storms may well last longer, and the likelihood of relatively intense storms is increasing, likely leading to greater and greater destruction and loss of life unless our adaptive efforts[22] are significantly increased.

Climate change also has the potential to influence the pattern and character of the normal year-to-year fluctuations of the climate. For the Pacific region and then for much of the US, the natural variation of the El Niño-Southern Oscillation (ENSO) is of critical importance, variously causing El Niño and La Niña events (i.e., unusual warming or cooling in the eastern tropical Pacific, respectively) that redirect the Northern Hemisphere jet stream, thereby creating either quite wet or quite dry winter conditions across various parts of the US (e.g., this year, the ocean conditions are causing the US West Coast to be inundated with very large amounts of rain). Research to date only hints at how ENSO may be affected, with some indication that the overall conditions may become more El Niño-like with more intense El Niño events (meaning, for example, more winter precipitation for California, increasing flooding potential in the spring and increasing the stock of burnable vegetation). However, there remains significant disagreement among model results and this area is, therefore, being investigated intensively by various research groups.

Changes in atmospheric winds and weather (a result of the warming) and increasing ocean temperatures (which also feed back to affect the weather) also lead to changes in ocean currents. Under normal conditions, warm ocean waters are pulled poleward to replace cold waters that sink to the ocean depths in high latitudes. As these waters are pulled poleward, for example in the Gulf Stream, heat is given off that tends to keep Europe relatively warm in winter, given its latitude. As climate change prevents ocean waters in high latitudes from cooling as much, the rate of sinking waters declines, and so less warm water is pulled poleward, providing less winter heat. While this slows the human-induced warming rate in Europe, it leaves that heat in lower latitudes, causing those regions to be warmer and even more moisture to evaporate, moisture that is likely to result in more intense rainfall events. Slowing the generation of oceanic deep water also slows the transport of dissolved CO_2 into the deep ocean, releasing somewhat the oceanic brake on the pace of global warming.

Fisheries, marine mammals, seabirds, and other marine life will all be significantly affected by these changes. Both the increasing temperature and freshening of upper ocean waters in some regions by increased precipitation will tend to increase stratification of the upper ocean, affecting the vertical distribution and productivity of biological activity.[23] Shifts in fisheries will occur (and some changes are already being observed) as ocean temperatures shift and changes in abundance will occur as the amounts of upwelling nutrients and associated biological activity are

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[21] Anthes, R. A., R. W. Corell, G. Holland, J. W. Hurrell, M. C. MacCracken, and K. E. Trenberth, 2006: Hurricanes and Global Warming—Potential Linkages and Consequences, *Bulletin of the American Meteorological Society*, **87** (May, in press). With regard to the most important limitation in detection studies, it has been the presumption by a number of investigators (e.g., Pielke et al., 2005, *Bulletin of the American Meteorological Society*, **86**, 1571-1575) that the response should be a linear trend in hurricane number (or in other factors) over the course of the century that is made dubious by many detection-attribution studies that indicate that human influences led to a time history of Northern Hemisphere temperature change during the 20th century consisting of warming early in the century, a slight cooling in mid-century (especially in the North Atlantic sector that is key in affecting hurricane characteristics), and then a sharp warming since the 1970s.

[22] Building societal resilience through adaptive efforts could include, in the short-term, more effective evacuation, stronger levees, beach restoration, enhancing vegetation cover of dunes, strengthening of buildings, etc., and longer-term, withdrawal from the most vulnerable areas, enhanced building codes, storm surge barriers (e.g., being proposed to protect New York harbor), adding capacity to evacuation routes, etc.

[23] See for example: Sarmiento, J., R. Slater, R .Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S. Spall, R. Slater, and R. Stouffer, 2004: Response of ocean ecosystems to climate warming, *Global Biogeochemical Cycles,* **18**, GB3003, doi:10.1029/2003GB002134.

reduced. The retreat of sea ice will also lead to changes in fisheries, as the ice edge is normally a very productive site as a result of the release of nutrients from the melting ice and the protection from intense waves provided by the ice itself. Marine mammals, including walrus, seals, and polar bears, depend on the presence of sea ice to raise their young and to hunt for food, and the retreat of ice is already having a significant impact.[24] The shifts in ocean conditions, both of sea ice and of biological activity, are also starting to have effects on sea birds, which are also facing increasing competitive pressures from birds that normally are shifting northward as warming increases.

An added result of sea ice retreat will be the potential for greater access by ships. The melting back of sea ice is already near to opening the Northern Sea Route that would connect the Atlantic and Pacific Oceans via open water north of Eurasia. Not only would such a route cut shipping time significantly, but the route will also increase seasonal access to arctic resources, both below coastal waters and on land (although, perversely, the summer melting of the permafrost will make transport over land much more difficult). Already the Northwest Passage is becoming navigable for icebreakers and in the decades ahead greater access should be possible. Environmentally, such access will greatly increase the risk of contamination from spills and other pollution, and there is virtually no experience or effective approach for cleaning up such spills. Politically, the increased access is already raising questions of sovereignty, ownership of coastal zone resources, and rights to the shifting fisheries that will result. The identification of such issues as part of the Arctic Climate Impact Assessment formed the basis of the policy guidance document that was prepared by the Arctic nations as a framework for future discussions.[25]

Overall, human-induced climate change is thus already having significant effects on the ocean, the weather systems that the ocean generates, and on the biological systems that are dependent on its resources. Adding on the impacts of sea level rise on the coastal environment, which is treated below, the global oceanic environment on which we all depend is already screaming, at least in a figurative sense, for actions to greatly slow the pace of change, especially as roughly an equal amount of change as has already occurred is almost certain to result as a consequence of past human activities.

Interactions and Impacts Linking Climate Change and the Terrestrial Environment

Changes in both the CO_2 concentration itself and in the climate will affect terrestrial systems. Because CO_2 is needed by plants to grow, the increase in its concentration will, as a whole, enhance plant growth and allow the stomata (pore openings) on the undersides of leaves to open less, allowing less harmful air pollution in and less moisture out, thereby improving the overall health and water use efficiency of plants. As a general result, the higher CO_2 concentration will thus lead to greater carbon uptake and enhanced storage as plant material and in soils as long as nutrients and sufficient soil moisture are available. Recent studies suggest that the CO_2

[24] For example, see report in the *Washington Post,* April 15, 2006 entitled "Warming Arctic is Taking a Toll," which reports on results of a scientific study appearing in the journal *Aquatic Mammals* that walrus calves are being found abandoned at sea (and almost certain to starve and drown) because there is no longer any sea ice for them to rest on in the areas shallow enough for their mothers to feed off the bottom.
[25] Policy Document is available at: www.acia.uaf.edu/PDFs/ACIA_Policy_Document.pdf

fertilization effect will be limited by tropospheric ozone concentrations[26] as well as the availability of nitrogen in ecosystems.[27]

However, different plants respond quite differently. Under conditions with adequate moisture and nutrients, many types of crops (key exceptions are maize, millet, sorghum, and sugar cane) respond quite strongly to the increase in the CO_2 concentration, but then so too do many weedy plants, necessitating additional control measures. Assuming that farmers can overcome problems with weeds and increased occurrence of pests and that moisture amounts are sufficient, the per acre yield of many food crops is likely to increase by tens of percent.[28] It is for this reason that the IPCC and other assessments suggest that overall global food production will increase, at least until the CO_2 concentration gets much higher when the effect can saturate or even changeover (i.e., become essentially toxic). Simple economic analysis would then suggest that with more agricultural production, food prices will drop and that there will be sufficient food, at least for those who can afford it, providing a net economic benefit to society. However, the situation in the real world is a good bit more complex. In the US, for example, overproduction currently leads to the need for subsidies as a result of overproduction, and so an increase in productivity and a decrease in commodity prices may well lead to calls for larger subsidies. With the climate also changing, there will also be a constant need to adjust seed strains to ensure optimal productivity,[29] creating greater needs for support of crop development programs at, for example, the land grant universities.

