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## **The Arctic as a Test Case for an Assessment of Climate Impacts on National Security**

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# **The Arctic as a Test Case for an Assessment of Climate Impacts on National Security**

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## **Abstract**

The Arctic region is rapidly changing in a way that will affect the rest of the world. Parts of Alaska, western Canada, and Siberia are currently warming at twice the global rate. This warming trend is accelerating permafrost deterioration, coastal erosion, snow and ice loss, and other changes that are a direct consequence of climate change. Climatologists have long understood that changes in the Arctic would be faster and more intense than elsewhere on the planet, but the degree and speed of the changes were underestimated compared to recent observations. Policy makers have not yet had time to examine the latest evidence or appreciate the nature of the consequences. Thus, the abruptness and severity of an unfolding Arctic climate crisis has not been incorporated into long-range planning. The purpose of this report is to briefly review the physical basis for global climate change and Arctic amplification, summarize the ongoing observations, discuss the potential consequences, explain the need for an objective risk assessment, develop scenarios for future change, review existing modeling capabilities and the need for better regional models, and finally to make recommendations for Sandia's future role in preparing our leaders to deal with impacts of Arctic climate change on national security. Accurate and credible regional-scale climate models are still several years in the future, and those models are essential for estimating climate impacts around the globe. This study demonstrates how a scenario-based method may be used to give insights into climate impacts on a regional scale and possible mitigation. Because of our experience in the Arctic and widespread recognition of the Arctic's importance in the Earth climate system we chose the Arctic as a test case for an assessment of climate impacts on national security. Sandia can make a swift and significant contribution by applying modeling and simulation tools with internal collaborations as well as with outside organizations. Because changes in the Arctic environment are happening so rapidly, a successful program will be one that can adapt very quickly to new information as it becomes available, and can provide decision makers with projections on the 1-5 year time scale over which the most disruptive, high-consequence changes are likely to occur. The greatest short-term impact would be to initiate exploratory simulations to discover new emergent and robust phenomena associated with one or more of the following changing systems: Arctic

hydrological cycle, sea ice extent, ocean and atmospheric circulation, permafrost deterioration, carbon mobilization, Greenland ice sheet stability, and coastal erosion. Sandia can also contribute to new technology solutions for improved observations in the Arctic, which is currently a data-sparse region. Sensitivity analyses have the potential to identify thresholds which would enable the collaborative development of “early warning” sensor systems to seek predicted phenomena that might be precursory to major, high-consequence changes. Much of this work will require improved regional climate models and advanced computing capabilities. Socio-economic modeling tools can help define human and national security consequences. Formal uncertainty quantification must be an integral part of any results that emerge from this work.

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# 1. Introduction: Global Climate Change and Arctic Amplification

The Earth has entered a period of rapid climate change, primarily driven by increases in atmospheric infrared opacity due to higher concentrations of greenhouse gases related to human activities. A significant fraction of the thermal energy from Earth that would normally pass through the atmosphere and be radiated into space is instead absorbed by the higher concentration of molecules that interact with infrared radiation and are there because of human actions. Part of this energy is re-radiated back to the surface, resulting in higher temperatures. The physical basis of the greenhouse effect has been known for more than a century. John Tyndall experimented with the greenhouse properties of gases starting in 1858 (Tyndall, 1870), and Svante Arrhenius described the warming effect of carbon dioxide quantitatively in a paper published more than a century ago (Arrhenius, 1896). Because of uncertainties in feedbacks associated with atmospheric and ocean circulation, water vapor concentrations, cloud properties, snow and ice cover, permafrost deterioration, biological and human adaptations, and other responses, precise quantitative forecasts will never be possible. However, there is no known mechanism by which the atmospheric radiative imbalance can be completely compensated by feedbacks. In the unlikely event that globally compensating feedbacks do exist, there is no known process by which the spatial distribution of heat transport would remain the same as it was before the atmosphere changed. The feedbacks themselves would arise from some combination of changes in circulation, hydrological cycle, surface properties, and biological response. For this reason, accelerating anthropogenic climate change is a virtual certainty. The severity and consequences of climate change are open questions that will always have some degree of uncertainty.

The most useful measurement of climate state is global average surface air temperature, which has increased by about 0.6 or 0.7° C since the start of the industrial revolution, e.g. (Jones and Moberg, 2003). Because Earth's climate is a complex and multifaceted dynamic system that is not sufficiently described by a single variable, "global warming" is only one aspect of the ongoing transition. Other features of global climate change include changes in size, frequency, timing, and distribution of weather events and precipitation, increased drought and desertification, decreases in ocean pH, loss of biodiversity and ecosystems, reduction in sea ice extent, changes in the nature of land ice, and increased rate of sea level rise. Earth's climate is a coupled, nonlinear dynamic system, so these changes are not independent, but include feedbacks that can lead to cascading, rapid, and unpredictable responses. Moreover, these aspects of the climate system are strongly coupled to the human systems of agriculture, land use, industry, fisheries, trade, water use, and migration. Instabilities and unpredictability in the physical and ecological parts of the Earth system lead inevitably to economic and geopolitical instability, e.g. (Stern, 2007), which can have national security implications.

It has long been known that the Arctic is a critical component in the Earth's energy distribution system. It is strongly influenced by changes in radiative forcings, and it also is a powerful driver of the rest of the system. The cause of this "Arctic amplification" is attributed primarily to ice-albedo feedback, first suggested by James Croll in 1875. Ice

and snow are much more reflective than the underlying surface or seawater. In a warming Earth, ice and snow begin to retreat at higher latitudes and altitudes, exposing the darker substrate and increasing the fraction of sunlight that is absorbed. The strong positive feedback led to the prediction that as the Earth warmed, the effect would be more pronounced in the Arctic, where rapid temperature increases should be accompanied by loss of ice and snow. More recent studies indicate the presence of other feedbacks, such as higher humidity, that also contribute to Arctic amplification, e.g. (Graversen, *et al.*, 2008).

According to (Serreze and Francis, 2006), we are now approaching a threshold beyond which Arctic amplification will accelerate, leading to strong increases in surface air temperatures over the Arctic Ocean in the near future. Model projections suggest that the threshold should be preceded by a “preconditioning phase” in which sea ice retreats and thins for several years. Even a thin, young layer of ice acts as an insulator and mechanical barrier that constrains the flow of heat from the ocean to the atmosphere, and limits wind-driven currents. However, once the threshold is crossed, the Arctic is expected to quickly transition to open water in the late summertime. Wintertime re-growth would be severely limited. Moreover, because thermal, hydrological, and mechanical coupling between open water and atmosphere are both qualitatively and quantitatively different, the entire Arctic system would be expected to dynamically reorganize itself into a new but unknown configuration. In general we know that the Arctic region will probably have reduced sea ice extent and significant changes in precipitation patterns but there is a great deal of uncertainty about how oceanic and atmospheric circulation, weather events, and ecosystems will adjust. There is no *a priori* reason to expect that the reorganization of such a highly nonlinear system would be reversible or even stable. Moreover, biological and human systems have adapted by natural and engineered optimization processes to the previously existing system, so it is unlikely that the net consequences of such a change would be beneficial.

The Arctic system may have already reached its tipping point (Serreze, *et al.*, 2007); (Holland, *et al.*, 2006). Consensus is growing that the transition to a seasonally ice-free Arctic Ocean is inevitable; however, there is no agreement about the speed or mechanism of this transformation. There is increasing concern among Arctic climate specialists that there will be strong global consequences. The possibilities of nonlinear cascading effects, particularly those involving changes in the hydrologic cycle, make prediction a challenge. The Arctic ice serves as a buffer for the temperature of the northern hemisphere and the Arctic region controls much of the heat flow and circulation. However, the chaotic nature of the fluid interactions creates enormous uncertainty about the global response.

There is no reason to think that these rapid and irreversible changes to the Arctic will be limited to sea ice. Recent models suggest that Arctic land temperatures will increase at 3.5 times the average global rate (Lawrence, *et al.*, 2008). This rapid warming could reach as far as 1500 km into the Alaskan, Canadian, and Siberian mainland, causing permafrost to deteriorate quickly over a large area. This warming, melting and thawing at high northern latitudes would also generate multiple cascading effects on the rest of the Earth system. Destruction of permafrost releases methane, a powerful greenhouse gas



that would accelerate the increase in the atmosphere's infrared opacity throughout the planet. Warmer temperatures in the Arctic will likely lead to an increase in another important greenhouse gas: water vapor. Arctic amplification also means that the average meridional temperature gradient that drives atmospheric and ocean circulation will change, altering weather patterns, storm tracks, temperature distributions, and currents worldwide.

Arctic amplification explains why the strongest evidence of rapid global warming has emerged first at high northern latitudes; this region has been described as the "canary in the coal mine." Because of feedbacks in the nonlinear Earth system, we expect the enhanced effects in the Arctic to have multiple cascading effects on the climate at lower latitudes (Alley, 1995). At the risk of mixing metaphors, we also describe the Arctic as the "regional tail that wags the global dog." Furthermore, Arctic climate change will have major direct effects on the economies, resource availability, infrastructures, shipping lanes, strategic assets, military operations, and indigenous peoples of the circum-Arctic nations, which include military and economic superpowers. Because of the global nature of the world economy and trade, the rest of the world will also be affected by these changes; see (Backus and Strickland, 2008). It is for these reasons that we believe the Arctic region should be the first major focus of Sandia's attempts to anticipate national security implications of global climate change.

A comprehensive report about Arctic climate change and its repercussions would require thousands of pages. Because of the swift pace of the change and rapidly expanding research, an exhaustive survey would also be out of date by the time it was printed. Our intention with this report is to provide a brief snapshot of the current state of Arctic change. We sacrifice depth and completeness in order to highlight the most noteworthy recent observations in section 2, and we list a subset of possible consequences in section 3. Section 4 provides a discussion of risk assessment methods that can be applied to climate change consequences, and why the term "conservative assumptions" has a very different meaning for engineers and security specialists than it does for scientific researchers. In section 5 we use scenarios as a framework for planning and discussion, and in section 6 we describe approaches for Arctic modeling and how models can be improved. Finally, section 7 provides recommendations about how Sandia can contribute to this very serious national security issue.

This report is not intended to be a complete analysis. Rather, we view it as a distillation of leading technical assessments on the subject of Arctic climate. The most comprehensive summary of the rapidly-advancing scientific understanding of global climate change is provided by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)<sup>1</sup>. This document (hereinafter called "AR4") was published in 2007, but because of its ponderous size and lengthy preparation time it is only current as of 2005. For a very complete review of the impact of climate change on the Arctic region, we recommend the Arctic Climate Impact Assessment - Scientific Report<sup>2</sup>, published by Cambridge University Press (hereinafter called "ACIA"). Despite the recent publication year, the ACIA is also slightly dated because of the extremely rapid pace of change, discovery, and scientific progress. The ACIA contains very few references after 2003, and it made extensive use of the IPCC Third Assessment Report

(TAR)<sup>3</sup>, which was published in 2001 and “frozen” a year or two earlier. Both of these reports are rich with graphics and data, and can be freely downloaded.

The AR4 and ACIA are based on peer-reviewed primary literature, but because of the slow pace of scientific publishing relative to the speed of recent developments, we have also turned to other sources. These include media reports, institutional press releases, and even the online log of a research vessel that was still at sea at the time of our writing. In keeping with our desire for brevity and readability, we have avoided simply repeating information or reproducing graphs and figures that are in the two reports or readily available on Wikipedia and elsewhere on the Worldwide Web. Likewise, to keep our reference list to a manageable size, we have chosen not to cite the primary literature that is already cited by AR4 and ACIA, except when we think it needs special emphasis. For that reason, most of our citations are to AR4, ACIA, and to information that has been published in the past five years or so. We encourage interested readers to go to those sources first.

This report was written during the last quarter of the International Polar Year 2007-2008. The fourth in a series of international polar years, IPY 2007-2008 began in March 2007 and will conclude in March 2009, extending over twenty-four months in order to provide researchers with two full annual cycles for their studies of the Arctic and Antarctic. IPY 2007-2008 demonstrates recognition by the international science community that polar regions are vitally important in the Earth climate system.

Starting almost two hundred years ago the early polar explorers—Nansen, Shackleton, Scott, Byrd, Amundsen, and others—used sextants, dog sleds, skis, and wooden ships to investigate unknown regions. We are fortunate today to have satellites, snow machines, hand-held GPS navigation, the Internet, and supercomputers to probe the polar regions. Yet we still face great uncertainties about the Arctic, its future, and its role in the Earth’s climate system. This report is an early survey of those unknowns as they relate to climate change and how we might address them.