In addition, while productivity will go up in both good and marginal farming areas, the increase will be greater in absolute amount in the better farming areas, and so the economics of farming in marginal areas is likely to worsen, leading potentially to the abandonment of farming in such areas unless a switch can be made to other crops for which there is demand (e.g., a non-food crop that can be used to produce biofuels). For those now growing niche crops (e.g., crops such as apples and broccoli in cool summer regions such as upstate New York and New England; tomatoes in regions where nighttime temperatures are cool enough for fruit to set; etc.), warming is likely to make such regions uncompetitive for continued production of these crops. Because soils are typically not fertile enough to compete economically with regions now growing warm season crops, farming in such regions is also likely to be threatened. Thus, while overall food production in regions such as the US is projected to increase, there are likely to be hard times for many farmers (and the rural communities are associated with them) as adjustments occur. Lost in the transformation is likely to be the effective role present-day farmers play in caring for the land, which is likely to create ecological challenges because returning such regions as the southern Great Plains to their pre-farming vegetation is unlikely to be successful due to the altered climatic conditions.

For natural systems such as forests and grasslands, the situation is more problematic. Each ecosystem type has a set of preferred conditions, as is evident from the changing distributions of

[26] Karnosky, D. F., K. S. Pregitzer, D. R. Zak, M. E. Kubiske, G. R. Hendrey, D. Weinstein, M. Nosal, and K. E. Percy, 2005: Scaling ozone responses of forest trees to the ecosystem level in a changing climate, *Plant, Cell, and Environment*, **28**, 965-981.
[27] Reich, P. B., S. E. Hobbie, T. Lee, D. S. Ellsworth, J. B. West, D. Tilman, J. M. H. Knops, S. Naeem, and J. Trost, 2006: Nitrogen limitation constrains sustainability of ecosystem response to CO_2, *Nature*, **440**, 922-925.
[28] Indeed, a number of studies suggest that, along with technology and seed enhancements, the increased CO_2 concentration is already contributing to higher yields.
[29] Note, however, that greater year-to-year variability or more frequently exceeding various temperature and/or moisture (or dryness) thresholds may make optimization to a narrow range of climatic variables more risky, and farmers may instead choose not to select seed strains that tolerate a wider range of conditions in exchange for slightly reduced productivity. A key determinant will be how rapidly improvements are made in the skill of seasonal forecasts, a topic on which research attention is being closely focused.

types of forest ecosystems going poleward or up a mountain. As climatic conditions shift, the preferred ranges for each type of ecosystem will shift, and numerical models that simulate this process indicate that the projected changes in climate over the 21st century will have profound effects. Starting from the Arctic (and focusing on the coarsest subdivision of ecosystem types), the tundra, which is summer home and nesting ground for many migrating birds and mammals, will be squeezed against the Arctic Ocean as the boreal forest becomes established further and further to the north. Across the United States and Canada, temperate forests and grasslands will push northward, with the northeast mixed forest giving way to more temperate vegetation and with forests giving way to savanna and grasslands in regions where precipitation does not increase enough to supply the needed moisture in the face of rising temperatures. For the southeastern and southwestern US, this balance will be particularly important. As described in the US National Assessment, if the summertime conditions become warmer and moister, the southeastern mixed forest can persist, but if precipitation does not increase sufficiently, the soils will dry and the temperatures will increase even more, creating a situation where more frequent fires become likely to accelerate the transition to a sparser savanna woodland situation. [30] In the southwestern United States, increased precipitation, particularly in the winter, may be sufficient to increase biological productivity in desert areas, allowing greater vegetation growth in winter. While seemingly beneficial, if summers become hotter and remain dry, the potential for increased fire is significant (e.g., increased wintertime growth of chaparral would likely only increase the likelihood of periodic fires, which can be particularly threatening to communities in the West).[31]

While adapting to a situation of relatively slowly shifting ecosystems on the continental scale may seem comparable to adapting to the reforestation of the Northeast over the 20th century, the actual situation on the local scale, both for wildlife and for communities, is likely to be much more challenging. This is the case because there are significant variations in the response of the different plant species that make up the ecosystems to the changes in CO_2 and climate, and this will mean that the preferred ranges of different species will shift by different amounts and at different rates, thus pulling apart current ecosystems without there becoming stable climatic conditions in which new ecosystems can evolve--instead, everything will be changing at once.

Determining the thresholds that might lead to abrupt changes in the functioning of natural systems is, however, particularly difficult, and there are likely to be thresholds or tipping points that initiate a sequence of changes beyond which systems are likely to collapse. For example, a temperature increase of about 1ºC per decade since 1970 in the Kenai Peninsula in Alaska has caused permafrost melting and allowed the over-wintering of spruce bark beetles and the influx of additional disease vectors, weakening the trees, and enhancing the extent and intensity of wildfire. Together, these effects have led to the sudden and widespread loss of the white spruce forest, and to a situation in which, even were the new climatic conditions stable, it would take centuries for new species to develop into a new, fully mature ecosystem; with stable conditions not likely for at least many decades, development of a new, mature forest system is likely far off in the future. As another example of the sensitivity of extant ecosystems, a massive die-off of pinyon pine (*Pinus edulis*) covering 12,000 square kilometers in the southwestern United States was observed during the recent severe drought. Although the soil moisture deficit was no worse

[30] National Assessment Synthesis Team, 2001: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change: Foundation*, US Global Change Research Program, Cambridge University Press, 612 pp. Available at http://www.usgcrp.gov/usgcrp/nacc/default.htm.
[31] Ibid.

than the one endured in the 1950s, the higher average temperature appears to have combined with the extreme dryness to make the trees more vulnerable to attacks from bark beetles.[32]

Increased frequency of droughts, wildfires, floods, and other extremes, including greater damage from increased and more persistent winds and precipitation from tropical cyclones, [33] are other types of changes that have the potential to exceed the adaptive capacity of existing ecosystems. In addition, more frequent fires and the reduced productivity of some ecosystems will limit the amount of carbon being taken up and stored by the biosphere, thus leaving a larger fraction of the emitted CO_2 to exacerbate global warming. For example, the recent Indonesian fires driven by ENSO drying and human land use changes led to significant releases of CO_2 to the atmosphere. A recent international comparison of coupled carbon climate simulations[34] found that all of the models projected some destabilization of tropical ecosystems, leading to soil drying, reduced plant/tree growth, and increased occurrence of fire and net emission of CO_2 to the atmosphere, thereby accelerating warming (positive feedback loop).[35] Models typically suggested that by 2100 these "carbon-climate" feedbacks would lead to the atmospheric CO_2 concentration being higher by 20 to 200 ppmv[36] and additional warming of 0.1 to 1.5ºC, with the worst-case model scenario projecting the complete die off of the Amazon rain forest. These feedbacks are not yet well understood or represented, requiring coupled treatment of climate change, CO_2 fertilization, nitrogen limitation, and the ability of trees to tap deep soil horizon water; however, these processes do indicate the potential for the likely outcome being more toward the upper end of the IPCC range of possibilities.[37]

Because projected shifts in the frequency, timing, intensity, and location of precipitation will lead to all sorts of challenges, issues relating to freshwater resources, although of a variety of types, were a common thread across all regions in the US National Assessment (see Table 1 for a brief summary of key regional consequences). For example, the increased likelihood of additional wintertime precipitation in the western US, as projected in both models used in the US National Assessment, increases the potential for mudslides and high river levels as well as increasing the likelihood of mountain precipitation falling as rain, causing accelerated loss of the snowpack, a further increase in runoff and an even greater likelihood of flooding. At the same time, warmer temperatures will lead to a rise in the snowline and, on average, a reduction in the springtime snowpack that is so vital for sustaining stream and river flows into the summer. For the rest of the US, projections indicate a continuation of the shift of precipitation toward more precipitation falling in the more intense (i.e., convective) rainfall events. Reducing the time for rainfall to seep into aquifers has the effect of increasing runoff, especially once the upper layer of soil has become saturated, thereby increasing the likelihood of high river levels and flooding. Warmer summertime temperatures, and a greater interval between significant rainfall events, are projected by many of the models to lead to increased evaporation of soil moisture in the Great Plains, and so a more rapid onset of drought conditions. For the Great Lakes, most models

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[32] Breshears, D. D., et al. 2005: Regional vegetation die-off in response to global-change-type drought, *Proceedings of the National Academy of Sciences*, **102** (Oct. 18), 15144-15148. Available at http://www.pnas.org/cgi/doi/10.1073/pnas.0505734102.
[33] Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years, *Nature* **436**, 686-688.
[34] Friedlingstein, P., P. Cox, R. Betts, W. von Bloh, V. Brovkin, S. Doney, M. Eby, I. Fung, B. Govindasamy, J. John, C. Jones, F. Joos, M. Kawamiya, W. Knorr, K. Lindsay, H.D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, S. Thompson, A.J. Weaver, and N. Zeng, 2006: Climate–carbon cycle feedback analysis; Results from the C^4MIP model intercomparison, *Journal of Climate*, in press.
[35] See, for example, the Cox et al. and Fung et al. references provided above.
[36] For comparison, the CO_2 increase from preindustrial to the present has been about 100 ppmv.
[37] Beedlow, P. A., D. T. Tingey, D. L. Phillips, W. E. Hotsett, and D. M. Olszyk, 2004: Rising atmospheric CO_2 and carbon sequestration in forests, *Ecological Environment*, **2**, 315-322.

project a few foot lowering of lake levels as the increase in summertime evaporation exceeds the increase in winter precipitation, significantly impacting community, recreational and commercial use of lake waters.[38] Reduced duration and extent of snowfall will also affect the Northeast and other areas, likely shortening the ski season and lengthening the time for warm weather recreational use of the landscape, assuming drying and fire do not become threats.

In the Arctic, the melting back of snow cover, river ice, and permafrost, combined with offshore melting back of sea ice, will have significant effects on wildlife and on movement generally across the region. For many types of wildlife, the snow cover provides protection and even habitat, and climate change is likely to break vital links (e.g., lemmings and voles survive the winter mostly between the snow layer and the underlying tundra, and their loss would deplete food resources for snowy owls and foxes, etc.). Reindeer and caribou depend on the snow cover to protect vegetation that serves as winter feed, and episodic freeze-thaw conditions can create ice crusts that cannot be easily broken, reducing access to the food necessary to survive. The migrating herds also depend on frozen river ice in springtime to cross rivers along migration routes to summer breeding grounds.[39] Warmer conditions are already leading to new species appearing in the Arctic, and these new species will tend to push existing species northward, likely eventually to extinction as the land ends and the Arctic Ocean begins.

In addition, the melting of permafrost (and frozen sediments on the continental shelves) has the potential to release large amounts of methane (CH_4) that is tied up in hydrates. On a per molecule basis, methane is roughly 20 times as effective as trapping infrared radiation as is a CO_2 molecule, which is why there is so much attention being devoted to human-induced changes in methane concentrations (human contributions have caused about a 150% increase in the preindustrial CH_4 concentration). While permafrost melting has begun, determining how much CH_4 is being released has proven quite difficult and so the IPCC projections do not yet account for the potential warming influence of such releases, but the potential for substantial releases is quite significant, especially because warming in the Arctic is projected to be greater than for the world as a whole.

Continued warming and changes in snowfall are also likely to further increase the ongoing retreat of mountain glaciers and the great ice sheets. In virtually all regions of the world, including on high tropical mountains, glaciers are retreating at a rapid rate. because the annual glacier runoff in many cases serves as water resources for wildlife and communities, the eventual loss of the glaciers is likely to have very significant consequences in many regions around the world. The area of the Greenland Ice Sheet that melts each year is also increasing, and satellite observations indicate that ice mass is decreasing.[40] What appears to be happening is that rather than small puddles forming and then refreezing in the fall, larger puddles are forming, and then finding channels and crevasses to flow to the bedrock and eventually into the ocean, allowing a greater fraction of the increase in downward infrared radiation caused by the higher greenhouse gas concentrations to go into melting of ice as opposed to the very energy intensive process of evaporation of water. The situation is much like what would happen if one of those decorative

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[38] Warmer lake temperatures also mean delayed formation of lake ice in the winter, perversely allowing a longer period for lake effects storms to dump snow on the surrounding regions.

[39] Arctic peoples and the energy industry also depend on the frozen ground to enable moving around the Arctic; warming has already reduced by about half the number of days the ground is hard enough for movement of some oil-drilling equipment.

[40] See "Changes in the Velocity Structure of the Greenland Ice Sheet" by Eric Rignot and Pannir Kanagaratnam, SCIENCE VOL 311 17 February 2006, as well as "The Greenland Ice Sheet and Global Sea-Level Rise by Julian A. Dowdeswell, SCIENCE VOL 311 17 February 2006, and also see Paterson, W. S. B., and N. Reeh, 2001: Thinning of the ice sheet in northwest Greenland over the past forty years, *Nature*, 414, 60-62.

ice statues on banquet tables were taken out of a freezer for longer and longer intervals—if out for only a short period, the thin meltwater layer on the statue might refreeze when the statue is put back in the freezer; however, if kept out longer, the meltwater created each time would be lost, and soon there would be no ice statue at all.[41]

Projections are that high-latitude warming of a few degrees Celsius (so perhaps 5ºF), which is projected for the second half of the 21st century, would be likely to lead to the melting of roughly half of the Greenland Ice Sheet over a period of up to several centuries,[42] mirroring a similar event that occurred during the last interglacial,[43] likely mainly as the result of a particular set of variations in the Earth's orbit at that time that brought comparable warmth to high northern latitudes. The effects on sea level of such extensive changes are discussed in the next section.