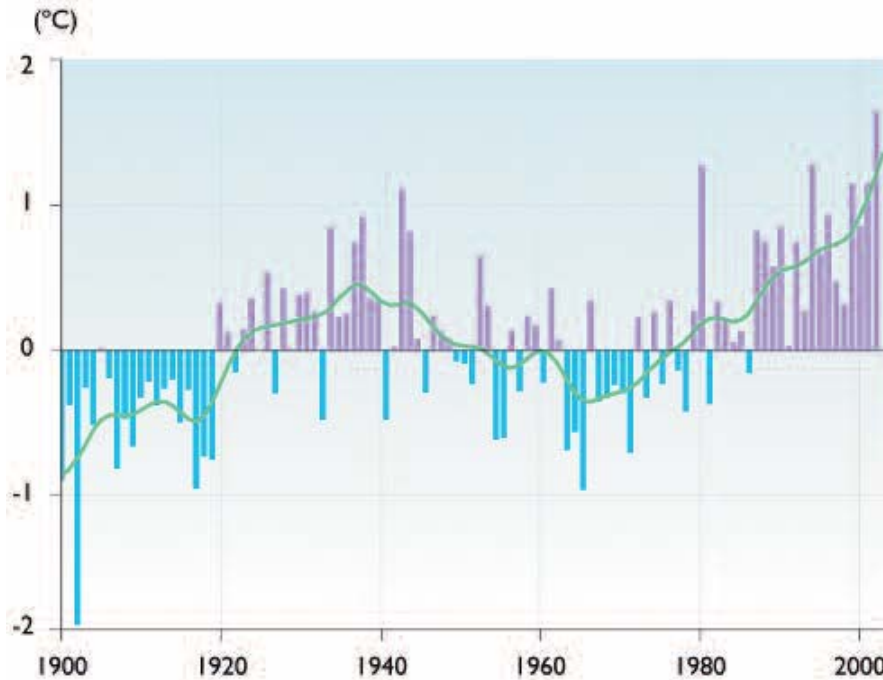
## 2. Arctic Climate Change: Observations and Projections

This section provides a very brief survey of some of the climate-related changes that are already taking place in the Arctic, or that have been observed in the paleoclimate record. Many of these changes had been predicted to be among the far-reaching effects of global climate change, and are expected to continue or accelerate, even if mitigation strategies are implemented. The present discussion is limited to observations of physical changes and projections for future changes. The consequences of these changes—both ongoing and anticipated—are discussed in the next section.

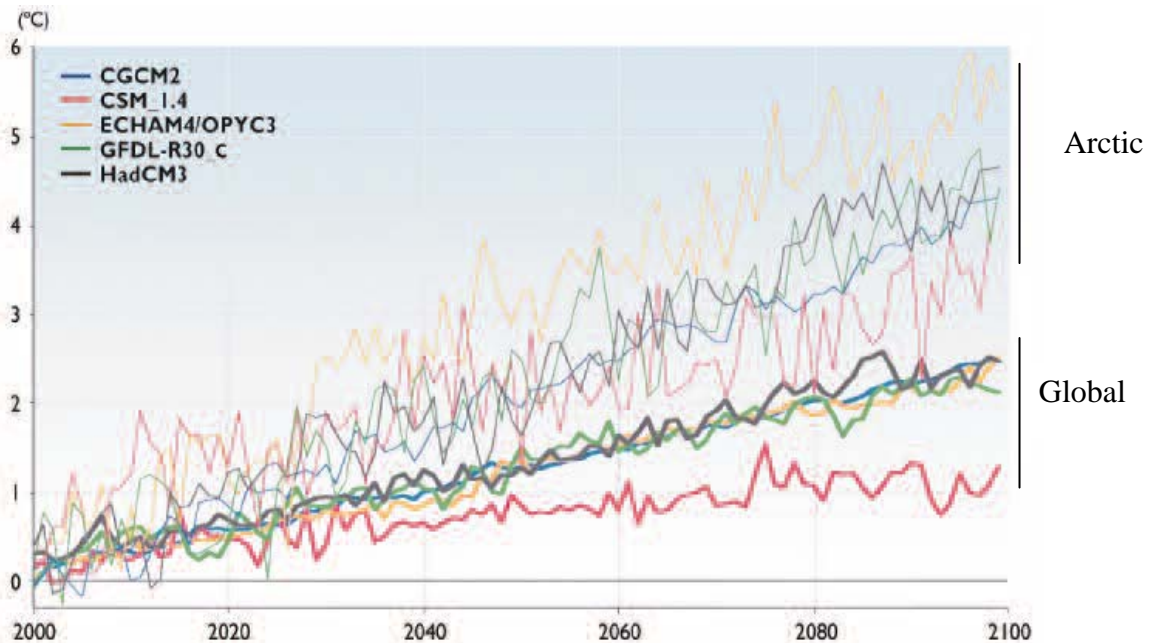
### 2.1 Surface air temperatures

The global mean surface air temperature is the standard geophysical parameter that researchers use to quantify global climate change because it integrates spatial and temporal changes in the Earth's energy balance and it can be determined empirically and objectively. The Arctic surface air temperature has long been considered to be a bellwether of global climate change because of ice-albedo and other feedbacks that lead to Arctic amplification. Mean annual surface air temperatures in the Arctic have increased by 2 or 3° C since the middle of the 20<sup>th</sup> century, with wintertime increases by as much as 4° C. As shown in Figure 2.1 below, the ACIA reproduces a graph of these average temperatures from land-based weather stations north of 60° N, going back to 1900, with maps showing that Alaska, western Canada and most of Siberia have experienced the most warming. The notable mid-20<sup>th</sup>-century cooling is attributed to increased sulfate aerosols from fossil fuel burning, which has since been overtaken by accelerating greenhouse warming because of cumulative nature of greenhouse gases. Eastern Canada, Southern Greenland, and Eastern Siberia have cooled, suggesting that circulation patterns have also changed. Figure 2.2 shows temperature projected by five models used by the IPCC for one emissions scenario.<sup>4</sup>

The five general circulation models (GCMs) used in the ACIA report to project future warming exhibited significant variability in projected seasonal and regional temperature increases, especially in polar regions. All five models predict that Arctic warming will be much greater than global warming, with estimates of an additional 4 to 6° C (relative to the 1981-2000 average) before the end of the 21<sup>st</sup> century for the moderately optimistic B2 emissions scenario of the IPCC. However, even the most sensitive of the five ACIA models greatly underestimated the change that has now emerged as the most visible sign of Arctic warming: the loss of sea ice. Higher Arctic temperatures are also responsible for observed accelerated melting of the Greenland ice sheet, which has global consequences. According to climatologist Konrad Steffan of the Cooperative Institute for Research in Environmental Sciences (CIRES, University of Colorado), “For every degree (F) increase in the mean annual temperature near Greenland, the rate of sea level rise increases by about 10 percent.”<sup>5</sup>



**Figure 2.1.** Annual average near-surface air temperature from stations on land relative to the average for 1961–1990, for the region from 60° to 90° N; updated from (Peterson and Vose, 1997) in ACIA, Chapter 1.

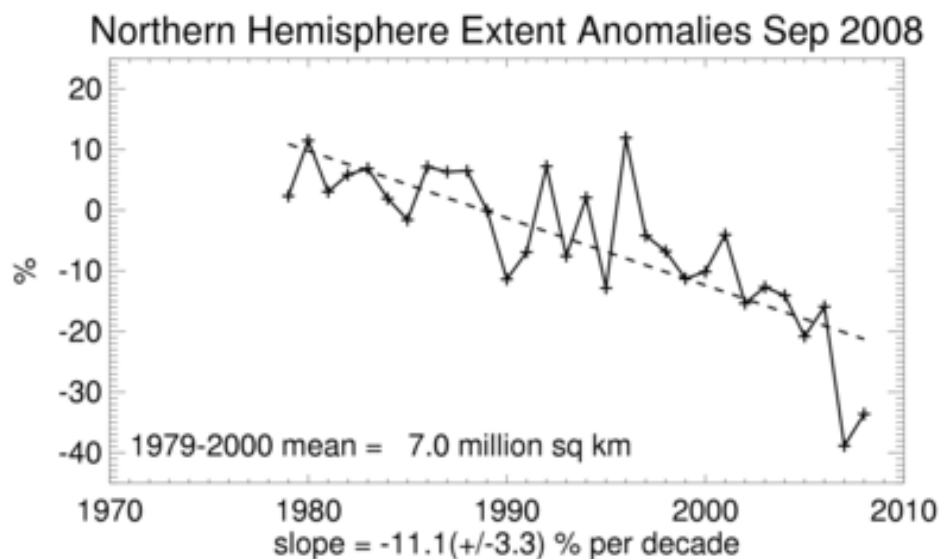


**Figure 2.2.** Average surface air temperatures projected by the five ACIA-designated climate models for the B2 emissions scenario (see ACIA Chapter 4 for further details). The heavy lines are projected average *global* temperature increases and the thinner lines the projected average *Arctic* temperature increases. 1981–2001 average temperatures shown.

## 2.2 Sea ice loss

Melting of Arctic sea ice has long been identified as one of the strongest signals of climate change. Ice cover is now disappearing at an alarming and unprecedented rate, well beyond the most pessimistic predictions. The most cautious ACIA model projected a “near-total melting of Arctic sea ice by 2100.” Taking recent trends into account, (Maslowski, 2007) now estimates that a seasonally ice-free Arctic could happen as early as 2013.

The extreme developments of the past two summers can be put into perspective by reviewing scientific reactions to the records of previous years. Prior to the 2005 ACIA report, the record for minimum sea ice was set in September, 2002, when its extent was reduced by 15% from the 1979-2000 average minimum of 7.0 million km<sup>2</sup> (Figure 2.3). At that time, according to researcher Mark Serreze of the National Snow and Ice Data Center (NSIDC),<sup>6</sup> “the 2002 sea-ice record is the most recent evidence of a downward trend in Arctic sea ice in the decades since satellite monitoring began.” Others pointed out that the 2002 minimum may have been the lowest in several centuries. Serreze suggested that, “with these trends, we may see an approximate 20% reduction in the annual mean sea ice by 2050, and by then we might be approaching no ice at all during the summer months.” This ice forecast may have seemed excessively pessimistic in 2002 but now appears restrained. By September 2007, the ice cover had decreased to 4.28 km<sup>2</sup>, nearly 40% below the long-term average.



**Figure 2.3.** Historical September arctic sea ice extent (NSIDC)

Because the canonical long-term average only considers the years 1979 through 2000, during which there was already a downward trend, the summer minimum sea ice extent may already have fallen by as much as 50% since the 1950s. The rate of loss is accelerating, apparently due to ice-albedo feedback effects. In the summer of 2008—for the second year in a row—the sea ice extent had dropped below 5 million km<sup>2</sup> before the

end of August, a low that had never been reached even at the time of the September minimum in previous years. Ice *volume* is difficult to measure as precisely as extent, because thickness cannot be determined by remote sensing. Nevertheless, there is evidence that ice volume is shrinking at an even faster rate than its areal extent because thicker, older ice is being replaced by younger, thinner ice. This makes the sheet more vulnerable in the future, because young ice is less resistant to melting. In 2001, before the recent acceleration in melting, the volume was already down by 40% according to the Office of Naval Research report “Naval Operations in an Ice Free Arctic”.<sup>7</sup> The sea ice has now almost certainly shrunk to less than half its pre-warming volume. According to NSIDC, the 2008 ice minimum has likely set a new record for low volume even though the area increased slightly from the all-time low in 2007.<sup>8</sup>

Many researchers think the tipping point has already passed and that losses will continue to accelerate, partly because of ice-albedo feedback but also because of more subtle positive feedbacks. For example more edges of the sheet are exposed to the mechanical action of waves. Large swaths of sea ice break off and melt much more rapidly because of the increase in edge length. Losses of ice from the remaining Arctic ice shelves (which are grounded, rather than floating) are accelerating even more rapidly. Ellesmere Island’s ice shelves are thought to be 4,000 years old, but are in the process of disappearing. In the summer of 2008, a 55 km<sup>2</sup> ice sheet broke off of the Markham Ice Shelf, bringing the total ice shelf loss to about ten times what had been predicted for the season.

This ongoing trend is particularly troubling because sea ice moderates global climate by reflecting incoming solar radiation and keeping the Arctic region cooler than it would otherwise be. The Arctic system is buffered by the ice in many ways. The temperature is buffered by the latent energy required for melting. The hydrological cycle is buffered by the capping effect that keeps liquid water isolated from the air. Wind-driven currents are buffered by the mechanical barrier provided by the ice sheet. Since the end of the last ice age about 10,000 years ago, the Arctic has been remarkably stable, probably because of the constancy of both land and sea ice and its ability to buffer small changes. It can be argued that this Arctic stability is to a large degree responsible for the atypical global climate stability during the period that witnessed the ascent of agriculture and civilization (Feynman and Ruzmaikin, 2007).

The recent rapid changes in ice extent and configuration of the physical properties of the Arctic Ocean have created a regional geography that is very different than any time in recorded history. This is likely to have a profound effect on the surrounding regions, and on global climate. Because the changes are happening so quickly compared to initial estimates of change, little research has been done to understand how these changes will continue to evolve or their consequences for Earth’s inhabitants.

## **2.3 Coastal erosion**

Erosion of the Arctic coast is also accelerating as a consequence of climate change. The extent and duration of open water adjacent to the shore is increasing, so wind and waves have a longer time to act on coastal sediments. The sediments themselves are

more vulnerable to erosion as the warming of hard layers of permafrost causes them to melt, lose their stability, and subside. Moreover, patterns of atmospheric circulation are changing, and stronger winds blowing across longer ice-free fetches produce higher waves with more erosive potential. Coastlines that were protected by large expanses of sea ice in the past are now being battered by big waves during the seasonal retreat of the ice. These increases in erosion will be exacerbated by rising sea levels and higher storm surges, if present trends continue. Erosion rates have already doubled along some sections of the Alaskan Arctic Coastline (Mars and Houseknecht, 2007), even prior to the recent record-breaking sea ice losses. Coastal erosion redoubles the positive feedbacks because it accelerates degradation of coastal permafrost which increases the release of greenhouse gases into the atmosphere. Greenhouse gases increase the rate of global warming, and the permafrost degradation increases the rate of coastal erosion, in a vicious circle characteristic of positive feedback.