While much of the above discussion has focused on the projected changes in seasonal to annual timescale changes, what really has most effect on people and the environment are the extremes of the weather that are combined to get the changes in the averages. The weather (i.e., the instantaneous state of the atmosphere) is determined by the interaction of all of the various forcings and gradients in the global system. Observations indicate that day-to-day weather conditions tend to vary about the mean conditions in a more-or-less standard way, creating a bell-shaped distribution of conditions with a few instances much above and below the average and a greater likelihood of the conditions being near the average expected at each time of year. The projected change in climate will shift this distribution, moving the average higher, and thereby creating a much greater likelihood that conditions will exceed a particular threshold (e.g., 90 or 95ºF). The likelihood of presently unusual events could also be changed if the shape of the bell-like distribution is changed, which could occur, for example, if the characteristics of the global circulation are changed (e.g., by moving the winter jet stream relative to mountain ranges such as the Himalayas, or by altering the oceans in ways that affect the irregular cycling or intensity of El Niño or La Niña events).

As a result of the changes in climate, conditions such as heat waves (which exacerbate the heat index and thermal stress in cities [44]) and drought conditions favorable for wildfires are expected to become more frequent and more intense. In fact, Dai et al. (2004) calculate that the amount of land experiencing severe drought has more than doubled in the last 30 years, with almost half of the increase being due to rising temperatures rather than decreases in rainfall or snowfall.[45] Not surprisingly, therefore, observations indicate that wildfires have been increasing on all

[41] Note that throughout this process, the temperature of the ice surface when out on the banquet table would still be at the freezing point, even with an infrared lamp shining on it. What matters is the amount of heat being delivered while the temperature is fixed at the melting point—not that the temperature has not risen (as some Skeptics use as an argument to try to find fault with attributing the unprecedented melting back of glaciers to the unprecedented human-induced increase in greenhouse gas concentrations.

[42] See Gregory, J. M., P. Huybrechts, and S. C. B. Raper, 2004: Climatology: Threatened loss of the Greenland Ice Sheet, *Nature*, **428**, 616; doi:10.1038/428616a. The IPCC's Third Assessment Report suggests that the time scale for such melting would be millennia, but the recent identification of the meltwater runoff mechanism for more rapid melting is likely to lead to reductions in the estimates included in future assessments.

[43] That such melting occurred is evident by the absence of older ice in ice cores drilled in southern Greenland, but the presence of ice that old in cores drilled in northern Greenland. Beach horizons on remote islands that are located a few meters above present sea level appear to confirm that a comparable amount of water (or perhaps even more from some loss of the West Antarctic Ice Sheet) had been added to the oceans. See "Paleoclimatic Evidence for Future Ice-Sheet Instability and Rapid Sea-Level Rise" Jonathan T. Overpeck, Bette L. Otto-Bliesner, Gifford H. Miller, Daniel R. Muhs, Richard B. Alley, Jeffrey T. Kiehl Science 24 March 2006: Vol. 311. no. 5768, pp. 1747 - 1750 DOI: 10.1126/science.1115159

[44] The very hot European summer of 2003 that led to a month-long heat wave that caused the premature deaths of tens of thousands is the type of rare event that is estimated to have become much more likely as a result of recent warming, and will become even more likely in the future (e.g., see Schär, C. et al., 2004: The role of increasing temperature variability in European summer heat waves, *Nature*, **427**, 332-336.)

[45] Dai, A., K. E. Trenberth, and T. Qian, 2004: A global dataset of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *Journal of Hydrometeorology*, **5**, 1117-1130.

continents, particularly sharply in North America, and projections are that this trend is likely to intensify with further increases in surface temperature.[46] In addition, freeze events, which are important to controlling many types of pests and associated diseases, are projected to be less likely. As already mentioned, the occurrence of more intense and more frequent heavy rainfall events is likely to increase the occurrence of flooding. Analyses by Milly et al. (2002) indicate that the frequency of very large floods has increased substantially during the 20th century, which is consistent with climate model simulations, and modeling studies suggest that the trend will continue in the future.[47] With respect to the potential severity of this type of effect, results from the Canadian climate modeling group cited in the US National Assessment indicate that the return period of what are now once in a hundred year events will, by the end of the century, likely be reduced to about once every 30 years, with even more severe events occurring once every hundred years. In that much of society's infrastructure is only designed to withstand once in a hundred year events, having more severe events occurring more often than once a century is likely to increase the likelihood of very damaging events,[48] causing very adverse and costly impacts for both society and the environment.

Some media reports and criticisms by skeptics question the rising concern about the increasing risks from more intense and more frequent occurrence of extreme weather events, indicating that no specific event can be attributed to global warming. To better understand the situation, consider the simple analogy of the Earth's weather being equivalent to a pot of slowly boiling water, with each bubble indicating an extreme event somewhere across the globe. If the heat under the pot is turned up, there will be more bubbles, some of which are the size of the previous largest bubble and perhaps some even larger. There is no way to say that any particular bubble was due to the increased heat or was bigger because of it, yet clearly the intensified bubbling is due to the additional heat. Now, the real world situation is further complicated by seasonal changes (roughly equivalent to the heat being slowly turned up and down, but each time to higher levels), spatial linkages resulting from the oceanic and atmospheric circulations (roughly equivalent to adding noodles to the boiling water), and the presence of mountains and other geographic features (roughly equivalent to having a pot of varying shape and thickness); as a result formally detecting the changes in extreme events is indeed a challenge. But there is no question that adding heat to the system will lead to greater extremes (were the subtropics not so warm, the incidence of tropical cyclones would be much less).

Consequences at the Coastal Interface of the Terrestrial and Marine Environments

At coastlines, the consequences of the changes in marine and terrestrial components come together. Because the coastal region provides habitat to so many species, from shrimp to shore birds, and from plant species to humans, past and projected changes occurring in this boundary environment have particular importance for the environment and society.

Bays, inlets, estuaries, barrier islands, marshes, wetlands, and more provide habitat to a wide range of species, in some cases year-round and in other cases at particular times as species

[46] Mckenzie, D., Z. Gedalof, D. L. Peterson, and P. Mote, 2004: Climatic change, wildfire, and conservation, *Conservation Biology*, **18**, 890-902.
[47] Milly, P. C. D., R. T. Wetherald, K. A. Dunne, and T. L. Delworth, 2002: Increasing risk of great floods in a changing climate, *Nature*, **415**, 514-17.
[48] A large hurricane striking New Orleans is only one example of a very damaging event. Other examples identified during the US National Assessment included a storm surge into New York harbor, and the entire northeast coastline that has been spared strong hurricanes for several decades has since become increasingly developed, and susceptible to very high damage events.

migrate from one region to another. These regions are breeding grounds for fish and fowl, and those, including humans, that live off of them. The particular conditions each species needs results from the balance between the saline ocean waters and the terrestrial freshwaters, all mixed by the tides and ocean currents and moderated and mixed by the particular weather conditions ranging from mild sea breezes to raging storms. Nutrients are provided by the oceanic and river flows and by atmospheric deposition, all then cycled through by the chain of living plants and animals (including both terrestrial and marine life). Productivity has been able to develop as a result of the relative stability of the shoreline environment, with niches being filled to make optimal use of available resources.

Climate change is not the only stress that is now being imposed on this environment. Harvesting, air and water pollution, encroachment, toxics, excessive nitrogen deposition, oxygen deprivation, and more are all creating stresses, and now comes sea level rise and climate change (i.e., warming, changes in precipitation that alter runoff, intensified storms, changes in winds and ocean currents, and more). Sea level has been roughly stable for the past several thousand years, yet has recently begun to rise. Warming of ocean waters (which leads to their expansion, just as mercury expands to fill a thermometer as the temperature increases) and water added to the ocean, likely mostly from melting of mountain glaciers, caused global sea level to rise 4-8 inches (10-20 cm) during the 20th century.[49] For the 21st century, the early projections have been that sea level will go up by another 12-20 inches (30-50 cm);[50] with the apparent acceleration in the melting of the Greenland Ice Sheet that has been observed,[51] the Arctic Climate Impact Assessment concluded that projections of sea level rise for the 21st century could quite possibly exceed 20 inches (50 cm), reaching toward the upper limit of the IPCC projections. What is particularly problematic is that the factors contributing the most to sea level rise, namely thermal expansion and the ultimate melting of the Greenland and West Antarctic Ice Sheets are likely to continue to contribute to sea level rise for centuries after the rise in greenhouse gases is halted, meaning that significant areas of the shoreline will be inundated and lost over coming decades and centuries, and that protection of the most valuable regions through levee construction needs to receive early attention.[52] To date, no nation has prepared for sea level rise of a meter or more within a century, but the possibility warrants appropriate planning beyond normal disaster preparedness.

While the rise in sea level itself might seem small, when amplified by the effects of storms creating waves and storm surges, the situation is particularly threatening. In the Arctic, the melting away from the shore of the sea ice away has allowed winter waves to pound the barrier islands, causing significant erosion. This is particularly a problem because coastal regions are where many native communities have been located, often for thousands of years, in order to harvest the bounty of both the land and the ocean. The most endangered community is currently

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[49] See IPCC Working Group I Third Assessment Report, 2001. Over the past few decades, the rate of rise is consistent with a rate that exceeds the upper end of this range, indicating that an acceleration in the rate may have begun during this period (e.g., see Rignot, E., and P. Kanagaratnam, 2005: Changes in the velocity structure of the Greenland Ice Sheet, *Science*, **311**, 986-990).

[50] The full range for the IPCC estimate is about 4 to 35 inches considering the full range of all emissions scenarios and climate sensitivities, whereas the central estimate used in the text is for the average response across all climate models and emissions scenarios.

[51] Although projecting a rather significant buildup of ice on East Antarctica, IPCC's Third Assessment Report projected only very limited melting of the Greenland and West Antarctic Ice Sheets over the 21st century. Observations since publication of that report suggest that at least the Greenland Ice Sheet is likely to experience significant loss of ice as the warming builds up over coming decades.

[52] Low levees have already been installed around LaGuardia airport due to a severe storm some 50 years ago, and many additional areas are at risk. Low lying islands in the Chesapeake Bay have also been lost over recent times, more due to natural land subsidence than human-induced sea level rise, but providing an insight into the likely consequences of an acceleration of the rate of rise due to global warming. And the severe loss of coastal wetlands in the Mississippi delta region (again due mainly to other factors up to the present) provides a telling example of how important the coastal islands are for protecting communities.

Shishmaref, which is being eroded away so rapidly that community relocation has already started. As the Government Accountability Office has projected,[53] relocation of all the endangered villages is going to be very costly. Both the climate changes themselves and the relocations will lead to substantial disruption of subsistence harvesting[54] and indigenous culture and traditions that have sustained these communities through thousands of years.

For coastal regions exposed to hurricanes and the waves and the storm surges that they create, the danger is also very great. While international assessments have generally suggested that developing countries are more vulnerable to global warming that developed nations because they lack the resources to be able to adapt, the developed nations have at risk far greater investments in coastal infrastructure, including roads, highways, railroads, airports, ports, sewage treatment facilities, and residential and commercial buildings. Many of these structures are fully exposed to the oceans, unlike New Orleans, which at least at one time was protected by extensive wetlands. With the power and duration of intense hurricanes observed to be increasing, and with greater changes likely ahead as ocean temperatures continue to rise, the coastal region is particularly at risk. While building levees is likely to be able to work for a while, if sea level rise reaches a few meters within a few centuries, retreat is ultimately going to be required in many regions.

Disrupted coastlines are also likely to disrupt the resident and migrating wildlife. While some new wetlands may be formed further inland, it is unlikely that such new areas will be as extensive or as able to fill the many roles of existing areas, especially as the process of coastal inundation will be continuous rather than allowing full development at some altered, but fixed, change in sea level.

Summary and Concluding Thoughts

While the discussion above has focused on the great variety of changes and interactions that the increase in the CO_2 concentration and changes in climate are leading to (and the above list is only a sampling), what will be experienced by the environment and society will be all of these changes together, plus the impacts of all of the other changes going on, ranging from air and water pollution to resource utilization and land cover change. While a number of these can be (and are being) ameliorated by regulations and policy, climate change presents several unique aspects. First, climate change will keep growing and growing—it is an influence that can only be slowed, not reversed (at least in any reasonable time horizon). Second, it is fully global, and because the world is environmentally and economically interconnected, impacts in one location can create impacts in other locations. And third, the changes are larger and occurring more rapidly than can be accounted for using any analogs to the past, making very real the potential for surprises, unexpected changes, unidentified thresholds, and tipping points. As Australian author and scientist Barrie Pittock has put it, “Uncertainty is inevitable, but risk is certain.”[55]

For the natural world, change is already evident. Analyses by Parmesan and Yohe (2003) indicate with very high confidence that a large fraction of the plant and animal species studied are showing a response consistent with that expected to result from changes in climate.[56] The types of responses include shifts in range (e.g., the Inuits are spotting types of birds never seen

[53] GAO, 2004: *Alaska Native Villages: Villages Affected by Flooding and Erosion Have Difficulty Qualifying for Federal Assistance*, Statement of Robert A. Robinson, Managing Director, Natural Resources and Environment, GAO-04-895T.
[54] It is substantially more difficult to catch a whale or seal by chasing it in open waters than by waiting for it to surface at an air hole.
[55] Pittock, A. B., 2005: *Climate Change: Turning Up the Heat*, Earthscan, London, 316 pp.
[56] Parmesan, C., and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems, *Nature*, **421**, 37-42.

before that far north), changes in number and vitality (e.g., the polar bear population around Hudson's Bay), and unprecedented susceptibilities (e.g., to pest outbreaks). There is no question that the natural world is changing, and the main question is how much change can occur before changes in keystone species begin to cause the collapse of ecosystems (e.g., of the Amazon rainforest[57]) and significant reductions in the ecosystem services (e.g., air and water purification, food and fiber generation, fish and shrimp production) that these systems provide to society. Of particular concern are how all of these changes affect migrating species from birds to butterflies and fish to whales, for they have generally developed a dependence on a timeline of resources at particular locations in order to survive, and significant loss could occur from substantial disruption of any of them.