Both ecological and human systems are affected by coastal erosion. Erosion rates of historically-stable shores can become remarkably fast. According to a 2005 report on Arctic Coastal Dynamics,<sup>9</sup> the island Muostakh of the Siberian Arctic Coast is experiencing coastal retreat rates of several meters per year. At this rate the island will be completely destroyed within 50 years. Its prehistoric carbon will be returned to the atmosphere, and its ecosystems will be irreversibly lost.

Other effects of coastal erosion include the increase of offshore sedimentation which can affect marine ecosystems and fisheries. Thawing of permafrost is also increasing the rate of Arctic river erosion and sediments that are carried to the sea. Benthic (bottom-dwelling) organisms are dependent on organic material that descends from the shallow, food-producing layers. Increasing the fraction of inorganic sediments from coastal erosion is likely to disrupt the balance of both shallow and deep-water ecosystems.

## **2.4 Permafrost degradation**

Permafrost is defined as sediment that has remained below the freezing point of water for two or more consecutive years. According to the U. S. Arctic Research Commission's 2004 report on Climate Change, Permafrost, and Impacts on Civil Infrastructure,<sup>10</sup> it makes up 24% of the land area in the Northern Hemisphere and contains about 30% of the worldwide soil carbon reservoir, which is now estimated to be about twice as much carbon as contained in the atmosphere (Schuur, *et al.*, 2008). The permafrost is concentrated in a geographical band at high latitudes that crosses Siberia, Fennoscandia, Greenland, Canada, and Alaska. One effect of polar amplification is the acceleration of permafrost melting inland from the Arctic Ocean. According to the 2005 ACIA summary, temperatures of permafrost on land surrounding the Arctic Ocean have increased by amounts ranging from a few tenths of a degree to as much as 3° C over the past few decades. The ACIA report estimates that permafrost degradation is likely to take place over 10 to 20% of the present area of permafrost. The permafrost area is likely to retreat northward by several hundred kilometers. This estimate may already be out of date, because new evidence suggests that changes are happening more rapidly.

New models and observational data suggest that temperature increases associated with the accelerated ice loss will penetrate up to 1500 km inland (Lawrence, *et al.*, 2008). This would lead to heat accumulation and rapid melting of permafrost. The heating and degradation of permafrost has several important effects on the Earth system. Like the Arctic sea ice, permafrost serves as a buffer. Permafrost moderates the transfer of heat, water, nutrients, and gasses between the solid Earth and the atmosphere. It also provides stability to sediments. This added stability prevents them from subsiding and eroding. Most importantly, carbon dioxide and methane are released to the atmosphere by bacteria and fungi as they process the organic material at temperatures above the freezing point. Many researchers are concerned that this could become a dominant positive feedback in the climate system. The warming accelerates the release of greenhouse gases, and the accumulation of these gases in the atmosphere reinforces the warming. This runaway greenhouse effect may be one of the reasons why past ice ages have ended so abruptly compared to their gradual onset.

If a significant fraction of the carbon now frozen in terrestrial permafrost were released to the atmosphere, it could dwarf the amount that is being released by human activities. Scientific understanding has progressed rapidly since compilation of ACIA and AR4. It has just been determined, for example, that in East Siberia alone the wind-blown Yedoma permafrost contains about 450 billion tons of easily-mobilized carbon (Zimov, *et al.*, 2006). This is about as much carbon as the rest of the Arctic combined, and the same amount of carbon that has been released by all the burning of fossil fuels since the beginning of the industrial revolution. If the Arctic were to warm up enough to decompose only 1% of the permafrost per year, it would double the carbon releases to the atmosphere from the present rate due to human activities (about 9 billion tons/year). There is mounting observational evidence that the Yedoma is releasing methane at an accelerating rate. For example, the area of Siberian thermokarst lakes is expanding because of the warming, and more methane is bubbling out (Walter, *et al.*, 2006). New models of the Yedoma suggest that it is vulnerable to future warming, with a tipping point for irreversible carbon mobilization that depends on both temperature and warming rate (Khvorostyanov, *et al.*, 2008).

Permafrost also exists along the coast and at the bottom of the sea. Most of this subsea permafrost was formed during past glacial epochs, when sea level was lower. It has remained stable during the interglacial periods between ice ages because its temperature is mediated by the ocean and floating sea ice and is protected from the heat from the sun and from the warm summer air. Within and beneath the subsea permafrost are methane hydrates, which contain vast stores of methane that have been locked up for hundreds of millennia. Subsea permafrost has been thought to act as an impermeable layer that keeps this methane source sequestered. Some researchers have speculated that climate change could release large quantities of subsea methane to the atmosphere, exacerbating the causes of global warming (Judge and Majorowicz, 1992; Kvenvolden, 1988).

As this report was in preparation, Igor Semiletov, the Chief Scientist of the International Siberian Shelf Study 2008 (ISSS-08) logged a new discovery on the International Arctic Research Center (IARC) University of Alaska Fairbanks expedition



web site. He reported the discovery of “several new areas of substantial methane seeps” by the research vessel *Yacob Smirniskiy* off the Siberian coast and a “new field of dissolved methane hot spots” in the Laptev Sea, which he says confirms the conclusion that “sub-sea permafrost is not a non-permeable lid for deep methane leakage.”<sup>11</sup> One of the expedition leaders, Orjan Gustafsson (Stockholm University) elaborated, “Yesterday, for the first time, we documented a field where the release was so intense that the methane did not have time to dissolve into the seawater but was rising as methane bubbles to the sea surface. These 'methane chimneys' were documented on echo sounder and with seismic [instruments].”<sup>12</sup> These findings are from an expedition that was still in progress at the time this report was written, and it is significant that the pace of Arctic change and discovery is exceeding the speed at which new data and papers can be peer reviewed and published.

## 2.5 Greenland ice sheet and sea level

Greenland has more land ice than anywhere else on Earth other than Antarctica. The volume of the Greenland ice sheet, which represents 10% of the world's freshwater, would raise sea level by about 7 meters if it were to melt (see NOAA's Arctic Report Card 2008).<sup>13</sup> Historically, the cap has been melting very slowly and has contributed to about 1.8 mm of sea level rise per year. The rate has been accelerating, but the increase has nearly been compensated by an increase in precipitation associated with higher temperatures, and the consequent accumulation of snow. The ice sheet covers about 85% of Greenland's land area and is more than 2 km thick in places. Large sheets of land ice have disappeared very rapidly at the end of past glacial periods when melting began, causing sea level to rise about 1.2 meter per century over the 8000 year period just prior to the Holocene (AR4). The area of surface melt is increasing, and grew by 16% between 1979 and 2002.

According to (Gregory, *et al.*, 2004), about half the volume of snowfall on Greenland is lost through melting of the ice sheet, and the other half is lost in the form of icebergs. Recent ice loss rates and the flow rates of glaciers have been determined by remote sensing methods, including satellite-based laser altimetry, gravimetry, and radar interferometry measurements. Net volume loss during the 1990s was about 60 km<sup>3</sup>/year, increasing to about 80 km<sup>3</sup>/year by the end of the century (Krabill, *et al.*, 2004; Thomas, *et al.*, 2006). More recent gravimeter measurements show that the rate has increased to as much as 248 km<sup>3</sup>/year (Chen, *et al.*, 2006; Luthcke, *et al.*, 2006; Ramillien, *et al.*, 2006; Velicogna and Wahr, 2006). The sheet is melting most rapidly at the edges, and in fact may be thickening toward the center due to increased precipitation. Additional increases in the loss of ice sheet volume are due to the acceleration of glaciers along the margin, (Rignot and Kanagaratnam, 2006; Stearns and Hamilton, 2007). The losses may continue to accelerate due to positive feedback mechanisms associated with water from melting at the surface that infiltrates and lubricates the flow (Parizek and Alley, 2004; Zwally, *et al.*, 2002), as well as increasing contact with warming and rising sea water (Bindshadler, 2006; Howat, *et al.*, 2005; Thomas, 2003). The large uncertainty associated with the estimates and the short period during which satellite observations have been made lead to questions of whether the recently-observed trends are a climate-change-induced acceleration or part of a recurring pattern of variability. Nevertheless,

(Wouters, *et al.*, 2008) have now determined that accelerating loss in Greenland ice sheet volume has contributed an average of 0.5 mm/year to rising sea levels between 2003 and 2008.<sup>14</sup> Most models predict that realistic emissions scenarios will lead to complete melting of the Greenland ice sheet, but there is lack of consensus as to how rapidly melting will occur.

## 2.6 Clouds and aerosols

Low-level boundary layer clouds tend to dominate in the Arctic with very high temporal frequencies in all seasons (Curry, *et al.*, 1996; Intrieri, *et al.*, 2002a). A particularly important feature is that these clouds are often mixed-phase (Shupe, *et al.*, 2005) even at quite low temperatures, consisting of liquid-water tops that precipitate ice (Pinto, 1998), or even multiple liquid-water layers embedded within precipitating ice (Intrieri, *et al.*, 2002b; Verlinde, *et al.*, 2007). Surface clouds may play an important role in the ice-albedo feedback process, because the added moisture from the increased open water due to sea ice melting promotes cloud formation. These clouds do not necessarily influence Arctic climate in the way one would anticipate from experience at lower latitudes. In the Arctic, clouds warm the surface rather than cool it for all but a few weeks a year, around the summer solstice. For most of each year, outgoing infrared radiation in the Arctic exceeds incoming visible radiation from the sun. Clouds interfere with the outgoing radiation and hence act to warm the surface. A large fraction of the outgoing radiation energy is “imported” from lower latitudes. To understand the surface cloud radiative forcing it is necessary to understand the factors that regulate the cloud microphysical processes, in particular the liquid-water phase.

Anthropogenic aerosols are a wild card for Arctic climate change. The radiative balance is directly affected by absorption and scattering of the aerosol pollutants associated with the sulfate-rich persistent haze that is present during the Arctic winter and spring. Because the haze absorbs light, the direct effect is to raise the temperature of the atmosphere. However, there are also low albedo, soot-contaminated aerosols that can lead to strong radiative heating of snow and ice at the surface. The mechanisms by which Arctic haze evolves—and which control its radiative effects—may involve organic processes at the sea surface, photochemical, and other processes that are subject to climatic feedbacks in ways that are poorly understood.

Subtle changes in aerosol conditions can also have major indirect radiative effects by changing the optical properties of clouds. Detailed cloud-resolving model studies suggest that modest increases in ice nuclei concentrations in Arctic mixed-phase clouds can transform a largely liquid stratus deck of wide aerial coverage into a broken, optically thin cloud system (Harrington and Olsson, 2001; Harrington, *et al.*, 1999; Jiang, *et al.*, 2000; Morrison, *et al.*, 2005; Prenni, *et al.*, 2007). Based on observations from the Mixed-Phase Arctic Cloud Experiment (M-PACE); (Verlinde, *et al.*, 2007) conducted on the north slope of Alaska in October 2004, (Fridlind, *et al.*, 2007) concluded that observed concentrations of ice nuclei are insufficient by several orders of magnitude to explain observed ice, and that other mechanisms have to be

invoked to explain ice formation in mixed-phase clouds. Aerosol variations also appear to have a direct impact on the surface cloud radiative forcing through the liquid phase: recent work (Garrett, *et al.*, 2004; Lubin and Vogelmann, 2006) suggested a longwave indirect effect of aerosol, in which higher droplet numbers and smaller droplet sizes increases the longwave emissivity of clouds. In addition to these aerosol effects, cloud liquid water content depends on cloud-scale dynamics, sea ice coverage and thickness, and large-scale atmospheric circulation patterns (Curry, *et al.*, 1990; Curry, *et al.*, 1996; Harrington and Olsson, 2001; Jiang, *et al.*, 2000; Vavrus, 2004), all of which have strong seasonal dependence.

## 2.7 Precipitation and extreme weather

An integral part of the Arctic hydrological cycle is precipitation. There is an enormous variation in precipitation around the Arctic region, ranging from 300 cm/year in southern coastal parts of Alaska, Iceland, and Norway, down to 15 cm/year in inland parts of Siberia.<sup>15</sup> Precipitation is controlled by proximity to warm ocean currents that provide heat and moisture, and by atmospheric circulation and weather patterns. Arctic precipitation also shows strong seasonal variability. Increases in Arctic precipitation rates were a predicted aspect of climate change. These increases have been observed in long-term weather records, but have been accompanied by decreases in the duration of snow cover, exacerbating positive ice/snow albedo feedbacks that lead to further warming.

Extreme weather events in the Arctic are usually associated with Arctic cyclones, which are low-pressure systems with high winds and counterclockwise flow. Arctic cyclones transport heat and moisture to higher latitudes, and are responsible for major precipitation events in the form of snowstorms and blizzards. These storms are the most damaging, and generate sea waves that are primarily responsible for coastal erosion. Research has shown that Arctic cyclone activity increased in the second half of the 20<sup>th</sup> century (Zhang, *et al.*, 2004)<sup>16</sup> and there is evidence that the distribution pattern of storms has shifted poleward. This trend is superimposed on a shorter-period oscillation, and suggests a link to ongoing Arctic climate change.

## 2.8 Arctic Oscillation

The Earth's climate system is characterized by oscillations on various times scales that span many orders of magnitude. Some oscillations are based on deterministic external forcings. For example the Earth's annual trip around the sun changes the distribution of sunlight falling on the surface, resulting in seasons. The wobble of the Earth on its axis, its changing tilt, and the variation of the orbital eccentricity on a ten-thousand-year timescale leads to Milankovitch cycles that result in quasi-periodic ice ages.