While modern society may seem less dependent on the natural world, many linkages remain, not only between communities and nearby ecosystems, but also with conditions around the world. Increased temperatures (along with higher absolute humidity—so much higher heat indices) will stress those not able to stay in and pay for air-conditioned space. While those in colder climates that have tight houses can readily transfer savings on heating bills to pay for increased cooling, those in more open homes in presently southern climates will have to invest in considerable structural upgrading to make air-conditioning a viable remedy. That the cost of upgrading will be high, and the need for it greatest among the poor, will create a serious issue of equity, with the least fortunate responsible for the lowest energy use yet suffering the largest consequences.

The effects will not only be personal. Not only do modern societies draw resources and food from ecosystems and countries around the world, but products also come from around the world and investment portfolios typically include a mix of international stocks, coupling one's economic state to the state of the world. In addition, with people traveling extensively for business and pleasure, the health of people around the world is interconnected, and what happens in one location can soon affect those in other locations. In that warm conditions are generally more favorable for the presence of disease vectors such as mosquitoes, warming will lead to the loss of the ally of freezing conditions for helping to control mosquito populations. As a result, except in regions (such as the US) where rigorous public health practices and community building standards have over time separated the disease from the disease vector and from people, warming and increased precipitation are likely to exacerbate the likelihood of exposure to disease vectors.[58] Even in countries such as the US, isolated occurrences are likely given the magnitude of international travel, and so extra resources will have to be devoted to maintaining high standards and quickly addressing new infestations (e.g., by spraying for mosquitoes). Changes in the distribution and level of activity of various plant species can also exacerbate health problems, as for example the increased production of pollen that can exacerbate incidence of asthma.[59]

The shifting climatic patterns and rising sea level are likely to be most problematic for small countries and other similarly sized entities. For island nations made up mainly of coral atolls, rising sea level and higher storm surges are already having deleterious effects on aquifers, and

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[57] For example, see Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, 2000: Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model, *Nature*, **408**, 184-187.
[58] For example, see Watson, R. T., J. Patz, D. J. Gubler, E. A. Parson, and J. H. Vincent, 2005: Environmental health implications of global climate change, *Journal of Environmental Monitoring*, **7**, 834-843, and Hunter, P. R., 2003: Climate change and waterborne and vector-borne disease, *Journal of Applied Microbiology*, **94**, 37S-46S.
[59] Beggs, P. J., and H. J. Bambrick, 2005: Is the global rise of asthma and early impact of anthropogenic climate change? *Environmental Health Perspectives*, **113**, 915-919.

continuing sea level rise is likely to inundate several island nations over the coming century. For small countries, especially those that have focused on growing a particular crop, shifting climatic patterns are likely to require changes in crop species, which is likely to be difficult to compete as there will likely be the need to break into new markets. Whereas many indigenous peoples, including the American Indian, have long traditions of adaptation, at the root of previous successes was often the ability to relocate; with tribal reservations now fixed, community relocation is no longer possible, and medicinal plants and other historic species are likely to shift to quite removed locations, negating the passed on ecological wisdom developed over so many generations.

For many regions, changes in water resources will be the most important effect, with increased competition for reduced resources among agricultural, community, industrial and ecological interests. For coastal regions, sea level rise and increases in storm intensity will pose the most important threats, requiring both enhancement of resilience in the near-term and possible relocation in the long-term. For those in urban areas, the increased likelihood of heat stress conditions and higher air pollution levels[60] may well pose the most significant threat. Because the particular situation of each region will depend on its individual circumstances, as indicated in Table 1, it is vital that the nation have an ongoing assessment activity that helps regions and sectors to understand, prepare for, and ameliorate the most deleterious circumstances. Such an effort, as is called for in the Global Change Research Act of 1990 [P. L. 101-606], was begun in earnest in 1997 with the undertaking of the US National Assessment; that this effort was essentially terminated in 2001 after having made significant progress in involving stakeholders in regional activities has been most unfortunate.

What is most clear is that global climate change is underway and that the risk of adverse consequences for both marine and terrestrial environments is quite high. While it will take substantial efforts and many decades to limit emissions of greenhouse gases and bring climate change to a stop as called for in the UN Framework Convention on Climate Change ratified by the US Senate in 1992, that virtually no effort is being made by the US to accomplish this in the face of all the scientific information about impacts is most unfortunate. For the people of the Arctic and of the US whom I have had the privilege of representing in assessment activities, I urge your most urgent consideration of a national effort to prepare for the inevitable climate change that lies ahead and to take actions to sharply limit the climate change that will be brought on by future emissions.

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Websites of Particular Relevance to Understanding of Climate Impacts:

[60] For a given level of pollution, higher temperatures accelerate the rate of formation of photochemical smog.

U.S. National Assessment of the Potential Consequences of Climate Variability and Change (http://www.usgcrp.gov/usgcrp/nacc/default.htm)
Arctic Climate Impact Assessment (http://www.acia.uaf.edu/)
Intergovernmental Panel on Climate Change: (http://www.ipcc.ch/)
Millennium Ecosystem Assessment: (http://www.millenniumassessment.org/en/index.aspx)
Climate Institute (http://www.climate.org/CI/index.shtml)

Table 1: Examples of important climate change consequences affecting regions of the US[61]

Regions and Subregions	Examples of Key Consequences Affecting:		
	the Environment	**the Economy**	**People's Lives**
Northeast New England and upstate NY Metropolitan NY Mid-Atlantic	Northward shifts in the ranges of plant and animal species (e.g., of colorful maples) Coastal wetlands inundated by sea-level rise	Reduced opportunities for winter recreation such as skiing; increased opportunities for warm-season recreation such as hiking and camping Coastal infrastructure will need to be buttressed	Rising summertime heat index will make cities less comfortable and require more use of air-conditioning Reduced snow cover
Southeast Central and Southern Appalachians Gulf Coast Southeast	Increased loss of barrier islands and wetlands, affecting coastal ecosystems Changing forest character, with possibly greater fire and pest threat	Increased productivity of hardwood forests, with northward shift of timber harvesting Increased intensity of coastal storms threaten coastal communities	Increased flooding along coastlines, with increased threat from storms Longer period of high heat index, forcing more indoor living
Midwest Eastern Midwest Great Lakes	Higher lake and river temperatures cause trend in fish populations away from trout toward bass and catfish	Increasing agricultural productivity in many regions, ensuring overall food supplies but possibly lowering commodity prices	Lowered lake and river levels, impacting recreation opportunities Higher summertime heat index reduces urban quality of life
Great Plains Northern Central Southern Southwest/Rio Grande Basin	Rising wintertime temperatures allow increasing presence of invasive plant species, affecting wetlands and other natural areas Disruption of migration routes and resources	Increasing agricultural productivity in north, more stressed in the south Summertime water shortages become more frequent	Altered and intensified patterns of climatic extremes, especially in summer Intensified springtime flood and summertime drought cycles
West California Rocky Mountains/Great Basin Southwest/Colorado River Basin	Changes in natural ecosystems as a result of higher temperatures and possibly intensified winter rains	Rising wintertime snowline leads to earlier runoff, stressing some reservoir systems Increased crop yields, but with need for greater controls of weeds and pests	Shifts toward more warm season recreation activities (e.g., hiking instead of skiing) Greater fire potential created by more winter rains and dry summers Enhanced coastal erosion
Pacific Northwest	Added stress to salmon populations due to warmer waters and changing runoff patterns	Earlier winter runoff will limit water availability during warm season Rising forest productivity	Reduced wintertime snow pack will reduce opportunities for skiing, increase opportunities for hiking Enhanced coastal erosion
Alaska	Forest disruption due to warming and increased pest outbreaks Reduced sea ice and general warming disrupts polar bears, marine mammals, and other wildlife	Damage to infrastructure due to permafrost melting Disruption of plant and animal resources supporting subsistence livelihoods	Retreating sea ice and earlier snowmelt alter traditional life patterns Opportunities for warm season activities increase
Coastal and Islands Pacific Islands	Increased stress on natural biodiversity as pressures from invasive species	Increased pressure on water resources needed for industry, tourism and	Intensification of flood and landslide-inducing precipitation during

[61] MacCracken, M. C., 2001: Climate Change and the US National Assessment, pp. 40-43 in *McGraw Hill Yearbook of Science and Technology 2002*, McGraw-Hill, New York, 457 pp.

South Atlantic Coast and Caribbean	increase Deterioration of corals reefs	communities due to climatic fluctuations, storms, and saltwater intrusion into aquifers	tropical storms More extreme year-to-year fluctuations in the climate
Native People and Homelands	Shifts in ecosystems will disrupt access to medicinal plants and cultural resources	The shifting climate will affect tourism, water rights, and income from use of natural resources	Disruption of the religious and cultural interconnections of Native people and the environment

Attachment 1: Arctic Temperature Change – Over the Past 100 years

Released 28 June 2005 by Gordon McBean, Lead author of Chapter 2, ACIA Report
The authors of Chapter 2 are: G. A. McBean, G. Alekseev, D. Chen, E. Førland, J. Fyfe, P.Y. Groisman, R. King, H. Melling, R. Vose and P. H. Whitfield

This note has been prepared in response to questions and comments that have arisen since the publication of the Arctic Climate Impact Assessment overview document – "*Impacts of a Warming Arctic*". It is intended to provide clarity regarding some aspects relative to the material from Chapter 2 *Arctic Climate - Past and Present* that will appear in full with the publication of the ACIA scientific report in 2005.

The authors of Chapter 2 began their work in 2000. It was recognized that the observational database for the Arctic is limited, with few long-term stations and a paucity of observations in general. Because at that time the published literature on Arctic temperature changes was not comprehensive nor up-to-date, it was decided to undertake a new set of calculations, based only on data sets that were fully documented in the literature, but updated to the present, using the documented procedures. The Global Historical Climatology Network (GHCN) database (updated from Peterson and Vose, 1997) was selected for this analysis. A comparison was made with the Climatic Research Unit (CRU) database (Jones and Moberg, 2003) because both databases were used in the Third Assessment Report (IPCC, 2001b) to summarize the patterns of temperature change over global land areas since the late 19th century. The GHCN dataset includes selected quality controlled long-term stations suitable for climate change studies. The US National Climate Data Center was asked to do the calculations since they had both datasets in their archives.

There are several possible definitions of the Arctic depending on, for example, tree line, permanent permafrost, and other factors. It was decided for purposes of this analysis that the latitude 60^{o}N would be defined as the southern boundary. Although somewhat arbitrary, this is no more arbitrary than choosing 62ºN, 67ºN or any other latitude. Since the marine data in the Arctic are very limited in geographical and temporal coverage, it was decided, for consistency, to only use data from land stations.

The analysis showed that the annual land-surface air temperature variations in the Arctic (north of 60ºN) from 1900 to 2002 using the GHCN and the CRU datasets led to virtually identical time series, and both documented a statistically significant warming trend of 0.09 ºC/decade during that period (Figure 1). Annual land-surface air temperature trends were calculated for the periods 1900-2003, 1900-1945, 1946-1965, and 1966-2003. Trends were calculated from annually averaged gridded anomalies using the method of Peterson et al. (1999) with the requirement that annual anomalies include a minimum of 10 months of data. For the period 1900-2003, trends were calculated only for those 5^{o} x 5^{o} grid boxes containing annual anomalies in at least 70 of the 104 years. The minimum number of years required for the shorter time periods (1900-1945, 1946-1965, and 1966-2003) was 31, 14, and 26, respectively.

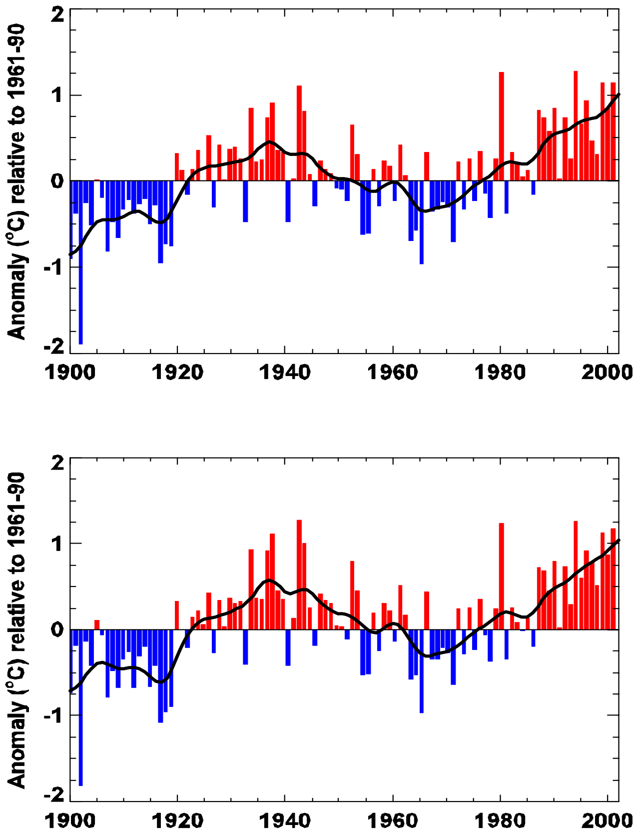

Figure 1. Annual anomalies of land-surface air temperature (ºC) from 60-90ºN for the period 1900-2002. Anomalies are relative to a 1961-90 base period. The smoothed curve was created using a 21-point binomial filter giving near decadal averages. Panel (a)(upper) depicts the GHCN time series (updated from Peterson and Vose, 1997), and panel (b)(lower) depicts the CRU time series (Jones and Moberg, 2003).

In response to critical comments about the ACIA analysis of the temperature record, it is important to note that the choice to use the CHCN dataset was made before the analysis was done, before the Polyakov et al. (2002) paper was published and based on the logical arguments that it was the most comprehensive land-station data base available and was well documented in the literature. As noted, the other well-documented database, of the CRU, gave virtually identical results.

It needs to be stressed that the spatial coverage of the region north of 60º N is quite varied. During the period (1900–1945), there are 7 grid boxes meeting the requirement of 31 years of data in the Alaska/Canadian Arctic/West Greenland sector. The largest number of grid boxes is in the North Atlantic sector (East Greenland/Iceland/Scandinavia) with 13 grid boxes. There were 10 grid boxes over Russia. The coverage for periods since 1945 is more uniform. Based on these analyses, the annual land-surface air temperature (ºC) from 60-90ºN, smoothed with a 21-point binomial filter giving near decadal averages, were warmer in the most recent decade (1990s) than they were in the 1930-1940s period.