There are also cycles associated with internal interannual variability of the Earth system, which appears to have natural oscillations. Our understanding of these is based primarily on empirical observations. The most famous cycle is the El-Nino/Southern Oscillation, which is associated with the temperature of tropical Pacific waters and their

coupling to atmospheric circulation. This oscillation is responsible for major shifts in weather and precipitation patterns on both sides of the Pacific Ocean.

The Arctic Oscillation is characterized by regional sea-level pressure variations that exhibit a see-saw pattern in which multi-year cycles between high and low pressure in the Arctic are balanced by pressure anomalies of the opposite sign at northern mid-latitudes. The “warm phase” occurs when the Arctic pressure is low, north Atlantic westerly winds are stronger, the U. S. gets a warm winter, northern European weather is warm and wet, and the Mediterranean region is dry. In the “cool phase” the Arctic pressure is high, westerlies are weak, the U. S. and European winters are cold, and the Mediterranean is stormy.

There is growing evidence the Arctic Oscillation is changing from a cool-phase dominated pattern to a stronger and longer warm phase. The most recent warm phase has come with new wind and ocean circulation patterns that have caused warmer saline waters to flow further into the Arctic Ocean than it usually does.<sup>17</sup> This change has helped accelerate the sea ice melting, which may create a feedback that sustains this phase for an extended period, leading to an ice-free Arctic and fundamentally different climate in the future.

## **2.9 Paleoclimate**

Some of the best data for reconstructing Earth’s past climate have come from the Greenland ice cores, which record stable isotope signatures of Arctic climate. The oxygen isotope ratio is a proxy for the temperature history over central Greenland and reveals a remarkable degree of relative stability since the last ice age ended about 10,000 years ago at the beginning of the Holocene epoch. Before that, global climate was constantly changing, sometimes very abruptly. Even during the stable Holocene, there is evidence for significant climatic shifts, especially on regional scales. Human civilization and agriculture arose during the Holocene, during a long period of relative climate stability.

One of the most significant scientific results from the Greenland ice cores is the recognition that climate can shift very suddenly and unexpectedly. In the past 100,000 years, there have been at least 25 fast climate transitions in which temperatures on Greenland shifted by 5° C within a few decades. Most notable is research showing that about 11,500 years ago, temperatures increased by 8° C within 40 years, with much of the warming taking place over shorter intervals (Alley, 2000).<sup>18</sup> These events appear to be related to sudden changes in the North Atlantic circulation that transports equatorial heat to high latitudes, possibly from an influx of freshwater that creates a buoyant layer, preventing cold water from sinking to be replaced by warmer surface waters from the south. Large freshwater discharges can result from rapid melting of ice sheets and collapses of ice dams with releases of water from lakes. These results suggest that rapid changes in the Arctic ice can be amplified in a cascading sequence with global consequences.

Newer methods of analyzing the ice cores are improving the resolution and revealing that changes can happen much faster than previously thought. (Steffensen, *et al.*, 2008) have now shown that as the precursor to a major warm period that began 14,700 years ago, the atmospheric circulation reorganized and shifted to an entirely different state within 1 to 3 years. Patterns of dust in the ice cores suggest that the shift was accompanied by major changes in precipitation patterns as far away as Asia. The sobering implication is that the current perception of climate stability might be an illusion. If the past is a guide to the future, there is good reason to think an abrupt global change could be triggered by the rapid changes that are now taking place in the Arctic.

The most significant global warming event known to have occurred in the history of the Earth is the Paleocene-Eocene Thermal Maximum (PETM). About 55 million years ago, global temperatures rose by 6° C within a period of about 20,000 years (Kennett and Stott, 1991). The temperature increase was greatest in the polar regions, where mean surface air temperatures rose to as high as 20° C (Shellito, *et al.*, 2003), and sea surface temperatures near the North Pole reached 22° C (Sluijs, *et al.*, 2006). One consequence of this global warming episode was the greatest mass extinction in the past 90 million years, with the loss of 35 to 50% of deep sea benthic foraminiferal species (Thomas, 1998). The leading hypothesis for the cause of this climate collapse is a runaway greenhouse warming involving the destabilization of sea floor methane hydrates and catastrophic releases of carbon to the atmosphere when the ocean temperatures warmed (Dickens, *et al.*, 1995). (Bowen, *et al.*, 2006) describe how recent advances in PETM research provide insight into current climate change.

*“During the PETM, carbon addition to the oceans and atmosphere of a magnitude similar to those anticipated through the 21st century. The event initiated global warming, biotic extinction and migration, and fundamental changes in the carbon and hydrological cycles that transformed the early Paleogene world.”*

The mean global temperature increase during this mass extinction was similar to the upper range of the IPCC estimates for 21<sup>st</sup>-century warming. Perhaps the biggest difference between this prehistoric climate change and the current warming is that temperature is currently rising hundreds of times faster than its average rate of increase during the PETM catastrophe.



### 3. Consequences of Arctic Climate Change

This section provides a list of some of the consequences of climate-related change in the Arctic. As physical and geographical changes proceed, new economic opportunities are emerging as well economic threats and the prospect of new conflicts. Many aspects of climate change can have impacts on national security because of effects on human activities both within the Arctic region and around the world.

#### 3.1 Shipping

In the summer of 2008, the North Pole could—for the first time in history—be circumnavigated in open waters. The Northwest Passage above Canada and Northern Sea Route (NSR) above Eurasia were simultaneously ice free. If the trend of decreasing sea ice continues or accelerates, these passages will become reliable for shipping, and will become the default routes for transporting goods between Europe, Asia, and North America for at least part of the year. The NSR is more than 40% shorter than the southern routes through the Suez or Panama canals, for shipments between Northern Europe and Northeast Asia or the American Northwest, according to information from the International Northern Sea Route Programme.<sup>19</sup> Shipping via the NSR also has the advantages of avoiding cargo ship size restrictions imposed by the canals and the increasing piracy problems in the Indian and Eastern Pacific Oceans. It has not been used as a major trade route because historically it has been choked with ice, and it was under strict Soviet control until 1991.

The NSR traverses Russian territorial waters. During the peak of its military power in the 1980s, the Soviet Union maintained a fleet of 16 icebreakers (half of which were nuclear) that patrolled the NSR. As the Soviet Union was in the process of dissolving, Russia formally opened the route to foreign ships in 1991. The Russian military icebreaker fleet is rapidly aging and, unless replacements are built, will decline to 3 ships by 2015. However, the Russian commercial icebreaker fleet is rapidly modernizing with the addition of icebreakers and ice-capable tankers that can navigate the NSR. Russia is in the process of shifting resources to the port of Murmansk, home of the Russian Northern Fleet, and the northernmost city in Fennoscandia. In recent public statements, former Russian president Putin promoted construction of new icebreakers. Many commentators expect international shipping through the NSR to grow rapidly if the climate trend continues and if Russia establishes a stable and reasonable tariff system.

The Northwest Passage is likewise becoming a viable shipping route, but an international disagreement is emerging over whether it traverses waters that are interior to Canada, or whether it is entirely in international waters. Neither the U. S. nor the E. U. recognizes Canadian claims of sovereignty. This is a major concern in Canada, and it was a significant campaign issue in Prime Minister Harper's 2006 election. However, the increased physical accessibility could lead the U. S. toward reconciliation. It may be to U.S.'s advantage to acknowledge Canadian control in return for guarantee of passage, thereby gaining a strategic and security advantage. Both the U. S. and the Canadian governments have announced plans to build up their Arctic fleets.

### 3.2 Oil, gas, minerals, resources

The Arctic is becoming more accessible for exploitation at precisely the same time that energy and minerals are becoming more valuable. According to a July 2008 report by the U. S. Geological Survey,<sup>20</sup> as much as 13% of the world's undiscovered oil and 30% of undiscovered gas reserves are in the Arctic seabed. A recent report by the Center for Strategic and International Studies (CSIS)<sup>21</sup> states that the Arctic may contain up to 100 billion barrels of oil and 25% of the Earth's remaining oil and gas. The CSIS summary reiterates the consequences of changing Arctic climate on these resources.

*“Climate change in the Arctic is occurring at an ‘unprecedented’ rate, and the Far North is the most appropriate place to study global warming... Until recently, experts saw arctic hydrocarbon resources as too expensive and too difficult to extract. This has changed as technology has progressed and the price of oil has continued to increase, and countries are now staking their claims.”*

The United Nations Convention on the Law of the Sea (UNCLOS) gives coastal states sovereignty in a zone that reaches to a 200-nautical mile limit, but stipulates an extension for islands, sea mounts, or shallow waters associated with the continental shelf. Since Arctic bathymetry is complicated, and shallow waters extend for hundreds of miles, there are overlapping territorial claims. Moreover, the U. S. has signed the UNCLOS, but has not yet ratified it. Arguments for and against ratification are listed in the CSIS summary.<sup>22</sup> Because of the changing conditions of the Arctic Ocean, the provisions of the UNCLOS may be a “moving target.” For example, circum-Arctic states have much more control over ice-covered waters in their Exclusive Economic Zones (EEZs) than they do over open water. Some of their control over these waters may melt away along with the ice.

There are tremendous reserves of onshore and offshore oil, gas, and natural resources that belong to Russia. Onshore and near-offshore fields such as Russia's Pechora basin and Ob River basin, Canada's Mackenzie Delta, and America's Prudhoe Bay are not in dispute, but as Arctic ice retreats, new offshore resources will continue to be discovered. The U. S. Arctic contains an estimated 13% of domestic oil reserves, the development of which is increasingly vulnerable to accelerated coastal erosion. Timber and mineral resources can be shipped to the Arctic from the Siberian interior using the well-developed river transport system that connects the Arctic to centers of Siberian commerce and the southern railway that connects to Europe and the Pacific coast. The changing physical conditions in the Arctic Ocean and the high-latitude land areas may create a new “gold rush” that has the potential for conflict as well as further environmental impact.

### 3.3 Territorial claims

Boundaries and international laws are not well defined or accepted by all parties, so the potential for conflict is high. There are only five nations with territorial claims in the Arctic: Russia, Canada, U. S., Denmark, and Norway. Sweden, Finland, Iceland, and semi-autonomous groups of indigenous peoples also have economic and strategic interests. There are a large number of border disputes of one kind or another currently in



the Arctic. Canada has declared that the now-opening Northwest Passage cannot be traversed without passing through its territorial waters, but the U. S. position is that these are international waters. However, Canada's Arctic Coastline remains undeveloped, whereas Russia has operating infrastructure on its Arctic coast and is poised for further economic development.

Russia is the most aggressive of the circum-Arctic nations, and is increasingly dependent on its mineral and fuel exports for income. According to Russian President Medvedev, "The Arctic for Russia holds great strategic meaning. This region is directly linked to meeting the long-term challenges of the country and its competitiveness in global markets."<sup>23</sup> In keeping with that sentiment, Russia is claiming most of the Arctic seabed under the United Nations Law of the Sea. The Russian government asserts that the Lomonosov Ridge, which traverses the Arctic Ocean from Siberia to well beyond the North Pole, is an extension of the continental shelf and therefore part of Russia's exclusive Extended Economic Zone (EEZ).

To address these issues, an Arctic Ocean Conference was held in Ilulissat, Greenland in May, 2008.<sup>24</sup> The conference was organized by Denmark's foreign minister Stig Møller, who cited the need to "fulfill our obligations in the Arctic area until the UN decides who will have the right to the sea and the resources in the region" and to "agree on the rules and what to do if climate changes make more shipping possible." This summit resulted in an Ilulissat Declaration:

*"Climate change and the melting of ice have a potential impact on vulnerable ecosystems, the livelihoods of local inhabitants and indigenous communities, and the potential exploitation of natural resources. By virtue of their sovereignty, sovereign rights and jurisdiction in large areas of the Arctic Ocean, the five coastal states are in a unique position to address these possibilities and challenges."*

The declaration also specifically rejected efforts by the international community to create laws to govern the use of the Arctic Ocean as an international trust, modeled after Antarctica. The emerging "Arctic Five" clearly intend to control oil, gas and mineral exploration, shipping, and environmental regulation, with focus on economic exploitation rather than ecological preservation. This puts the Arctic Five at odds with the European Union, which is attempting to exert influence over the future of the Arctic, with stronger focus on environmental protection. It also appears to be at odds with Møller's statement that the UN should make the decisions about use of the sea and resources.

### **3.4 International conflict and military operations**

The Ilulissat Declaration is the most recent development and may be the first step in diffusing the escalating rhetoric and resolving border claims. Nevertheless, the potential for conflict remains, and the stakes continue to grow along with the area of open Arctic waters. Russia has been expanding its aging nuclear icebreaker fleet, aggressively pursuing its claims to the Arctic seabed, and used a deep-submersible submarine in 2007 to plant its flag on the seabed under the North Pole. The U. S. Coast Guard has called for more icebreakers and is planning new facilities on the Arctic coast of Alaska. China is

maintaining an Arctic research vessel.<sup>25</sup> Canada recently announced plans to construct a military base and deepwater port adjacent to the Northwest Passage and to build a small fleet of boats to patrol the passage where it passes through its claimed territorial waters.

Territorial disputes are emerging among all five Arctic coastal nations. Even Denmark and Canada have clashed over jurisdiction of tiny Hans Island, a barren and uninhabited 1.3 km<sup>2</sup> bit of land in the straight between Ellesmere Island and Greenland. The dispute is largely symbolic, but has become the most visible focus of Canada's plan to assert sovereignty over its northern territorial islands and waters. Conflict can be precipitated over disagreements over sovereignty, over economic and exploration rights, or over freedom of passage. The military infrastructure is changing in anticipation of potential conflict, but this infrastructure is itself vulnerable to accelerating climate change. Some military installations in the Arctic already succumbed to the changing climate. As a highly visible example, three NORAD early-warning radar stations were decommissioned last year, at least partially due to coastal erosion and soil instability.<sup>26</sup>

### 3.5 Roads and infrastructure

Climate change and the anticipated acceleration in permafrost loss have significant implications for Arctic infrastructure (Lawrence, *et al.*, 2008). The ACIA report discusses infrastructure issues in detail, and provides a summary of engineering projects that may be impacted. The following paraphrased bullets are extracted from the ACIA infrastructure chapter:

- Northern pipelines (such as the Trans-Alaska Pipeline and the proposed gas pipeline from the North Slope of Alaska) are likely to be affected by frost heave and thaw settlement. Slope stability is also likely to be an issue in discontinuous permafrost.
- The settlement of shallow pile foundations in permafrost could possibly be accelerated by temperature increases over the design life of a structure (~20 years).
- Large tailings disposal facilities might be affected (negatively or positively) by climate change, due to the long-term effects on tailings layers.
- The availability of off-road transportation routes (e.g. ice roads) is likely to decrease owing to a reduction in the duration of the freezing season. The effect of a shorter freezing season on ice roads has already been observed in Alaska and Canada (this is already happening and is limiting drilling in the Arctic).
- Climate change is likely to reduce ice-cover thickness on bodies of water and the resulting ice loading on structures such as bridge piers. However, until these effects are observed, it is unlikely that engineers will incorporate them into the design of such structures.
- The thickness of Arctic sea-ice cover is also decreasing in response to climate change, and it is possible that this will affect the design of offshore structures for ice loadings, and the design of ice roads used to access structures over landfast ice in winter.
- Precipitation changes are very likely to alter runoff patterns, and possibly the ice–water balance in the active layer. It is very difficult to assess the potential effects of

these changes on structures such as bridges, pipeline river crossings, dikes, or erosion protection structures.

- The stability of open-pit mine walls will possibly be affected where steep slopes in permafrost overburden have been exposed for long periods of time. The engineering concerns relate to increased thaw depth over time, with consequent increased pore pressures in the soil and rock, and resulting loss of strength and pit-wall stability.
- The cleanup and abandonment of military and industrial facilities (including oil production facilities) throughout the Arctic sometimes involves storage of potentially hazardous materials in permafrost. There is some chance that permafrost degradation associated with climate change will threaten these storage facilities.

There will be enormous economic costs associated with re-engineering, retrofitting, and rebuilding Arctic infrastructure to withstand expected climate change. However, it is clear from this list of impacts that the uncertainty is large, and much of the cost will be associated with designing infrastructure to withstand large and poorly-defined margins of uncertainty.

### **3.6 Ecosystems**

Arctic ecosystems are many and varied. They support large mammals such as polar bears, walruses, and seals, as well as numerous resident and migratory birds. Terrestrial ecosystems include boreal forests, Arctic tundra, and polar deserts. Freshwater ecosystems include rivers and streams, lakes and ponds, and wetlands. Marine ecosystems in the Arctic are unique, and the sea ice plays an enormously important role. Ice controls the exchange of heat, moisture, and gases at the ocean/atmosphere interface, it affects the amount of sunlight that penetrates into the water, and it creates habitat for predators and prey both above and below the surface. There are both shallow and deep marine ecosystems. All are experiencing strong climate-related changes, and some of them—such as the remote and little-explored ecosystems of the Ellesmere Island ice shelves—are on the verge of disappearing altogether. The ACIA report has several chapters on ecosystem impacts, some of which are considered to be likely or very likely. Most of these impacts are already happening and are expected to continue and/or accelerate. Some of the bullets, extracted from the ACIA report, are paraphrased and briefly summarized here:

#### **Arctic tundra and polar desert ecosystems**

- The dominant response of Arctic species may be to migrate rather than adapt.
- Very long term response may be increased diversity through speciation.
- Populations may change primarily because of extreme events.
- Forest and shrubs may invade tundra, reducing albedo and further increasing temperature.
- Soils may continue warming and drying, but the net affect on carbon is uncertain.
- Rapid climate changes will very likely increase fire, disease, and pest outbreaks.

## **Freshwater ecosystems**

- Impacts are very uncertain due to complexity and lack of long-term monitoring.
- Increased winter river flows may increase under-ice habitat.
- Lower summer water levels of lakes and rivers may affect aquatic habitats.
- Permafrost thawing may increase nutrient, sediment and carbon loadings.
- Increased sediments are likely to be harmful to benthic fauna.
- Lakes are very likely to drain catastrophically due to permafrost thaw.
- Biodiversity will very likely be affected across most of the Arctic.
- Microbial decomposition rates are very likely to increase
- More organic matter and nutrients will very likely lead to greater biological production.
- Many species will shift their ranges and community compositions.
- Spawning grounds for cold-water fish are likely to diminish.
- There will likely be an increase in fish, mammal and bird diseases and parasites.
- Migration patterns of aquatic mammals and waterfowl are likely to change.
- Reproductive success is likely to be altered by changes in habitat.

## **Marine ecosystems**

- Area and intensity of phytoplankton production will increase.
- Different phytoplankton species composition is favored by mixing depth.
- Southern range of zooplankton, benthic fauna, and fish species will recede.
- More adaptable zooplankton species may be favored.
- Production of shrimp and crab species may decline.
- Spawning and feeding behavior of fish will change.
- A mismatch in timing between zooplankton and fish larvae may emerge.
- Cod, herring, walleye, pollock, and some flatfish may increase and move north.
- Capelin, polar cod, and Greenland halibut will decline and range will shrink.
- Marine mammals and seabird distributions will shift poleward.
- Mammals that depend on ice will suffer dramatic declines.
- Temperate mammal species will benefit and increase.
- Seabird production is unpredictable due to unknown changes in food supply.
- Declines of polar bear, and ringed, harp, hooded, and spotted seals.
- Increased distribution of harbor seals and grey seals.
- Possible declines in bowhead, narwhal, grey, and beluga whales.

There are many studies published since the ACIA report showing that many of these changes are already taking place. (Hoste, *et al.*, 2007) have observed losses in microbial biomass and other marine ecosystem changes. Ecosystems that depend on Arctic permafrost are being threatened by its rapid degradation (Lawrence, *et al.*, 2008). Boreal forests have already become more vulnerable to insects and wildfires. Native tundra is yielding to invasion of shrublands. Polar bear populations are declining because they can no longer migrate to their den sites on land and reach their prey on the ice. Polar bears are also being observed at sites far inland from the Arctic coast, formerly a rare event. Changes in marine ecosystems are having an effect on production of fisheries, which have direct economic and geopolitical impacts.

### 3.7 Fisheries

The Arctic is home to some of the world's most productive fisheries. As the ice-sea boundary moves northward, the area of ocean open to indigenous and commercial fishing will increase. The change in surface conditions, coupled with increasing air temperatures, will have a profound effect on marine ecosystems. In the Bering Sea, the seasonal growth of shallow-water phytoplankton colonies is initiated by the annual retreat of sea ice. Earlier loss of ice leads to later blooms, which form the bottom of the food chain for the entire marine ecosystem. The seabed (benthic) ecosystem dominates the cold-water, ice-covered Arctic Ocean, which is associated with high productivity of crustaceans and the seabirds and marine mammals that feed on them and one another. The water-column (pelagic) ecosystem tends to dominate warmer ice-free waters, but it is unclear how the ecosystem balance will adapt to changes in the seasonal timing of ice retreat and increased temperature.

Fisheries researchers suggest that climate change has the potential to change geographic distributions of existing fish species, allow new species to establish themselves, change the timing of seasonal migrations and spawning, change abundances, mortality and growth rates, modify predator-prey and competitor interactions among species, in addition to rebalancing the pelagic and benthic communities according to fisheries expert Gordon Kruse.<sup>27</sup>

The most complete summary of how climate change will impact Arctic fisheries can be found in Chapter 13 of the ACIA: "Fisheries and Aquaculture" which includes this discussion in the summary:

*"Modeling studies show that it is difficult to simulate and project changes in climate resulting from the response to forces that can and have been measured and even monitored on a regular basis for considerable periods and on which the models are built. Furthermore, current climate models do not include scenarios for ocean temperatures, watermass mixing, upwelling, or other relevant ocean variables such as primary and secondary production, on either a global or regional basis. As fisheries typically depend on such variables, any predictions concerning fisheries in a changing climate can only be of a very tentative nature."*

The economic and social impact of climate change on fisheries is virtually impossible to forecast because of the complexities of the natural systems and the associated human response.

### 3.8 Indigenous populations

The rapid loss of Arctic sea ice poses a particularly severe problem for high-latitude indigenous populations whose traditional subsistence lifestyles depend on the abundance of wildlife and healthy ecosystems that depend on the ice. These native peoples include the Inuit, Aleuts, Athabascans, and Gwich'in of Alaska, Canada, and Greenland, the Sami of Scandinavia and Russia, and many smaller native Siberian groups. Many indigenous hunters are dependent on stable and predictable sea ice, which they use every spring to get to their whaling sites, and to transport their wildlife harvests home. For many groups,

the subsistence way of life is a central part of the cultural and spiritual heritage that may be lost if they are forced to convert their diet to imported foods and participate in a cash economy. Such disruptions in the traditional ways of native people typically lead to severe social problems. Impacts on indigenous populations are reviewed in detail by the ACIA.

To provide one example of impacts and their economic costs, the state of Alaska recently allocated funds for projects to boost the protections of some of the state's endangered coastal villages from erosion due to climate change. According to a 2003 report by the U. S. General Accountability Office,<sup>28</sup> 184 of Alaska's 213 native villages are having problems with increased erosion and flooding. Several villages are becoming uninhabitable because the erosion is exacerbated by sinking of the ground due to warming and disintegrating permafrost. For example, the Yupik Eskimo village of Newtok is receiving \$3.3 million to relocate its 321 residents to a new site on higher ground. Other projects are reinforcing sea walls and other erosion control measures to delay relocation of other villages. Changes in the environment coupled with higher energy costs are driving many Alaskan natives to migrate to cities. The Mayor and Schools Superintendent of Anchorage recently sent a letter to the Governor of Alaska asking to establish a task force to find ways to deal with this migration.<sup>29</sup>

### **3.9 Sea level rise**

Increasing sea level is the most obvious and dramatic means by which the "Arctic tail" can wag the "global dog." Many papers have pointed out the vulnerability of Greenland ice to a warming climate. Precipitation rates are projected to increase as a consequence of the higher temperature and humidity associated with climate change, but ice melting is expected to increase at an even higher rate, leading to net decrease in ice volume (IPCC TAR Working Group 1). (Gregory, *et al.*, 2004) analyzed the effect of all the IPCC scenarios and concluded that the Greenland ice sheet is likely to disappear during the next 1,000 years, leading to an average sea level rise of seven meters or more. At the end of the last glacial period, estimated sea level rise was in excess of 1 meter per century for thousands of years. A sea level rise of 7 meters in 1000 years is not unprecedented (AR4) and 3-5 meters in a century is not impossible during the most abrupt transitions.

The average global sea level rise during the 20<sup>th</sup> century was between 10 and 20 cm, and mostly due to thermal expansion. For virtually all of human history, the rate of sea level rise had been an order of magnitude slower. Moreover, ice loss would be irreversible on a historical time scale even if global conditions and atmospheric greenhouse gas concentration were to return to their present level. This hysteresis in thermal response is at least partially due to ice albedo feedback: the land surface is darker and absorbs more energy. It is also at a lower altitude than it was when the ice sheet formed, so precipitation and accumulation would be taking place at a higher temperature than it did when ice was accumulating, even if the climate were not changing.

Even when sea level rise is slow, it can be relentless and can—over time—change the face of the Earth. About 20,000 years ago, at the last glacial maximum, sea level was

about 120 m lower than it is now. As the continental ice sheet melted, sea level rose, but not at a steady rate. Most of the rise took place between 15,000 and 6,000 years ago, when it rose at rates in excess 1 meter per century (AR4). This might be considered a “normal” rate of sea level rise during Earth’s warming periods. This is a long-term average, and the shorter-term rate greatly exceeded it at times of rapid ice loss. For example, about 14,000 years ago sea level rose by 3-5 meters per century for four centuries in a row—a rate that might seem extreme, but not impossible. A rapid melting of the Greenland and West Antarctic Ice Sheets could conceivably lead to such a rate.

The IPCC AR4 provided sea level rise projections—based on various carbon emission scenarios—that range between 18 and 59 cm by the end of the 21<sup>st</sup> century. However, these projections neglect the possibility of rapid changes in Greenland or Antarctic ice flow, and do not include the possibility of runaway feedbacks in the carbon cycle (such as the loss of permafrost and methane hydrates). Ice sheet dynamical processes, permafrost deterioration, and methane hydrates are not well enough understood to include in the models. However, climate models do suggest that global temperatures will rise to a level that will nearly eliminate the Greenland ice sheet, so sea level rise is a question of rate, not of magnitude. Temperatures in Greenland are expected to reach those of the last interglacial period, 125,000 years ago. Paleooceanographic reconstructions suggest sea level was 4-6 meters higher at that time (Rohling, *et al.*, 2007), with some evidence for sea-level fluctuations of up to 10 meters around this mean, and average rates of 1.6 meters per century.