The analysis of Polyakov et al. (2002) showed the 1930-1940s period warmer than the most recent decade. They used individual stations and the distributions of stations, according to the Figure 1 in their paper, was quite varied for different time periods. The total number of stations of more than 65 years is 8 stations in the Alaska/Canada/West Greenland sector compared to 43 stations in the North Atlantic/Russian sector. Over the whole period of record, their analysis considered 18 stations for the Alaska/Canada/West Greenland sector compared with 50 stations from the North Atlantic/Russian sector. The Polyakov paper also considered only maritime (or coastal) stations north of 62ºN, while the analysis presented in Chapter 2 of the ACIA report considered all land stations north of 60ºN. It should be noted that several of the locations of greatest warming in recent decades are apparent as a result of the continental stations between 60º and 62ºN (in Russia, Canada and Alaska).

Another important paper is that of Johannessen et al. (2004) who found, with a dataset extensively augmented by Russian station data not previously available, that the "early warming trend in the Arctic was nearly as large as the warming trend for the last 20 years" but "spatial comparison of these periods reveals key differences in their patterns". Their analysis, consistent with the analysis presented in the ACIA Chapter 2, showed that average annual temperatures were higher in the most recent decade than in the 1930-1940 period. Further, the pattern of temperature increases over the past few decades, they note, is different and more extensive than the pattern of temperature increases during the 1930s and 1940s, when there was weak (compared to the present) lower-latitude warming.

Chapter 3 of the ACIA report, entitled "The Changing Arctic: Indigenous Perspectives" documents the traditional knowledge of Arctic residents and indicates that substantial changes have already occurred in the Arctic and supports the evidence that the most recent decade is different from those of earlier in the 20th century.

Although all databases suffer from a lack of data in the Alaska/Canada/West Greenland sector except for the last 50 years, Polyakov et al. (2002), ACIA Chapter 2, Johannessen et al. (2004), Serreze, et al. (2000) and other analyses all show that the recent decades are warm relative to at least most of the period of instrumental record.

The rate of warming in the recent decades is also much greater than the average over the past 100 years (Figure 2). Least-squares linear trends in annual anomalies of arctic (60º to 90º N) land-surface air temperature from the GHCN (updated from Peterson and Vose, 1997) and CRU (Jones and Moberg, 2003) datasets for the period 1966-2002 both gave warming rates of 0.38 (ºC/decade). This is consistent with the analysis of Polyakov et al. (2002) and confirmed with satellite observations over the whole Arctic, for the past 2 decades (Comiso, 2003).

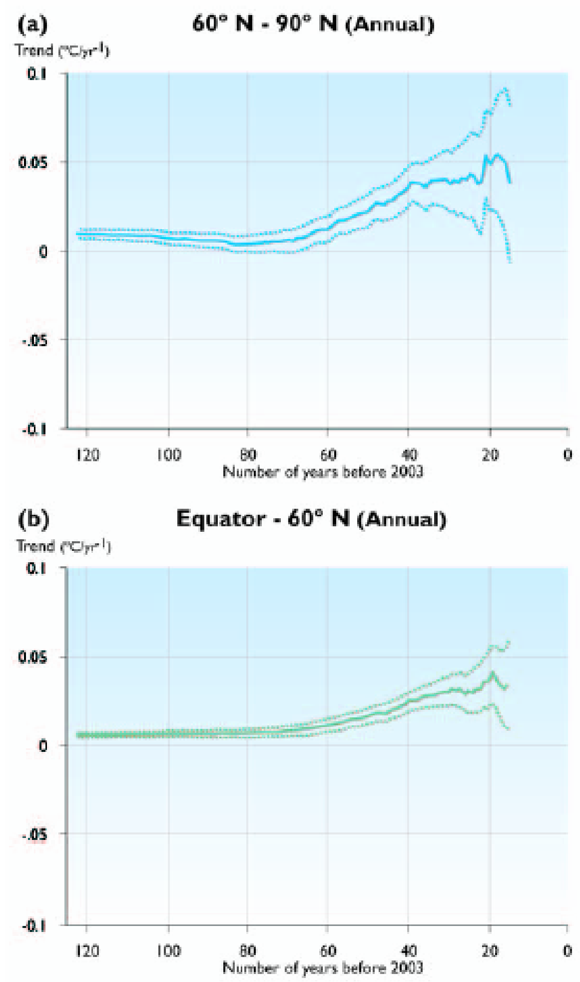

Figure 2. Trends in land-surface air temperatures (solid lines) and their 95% significance levels (dashed lines) over the past 120 years for (a) 60º to 90º N and (b) 0 to 60º N (data from the GHCN dataset, updated from Peterson and Vose, 1997).

The modeling studies Johannessen et al. (2004) showed the importance of anthropogenic forcing over the past half century for modeling the arctic climate. "It is suggested strongly that whereas the earlier warming was natural internal climate-system variability, the recent SAT (surface air temperature) changes are a response to anthropogenic forcing". A new paper, published after completion of the ACIA Chapter, by Bengtsson et al. (2004) states in its summary, with reference to the warming of the 1930-40s: "This study suggests that natural variability is a likely cause…"

As stated by the IPCC (2001b), model experiments show "a maximum warming in the high latitudes of the Northern Hemisphere". In reference to warming at the global scale, the IPCC (2001a) also concluded, "There is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities". Karoly et al. (2003) concluded that temperature variations in North America during the second half of the 20th century were probably not due to natural variability alone. Zwiers and Zhang (2003) were able to detect the combined effect of changes in greenhouse gases and sulfate aerosols over both Eurasia and North America for this period, as did Stott et al. (2003) for northern Asia (50–70º N) and northern North America (50–85º N). In any regional attribution study for the Arctic (which has not yet been published), the importance of variability must be recognized. In climate model simulations, the arctic signal resulting from human-induced warming is large but the variability (noise) is also large. Hence, the signal to noise ratio may be lower in the Arctic than at lower latitudes. In the Arctic, data scarcity is another important issue. However, it is implausible to conclude that the warming of the recent decades is not of anthropogenic origins.

In the context of this report, the authors agreed on the following terminology. A conclusion termed as "very probable" is to be interpreted that the authors were 90-99% confident in the conclusion. The term "probable" conveys a 66-90% confidence.

The conclusions of Chapter 2 were that:

"Based on the analysis of the climate of the 20th century, it is very probable that the Arctic has warmed over the past century, although the warming has not been uniform. Land stations north of 60º N indicate that the average surface temperature increased by approximately 0.09 ºC/decade during the past century, which is greater than the 0.06 ºC/decade increase averaged over the Northern Hemisphere. It is not possible to be certain of the variation in mean land-station temperature over the first half of the 20th century because of a scarcity of observations across the Arctic before about 1950. However, it is probable that the past decade was warmer than any other in the period of the instrumental record."

Polar amplification refers to the relative rates of warming in the Arctic versus other latitude bands. Using comparable data sets (the GHCN dataset), the warming for land stations over the region north of 60^{o}N, is almost double that for stations in the latitude bands 0-60^{o}N (Figure 2). The conclusions of Chapter 2 were that:

"Evidence of polar amplification depends on the timescale of examination. Over the past 100 years, it is possible that there has been polar amplification, however, over the past 50 years it is probable that polar amplification has occurred."

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