New constraints on the possible near-term acceleration of sea level (Rahmstorf, 2007) suggest that it could rise between .5 and 1.4 meters by the end of the 21<sup>st</sup> century. However, this estimate also ignores the possibility of a fundamental shift in the dynamics of ice sheet processes. (Carlson, *et al.*, 2008) point out that with the current greenhouse warming, the increase in summer surface air temperatures in the Arctic will be very similar to the increase that caused the final collapse of the Laurentide ice sheet, which raised sea level by 1.3 meters per century. According to the lead author of that study, “We conclude that we could be grossly underestimating how much the Greenland ice sheet could melt by the end of this century.”<sup>30</sup>

### **3.10 Climate change risk assessment**

Since projected consequences are based on models that cannot explain the rapid sea level increases that happened during warming periods in the past, we believe they are overly optimistic in their tendency to produce estimates of sea level rise that are low. Conservative engineering and security planning would anticipate the highest-consequence possibility. Paleoclimate data imply that the poorly-understood processes of ice-sheet dynamics, permafrost loss, and/or methane hydrate destabilization can accelerate to their prehistoric high rates that led to sea level rises of up to 5 meters per century, suggesting that model uncertainty is grossly underestimated.

Sandia is in a particularly good position to contribute to a risk assessment associated with climate change based on quantification of margins and uncertainties (QMU) by applying the same methodologies developed to ensure the safety, security, and reliability

of the nation's nuclear weapons stockpile. Implicit in QMU methods is a conservative engineering perspective in which the primary focus is on keeping the uncertainty in a decision parameter below some acceptable fraction of the margin that describes an established requirement for that parameter. This engineering perspective, as applied to climate change, is described in the next section.

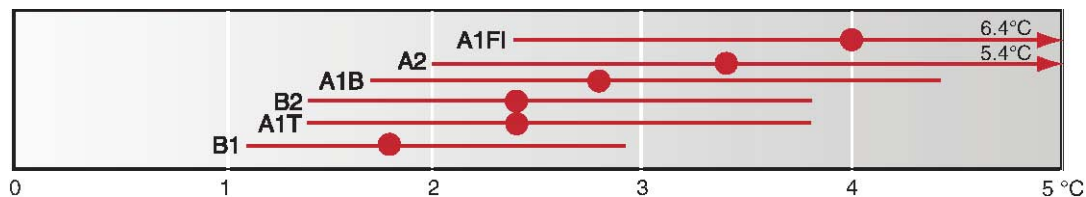


## 4. Probabilistic Risk Assessment: an Engineering Perspective for Climate Change

The large and growing body of literature on global climate change is mostly written from a scientific perspective that focuses on the *most probable* future. A scientific approach is the most appropriate method for gaining understanding of natural systems by applying physically-sound theory, empirical observations, and validated models. The most conservative scientific estimates are those that deviate the least from prior expectations. Scientific conservatism, when applied to climate change, tends to downplay the degree of change.

For complex, non-deterministic, chaotic systems such as Earth's climate, reliable prediction of the future is not possible. Climate forecasts are similar to weather forecasts in that, at best, they can only be probabilistic in nature. However, climate and weather have very different time scales, and climate projections have a significant uncertainty due to lack of understanding. As Mark Twain said, "climate is what we expect, weather is what we get." Whereas long-term comparisons can be made between weather forecasts and observations, the climate future unfolds too slowly for such statistical validation. The best that climate scientists can do is to generate probability distribution functions which encapsulate the best estimate of the future, plus some bounds on its uncertainty. From a scientific perspective, the lower bound on expected climate change is considered to be the conservative estimate.

The IPCC reports present climate forecasts as assessments of the most probable future. For example, the AR4 provides a graph of "warming by 2090-2099 relative to 1980-1999 for non-mitigation scenarios" in terms of "best estimate and likely ranges of warming". "Likely" is defined by the AR4 as an outcome that occurs with a probability of more than 66%. Thus, the ranges provided in Fig. 4.1 are of the most interest scientifically because they are the most probable.



**Figure 4.1.** Estimated temperature bands for various emissions scenarios from IPCC AR4 Synthesis Report. Dots and bars show best estimates and "likely" ranges of warming for the 2090s relative to the 1980s and 1990s.

National security concerns, in contrast to science, are focused on the high-risk occurrences. For security applications—as for engineering—it is the low-probability but high-consequence set of events that must be the primary focus of planning and mitigation efforts. Engineers include significant margins into their designs to account for low-probability occurrences. For example, structures are designed for 100-year weather events and highest loads in the unlikeliest combinations that may have a low probability of ever occurring over the lifetime of the bridge. Bridge designs must consider the non-

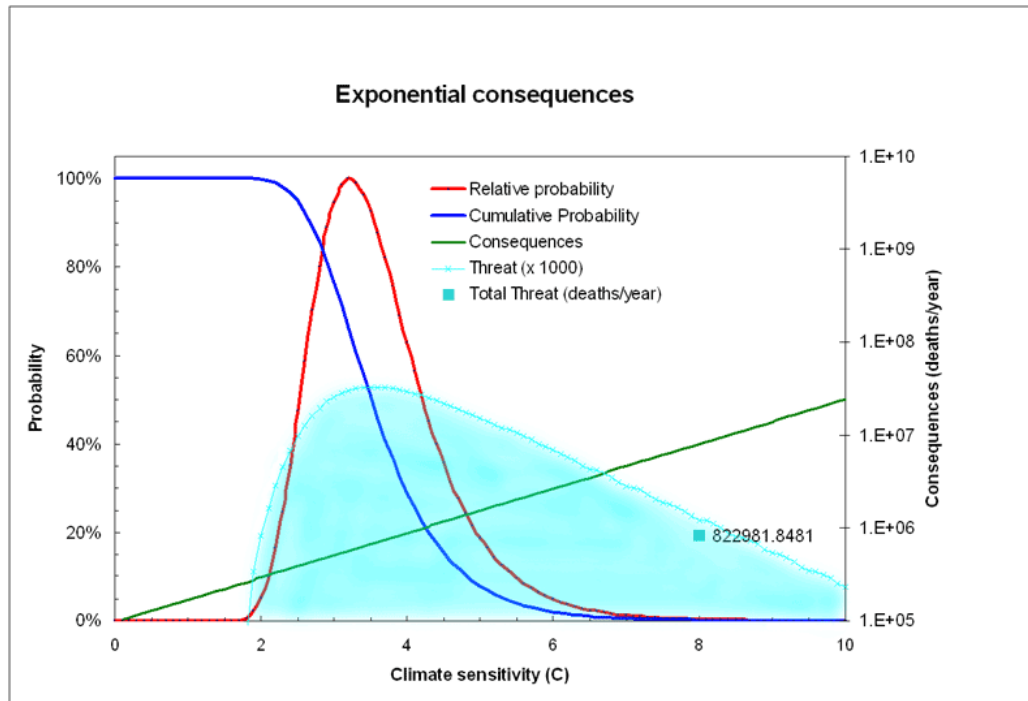
zero probability that several fully-loaded tractor-trailer rigs could simultaneously be stalled in traffic during a severe winter storm. Neglecting the tail of the probability distribution of traffic and weather can lead to catastrophic consequences. Likewise, because of the extreme consequences associated with any nuclear weapon failure, extreme tolerances are imposed for nuclear weapons engineering.

Few events can have consequences that would exceed those of an accidental nuclear explosion. Two occurrences that can lead to even greater catastrophe are 1) impact by a large asteroid, and 2) extreme and abrupt global climate change. Both of these possibilities can be described as tails of probability distributions, and neither can be ruled out by the science. When the consequences include global collapse of civilization, a probability of a few percent is not insignificant. Conceptually, the total risk from climate change can be estimated the same way as the total risk from asteroids: by multiplying the likelihood derived from a probability distribution by the magnitude of the consequences, and summing. The asteroid-threat literature makes use of this method (Chapman and Morrison, 1994), and these estimates are well established and accepted by a community that is dominated by engineers and national security specialists. By contrast, the climate-change literature, such as the IPCC AR4, is focused on the most probable scenarios. The climate change community is dominated by scientists who are most interested in the likeliest future as opposed to the most consequential. As climate change becomes increasingly recognized as a national security issue, we expect a more engineering-oriented risk approach to emerge, which will require more emphasis on uncertainty quantification, especially at the high end of the range of the projections.

There is ongoing research to formally quantify the uncertainty in the equilibrium temperature due radiative forcing equivalent to doubled CO<sub>2</sub> (likely before the end of the 21<sup>st</sup> century). Some assessments of this climate sensitivity result in the generation of probability density functions rather than the simple “likelihood bounds” as provided by the IPCC (Fig. 4.1). These studies consistently show that the high-end sensitivities have a significant probability. For example, (Forest, *et al.*, 2002) give a 5-to-95% confidence interval of 1.4 to 7.7 °C climate sensitivity. This is not inconsistent with the IPCC AR4 17-to-83% confidence interval of 2 to 4.5 °C, and suggests that distribution is strongly skewed with a sharp cutoff at the low end and a fat tail at the high end. The sharp low-end cutoff is not unexpected, because the best understood feedbacks are strongly positive (e.g. water vapor) and any perfectly-canceling negative feedback would need to cancel not only the forcing but also the large positive feedbacks.

(Murphy, *et al.*, 2004) have used the ensemble method in a “perturbed physics” method which systematically varies 29 model parameters to determine a probability distribution function that has a 5% to 95% range of 2.4°C to 5.4 °C, with a median of 3.5°C and a “most probable” value of 3.2°C (Fig.4.2). This is probably the most sophisticated analysis to date because it makes use of more advanced models and is consistent with the transient effects of climate change and forcing. Processes that determine climate sensitivity are varied systematically and uncertainties are weighted according to an objective index. However, it still does not account for lack-of-knowledge epistemic uncertainties, and still does not make use of a fully coupled

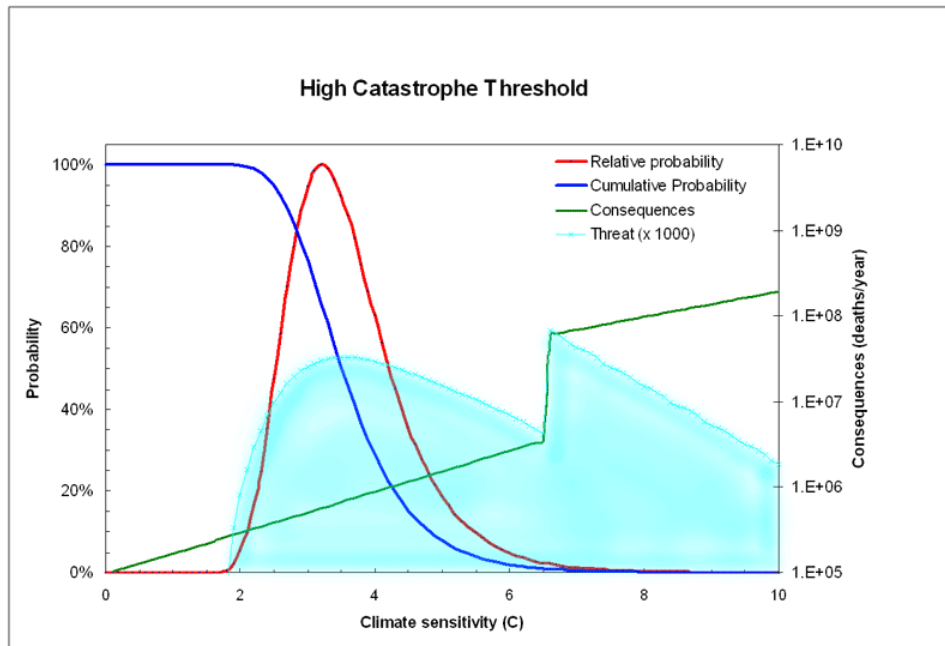
ocean model. Nevertheless, we have chosen to use the Murphy *et al.* probability distribution function to illustrate the importance of the oft-neglected high-end tail to estimate the climate change threat.



**Figure 4.2.** Using the probability distribution of Murphy *et al.* (red) a cumulative probability is derived (blue). The consequence curve (green) assumes an exponential increase of fatalities from the current WHO estimate at 0.8 °C to a global extinction event at 20 °C.

Human consequences associated with wars, disease, and natural disasters are typically measured in fatalities, or in fatalities per year for ongoing losses. Risk assessments result in estimates of expected deaths per year associated with the risk being quantified. For climate change, this is a difficult task because there is no way to validate the consequences of climate change that has not yet occurred. Nevertheless, a baseline has been established by the World Health Organization<sup>31</sup> which estimated in 2005 that 150,000 deaths per year are currently attributable to anthropogenic climate change. We assert that a global catastrophe threshold exists, above which civilization collapses and a significant fraction of the Earth’s population perishes. This uncontroversial claim is the basis for the risk estimates associated climate change caused by asteroid impacts (Chapman and Morrison, 1994). The global catastrophe threshold for impacts is assumed to be that for which dust injected into the stratosphere would depress land temperatures by “several to perhaps 10 °C” for more for a period of months (Covey, *et al.*, 1990) to as long as a year (Toon, *et al.*, 1995), leading to a “nuclear winter” agricultural disaster that could cause global economic, social, and political structures to fail (Turco, *et al.*, 1991). Climate change due to an asteroid impact is assumed to be rapid, but transient, because it is due to forcing by short-lived atmospheric components (dust) as opposed to long-lived greenhouse gases such as CO<sub>2</sub>. For sake of argument, we adopt the same catastrophe

threshold of “several to perhaps 10 °C or more” for climate sensitivity. The anthropogenic temperature change is in the opposite direction, and longer-lasting than for an impact, but is reasonable to suggest that the magnitude is similar. The estimated chance of a globally catastrophic impact by a >1.5 km diameter asteroid in the next century (accounting for Earth-crossing asteroids yet to be discovered) is less than one in 10,000. Published probabilities for anthropogenic climate change suggest the chances of a greenhouse gas induced global catastrophe are hundreds of times greater.



**Figure 4.3.** The low range of the consequence curve (green) is the same as for Fig. 4.2, but assumes that 6.5 °C causes a global environmental collapse that kills about ¼ of the world’s population over 25 years.

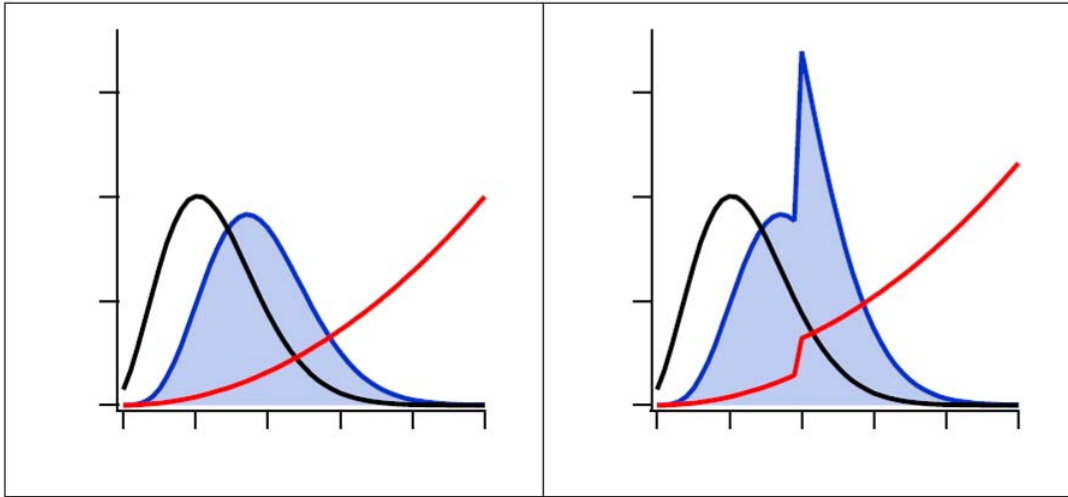
The total risk can be calculated by dividing the climate sensitivity probability distribution into bins, multiplying the relative probability of each bin by the consequences (in fatalities/year) and integrating. It is instructive to illustrate the results with a few “back-of-the-envelope” calculations using assumed consequence curves represented by the descriptions in Table 4.1. In all cases, the WHO estimate of current climate-change fatalities/year of 150,000 is assumed at 0.8 °C, and the entire population of the Earth is assumed to die immediately ( $6 \cdot 10^9$  deaths/year) for  $\Delta T_{2x} = 20$  °C. For Case 1, and for the other three cases below their threshold, the fatality rate was interpolated exponentially between these two end values. The threshold fatality rate was assumed to be  $6 \cdot 10^7$  deaths/year, which would lead to a loss of about 25% of the world’s present population in 25 years, consistent with the catastrophe threshold defined for the impact threat. Since these curves are constructed for illustration purposes, the nature of the curves is more important than their quantitative properties.

**Table 4.1 Risk as a function of threshold**

Case	Description	Threshold sensitivity	Risk (deaths/year)
1	Exponential	No threshold	820 thousand
2	Low threshold	3.5 °C	35 million
3	Middle threshold	5.0 °C	5.8 million
4	High threshold	6.5 °C	1.4 million

To perform the integrations, we digitized the probability distribution function from Figure 3 of (Murphy, *et al.*, 2004) and extrapolated smoothly as it entered the high-end tail. The consequence curves and resulting threat curves for cases 1 and 4 are shown in Figs. 4.2 and 4.3. It is the area under the threat curve that is equal to the expected loss of life for a given assumed consequence function, and in all cases these are dominated by the high-end tail, as expected. Significantly, assumptions of global catastrophe that are not significantly different from those assumed for the asteroid threat lead to a total climate change risk of millions/year (Table 4.1) as opposed the current best estimate of 80 deaths/year from the asteroid hazard (Harris, 2008). These examples also demonstrate our argument that the climate sensitivity probability distribution functions are not symmetric in terms of their contribution to the total risk. From a security perspective, it is much more important to quantify the high-end (right-hand side in Figs. 4.2 and 4.3) tail than it is to determine the mean or most probable climate sensitivity. Unfortunately, it is the high-end tail that is least constrained by the models, and the least emphasized in the scientific literature.

This concept is generalized and illustrated schematically in Figure 4.4, taken from the Report for the IPCC Workshop on Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and Options (Manning *et al.*, 2004)<sup>32</sup>. An idealized graph of probability, consequence, and risk is shown. The horizontal axis represents a magnitude of change (which could be global average surface temperature anomaly, sea ice loss, or some other parameter that has consequences for humans). The black curve is a probability distribution for the change, and the red curve represents some measurement of consequences associated with the change (which could be numbers of fatalities, dollars required to repair damage, or some other quantifiable loss). The product of these two curves results in the blue risk curve. The integrated area under the blue curve is the total risk, which is a quantitative assessment of the full spectrum of possible outcomes. The left-hand panel shows a case where the consequences are a smoothly increasing function of the change, demonstrating how important the upper uncertainty can be for total risk assessment. The right-hand panel represents the case of a consequence threshold, for which the upper uncertainty is amplified. According to the Workshop Report, “This perspective shows that when faced with uncertainty it is not sufficient to identify only a most likely outcome to the exclusion of other perhaps less likely but more consequential outcomes”.

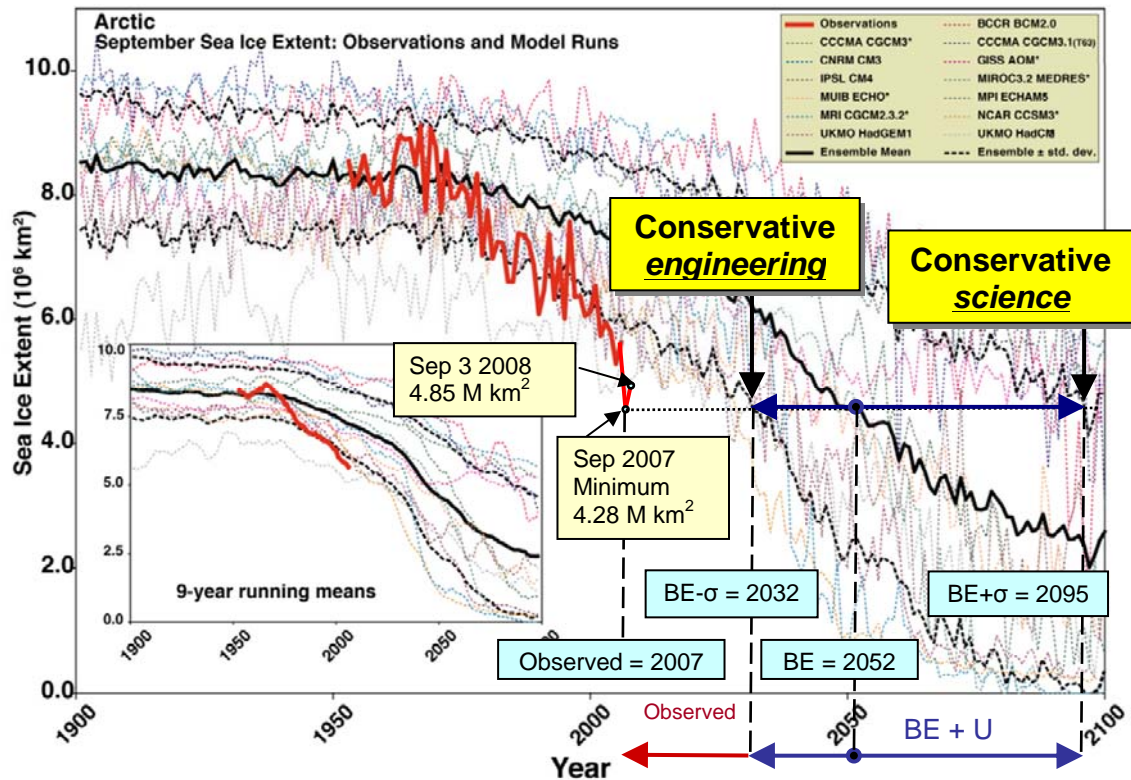


**Figure 4.4.** Schematic of probability, consequence and risk, from the IPCC Workshop Report on Uncertainty and Risk (Manning, *et al.*, 2004).

We suggest that a conservative engineering approach is needed to properly quantify the climate change threat, which requires stronger focus on the high-consequence, “catastrophic climate change” tail in the distribution of possible future climate states. Moreover, early-warning systems must be developed that are capable of identifying the onset of unexpected climate change and anticipating its evolution so that consequences can be minimized.

An example germane to security consequences of Arctic climate change is illustrated in Fig. 4.4, which is based on Fig. 1 of (Stroeve, *et al.*, 2007). It is a plot of observed Arctic September sea ice extent (red) together with 13 IPCC AR4 climate model predictions. The mean of the climate models are shown as a solid black line, and the standard deviations are the dotted black lines. We have added the 2007 and 2008 ice minima that have occurred since this figure was originally published. The actual ice loss has exceeded not only the standard deviation of the ensemble of forecasts, but has gone beyond the most extreme of individual models.

For illustration purposes, consider what might have been reasonable security questions for decision makers to ask several years ago, perhaps to allocate funding for vessels used to patrol the opening Northwest passage.



**Figure 4.5.** Observed September Arctic sea ice extent (red) and predictions, based on Figure 1 of (Stroeve, *et al.*, 2007). Concepts of *best estimate*, *uncertainty*, *conservative engineering*, and *conservative science* are illustrated. These models were overly conservative from the perspective of science, and insufficiently conservative from the perspectives of engineering and security, on which planning is based.

1. What is the best estimate based on IPCC climate change models, for the first year that Arctic sea ice will diminish below 4.3 million km<sup>2</sup>?
2. What is the uncertainty in this estimate?

Based only on model information, a reasonable approach would have been to base the estimate and uncertainty quantification on a statistical analysis of the projections, leading to a best estimate of 2052 for the year to prepare for, likely to be no sooner than 2032 and no later than 2095. However, this estimate ignores the lack-of-understanding component in the uncertainty. It is possible that sea ice, and its interaction with the climate system, is poorly modeled. It is exceedingly difficult to quantify this contribution to uncertainty and engineering conservatism requires that it be assumed for high-consequence planning to be large and the Arctic could become seasonally ice free much sooner than expected.

The conservative estimate from a scientific perspective would have been the later date, because the Arctic Oscillation is poorly understood, the models may have



insufficient resolution for regional projections, and a regression to the long-term mean cannot be ruled out. Engineering conservatism, however, forces us to consider the possibility that we do not understand the positive feedbacks and potential for cascading and mutual reinforcing failures of climate stability. The conservative estimate for security considerations would have been to prepare for this loss before 2032.

Because planning for national security requires emphasis on high-consequence scenarios, scientifically-conservative models that focus on best estimates are insufficient. There is an urgent and growing need for improved uncertainty quantification to enable better estimates of the high-consequence tails in the probability distribution functions of future climate change. The following section recognizes that there is a non-zero probability of high-consequence changes, and discusses the implications of such scenarios for national security without detailed quantification of their likelihood. However, we do not consider any of the scenarios to be highly unlikely.



## 5. Arctic Climate Scenarios and Implications for National Security

This section demonstrates a process for Arctic climate scenario development and extension of the results to problems of national security. To fit within the scope and resources of this study, we limited the bases of the scenarios and the extent to which climate impacts were investigated. In that respect, this section is a survey of the problem and demonstration of a method for more detailed investigations. The list of national security implications for each scenario should be explored and developed further in succeeding studies.

### 5.1 Arctic scenario development

Scenarios are stories about the future. They are hypothetical chains of events that lead from the present to an uncertain future. Scenarios and narratives built from scenarios are one means to plan for contingencies and possible mitigation actions for a range of possible futures. The use of scenarios implicitly acknowledges conservative engineering risk planning by recognizing that high-consequence events may have non-zero probability, without attempting to quantify the likelihood.

We used recommendations from Peter Schwartz, *Art of the Long View*, as well as recommendations from the *Arctic Climate Impact Assessment – Scientific Report* (ACIA), to develop general Arctic climate scenarios for this study. Methods used to build these scenarios are listed in Appendix A: Arctic Climate Scenarios Development and Selection.

For the purposes of this study, we developed Arctic Climate Scenarios that impact Sandia's mission areas. Peter Schwartz recommends that crucial uncertainties be identified and used as bases, like dimensions of a multi-dimensional vector or axes of a spatial representation. Scenarios can be built from two or more of these uncertainty dimensions. Scenario "stories" are then developed. For this study, we concentrated on just two crucial uncertainties. The two dimensions of uncertainty that we used for this study are:

1. *Arctic climate and weather;*
2. *Time scale or rate of change.*

There are other crucial uncertainties—energy futures and energy economics for example—which are clearly important to Sandia's interest and could be added to future studies. Additional dimensions of uncertainty that could be used for future scenario developments include:

1. *Duration of the change.*
2. *Future energy costs.*

Several specific climate events of interest were identified in the literature in advance of our scenario development. We used the area described by climate and rate-of-change to examine the relationship among scenarios and also to “discover” new climate scenarios with significant consequences. A scenario map can provide insight into transitions between climate states and possible cascading events.

We used the first two axes of uncertainty mentioned above, climate and rate-of-change, to build a scenario map that projected consequences and possible human response.

The Arctic climate events of interest that we identified in advance are:

- Ice-free Arctic summers: Shipping, resources, Arctic ports in Siberia, oil and gas, minerals;
- Severe storms in circum-Arctic nations. Radically altered hydrological cycle and surface water locations that completely changes storm patterns and makes some potential ports or bases inaccessible;
- Accelerated ice loss from Greenland, sea level rise, icebergs;
- Rapid permafrost thaw;
- Ecological collapse;
- “Arctic tail wagging the global dog” by alteration of circulation, and changing meridional temperature gradient, changes in climate throughout the northern hemisphere is accelerated;
- Cascading climate-related events and a failure of climate stability.

## **5.2 Scenarios, probability, “long-tail” events, and “Black Swans”**

The two literature sources we used for scenarios and methods contradicted each other regarding use of scenarios that are unlikely or implausible. In addition to likely scenarios, we chose to include scenarios that currently seem less likely in light of recent climate trends and forecasts from climate modeling efforts, such as the ensemble modeling runs of the IPCC reports. We include these less likely scenarios so that a full range of possible future climates can be considered in this scenario development. According to the IPCC AR4 guidance notes for addressing uncertainty, an “unlikely” scenario is one that has a probability of less than 33% of occurring. High-consequence engineering assessments for nuclear weapons safety and the threat of asteroid impacts are concerned with occurrences that are many orders of magnitude less probable, so our “less likely” scenarios are actually much more likely than events that are typically considered by engineers. We concentrated on climate scenarios and impacts over roughly the next four to five decades to mid-21<sup>st</sup> century.

There are several compelling reasons to include low-probability events in scenario developments. Successful scenario-building exercises in the past have demonstrated that future events that may appear to be improbable are essential to cover the full range of possible futures. For example, Royal Dutch Shell included events and oil prices that seemed unlikely at the time to successfully anticipate market events like the oil shocks of

the 1970's. As part of this planning process, leading signposts and indicators can be identified and monitored to provide early warnings of unlikely conditions or states.

Another reason to include low-probability scenarios in planning exercises is the demonstrated importance of “long-tail” events that result from power-law distributions (Taleb, 2007). Power law distributions can be used to accurately describe many important geophysical, financial, computer science, and socio-economic processes. The frequency and magnitudes of hurricanes, tornadoes, and earthquakes, for example, are well-represented by power law distributions. Hence, low-probability events are in fact far more probable than would be anticipated by the commonly-assumed bell-shaped probability distribution—often many orders of magnitude more probable. Many systems that are considered to be complex (rather than just complicated) are well-represented by power law distributions.

In practice, it is difficult to perform risk analyses for processes or systems that are described by power laws. There are rarely sufficient numbers of historical cases to provide information on events “in the tail.” These events are referred to in the recent literature as “Black Swans” (Taleb, 2007).

Scenario development, as advocated by Peter Schwartz, requires a significant investment of time and should, ideally, include representatives from stakeholder groups across an organization (see Appendix A). We develop four scenarios can serve as the first steps toward more detailed scenarios that could be included in a follow-on study. Our scenarios will be described as four domains in a space defined on one axis by degree of physical environmental change, and on the other axis by the speed of change. We begin by defining five cases of change in the physical environment. To avoid confusion, we adopt the term “case” to describe the set of different possibilities for the future physical environment, and “scenario” for the consequences with national security impacts. We postulate the four scenarios and for clarity in the descriptions we use language that treats them as axiomatically true.

### **5.3. Physical environment: climate and weather**

The five physical environment cases that we considered as the basis for scenario development are:

1. Surprising Reversal: The Arctic region doesn't follow current global trends. Instead, the Arctic gets colder. We consider this to be very unlikely.
2. Back to the Holocene: Natural climate variability in the Arctic dominates over the next four decades. We do not think this is likely.
3. Unpredictable Variation: Climate variability increases along with more extreme weather. This is a likely short term (a few decades) projection.

4. Steady Climate Deterioration: An emissions-driven range of IPCC scenarios leads current climate trends to continue up to a tipping point. This is the most likely short or long-term expectation.

5. Abrupt Collapse and Chaos: Climate changes abruptly with rapid warming, and earlier-than-expected retreat of summer sea ice, past the point of no return. We believe the likelihood of this is highly dependent on the rate of future greenhouse gas emissions.

## **5.4 Five possible futures for the physical environment and Arctic climate cases**

### **1. Surprising Reversal: The Arctic gets colder.**

While current climate trends measured at land stations north of 60° N indicate a warming trend of about 0.09° C per decade over the last century (ACIA report, Ch.2), this case builds on the premise that the Arctic region will enter a cooling period similar to the one that occurred in the middle of the 20<sup>th</sup> century. This cooling period might result from a persistent positive phase of the Arctic Oscillation. The Arctic Oscillation is in a positive phase when higher atmospheric pressures exist in mid-latitudes with lower pressures in the Arctic, resulting in surface temperatures in Greenland and Newfoundland as well as Arctic stratospheric temperatures that are colder than the long-term average. Arctic temperatures can be influenced by other high-latitude oscillations including the Pacific Decadal and North Atlantic Oscillations. Such a cooling could also be caused by an unexpected increase in reflective aerosols from a series of volcanic eruptions, higher rates of forest burning, new sources of air pollution from changes in patterns of fossil fuel consumption, or a slight decrease in solar output as has occurred in the past. Changes in solar activity and aerosols are associated with the cold period known as the Maunder Minimum (Hidore and Oliver, 1993).

While we do not believe an extended reversal to an Arctic cold period is likely given recent trends, we include this case for the sake of a complete range in our scenario development to include lower-probability events. This unlikely scenario has relatively low consequences compared to the others.

### **2. Back to the Holocene: Natural climate variability dominates.**

Case 2 projects that, as events unfold over the next four decades, changes in climate will be bounded by those of the last ten thousand years. The last ten millennia in the current inter-glacial period have seen an unusually stable climate when compared to the long-term record. This case does not appear likely given very recent atmospheric trends, but could conceivably emerge if the low-end of emissions scenarios and climate sensitivity estimates turn out to be correct. We include it for the purpose of building a set of scenarios that include low probability cases. This case includes the possibility that climate change occurs at a slower pace than expected and is the least consequential of all cases we considered, but is not likely.

### **3. Unpredictable Variation: Increased climate variability; more extreme weather.**

This case projects more intense and more frequent Arctic storms. Late-forming land-fast ice leaves coastal zones vulnerable to storm surge and erosion. Higher sea surface temperatures at mid-latitudes are believed to increase the intensity of storms (Curry, *et al.*, 2006; Emanuel, *et al.*, 2008; Holland and Webster, 2007). An increase in extreme weather is forecast by IPCC model ensembles. In this scenario, past patterns of weather do not continue and are replaced by a climate that is highly variable and unpredictable. Precipitation events in the Unpredictable Variation Case are unprecedented with snow and rain amounts that are immense. Some villages, ports, and industrial facilities in and near the Arctic become uninhabitable or unusable. Planning and capital investment and infrastructure for Arctic ventures become increasingly difficult because nobody knows what the near-term future environment will be like. We consider this case to be relatively likely, with high regional consequences.

### **4. Steady Climate Deterioration: Climate trends continue to a tipping point.**

Climate trends over the next four decades fall within the range forecast by IPCC models. As expected, Arctic temperature increases are significantly higher than average global increases. We consider this to be the most likely scenario. Temperature increases are dependent on greenhouse gas emission scenarios. This scenario has high global consequences and extremely high regional consequences.

Changes in surface air temperature north of 60° N between the 1981–2000 baseline and 2100 as projected by the five ACIA-designated models forced with the A2 and B2 emissions scenarios (from ACIA). The Arctic Ocean becomes ice-free in the summer, and stays ice-free for a longer period of time every year. Coastal erosion becomes more severe, permafrost deterioration accelerates, and the area of deterioration increases rapidly. Melting of the Greenland ice sheet accelerates and sea level begins rising at a rate of 1-2 cm per year. The discharge of freshwater from Siberian and North American rivers into the Arctic increases greatly. Land and marine ecosystems change rapidly. Large areas of tundra are replaced by shrub land and forests grow northward. Fisheries change and move. Many large mammals, including polar bears, suffer population collapses. Many fish and bird species go extinct.

### **5. Abrupt Change: Rapid warming and melting; past the point of no return.**

Climate trends that are forecast by the ensemble of models run for the IPCC report may prove to underestimate change. In the “Abrupt Change” case, sea-ice modelers including Wieslaw Maslowski (Naval Postgraduate School) and Mark Serreze (NSIDC) prove to be correct in their suggestion that the Arctic will be seasonally free of ice by the summer of 2015 or sooner. The darker Arctic Ocean and rapidly-warming tundra contribute to positive feedbacks in Arctic climate. Glacial melt and increased river runoff raise sea levels and modify ocean circulation. Warming tundra releases greater amounts of greenhouse gases, methane in particular. There is a possibility that this could lead to a runaway greenhouse effect, with a hydrological cycle that would completely alter the circulation patterns of the ocean and atmosphere. This change in the hydrologic cycle

might create deserts in agricultural regions, cause the collapse of the Greenland and West Antarctic ice sheets, and make entire countries incapable of supporting their present populations. Moreover, the changes would continue in a way that weather is no longer stable or predictable anywhere. This is the climate change “doomsday” scenario, with extremely high consequences for the Arctic region and for the rest of the world.

## **5.5 Rates of climate change: expected, severe, and catastrophic**

The three categories for rates of climate change used in the CSIS-CNAS Report, (Campbell, *et al.*, 2007), can be used to describe anticipated rates of climate change in the Arctic. The following scenarios describe global temperatures, which may be amplified by a factor of up to 3.5 in Arctic land surfaces (Lawrence, *et al.*, 2008).

Expected (CNAS Case 1): Moderate, 1-2 °C over the next 30 years.

In this case, Arctic climate change occurs at the rate expected by the ACIA and IPCC reports. We take that to be the baseline or moderate case as did the CSIS-CNAS report, which quantified this rate as follows: “The *expected* climate change scenario considered in this report, with an average global temperature increase of 1.3°C by 2040, can be reasonably taken as a basis for national planning.” This would correspond to increases of as much as 4.5° C in some areas of the Arctic.

Severe (CNAS Case 2): Fast and Severe, 2-4° C over the next 30 years.

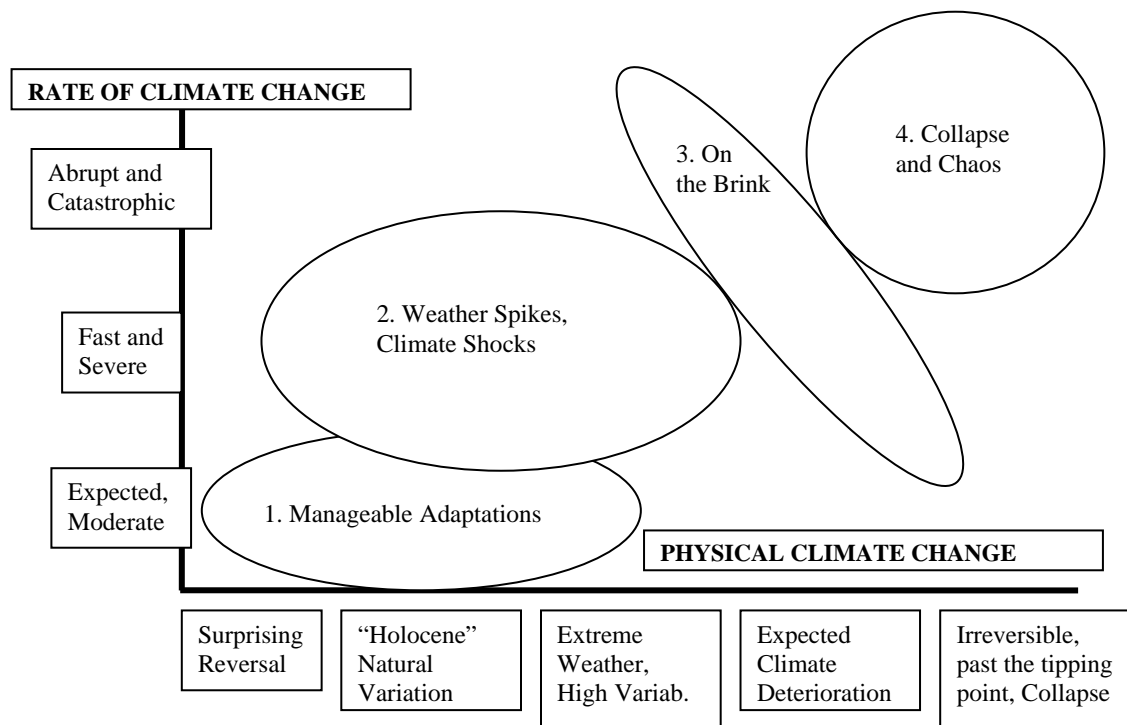
In the case of *severe* climate change, corresponding to an average increase in global temperature of 2.6°C by 2040, massive nonlinear events in the global environment give rise to massive nonlinear societal events. Increases in some parts of the Arctic could exceed 9° C.

Catastrophic (CNAS Case 3): Abrupt and Catastrophic, 4-6° C over the next century.

The *catastrophic* scenario, with average global temperatures increasing more than 3° C by 2040 and as much as 5.6° C by 2100.

## **5.6 An Arctic Climate Scenario Map**

In order to develop specific scenarios, we plotted the five cases for physical environments against the three possible rates of change discussed in the previous section. In the resulting two-dimensional space, we identified regions of climate change impacts and consequences as scenarios. Four major scenarios emerged as congruent areas on this map.



**Figure 5.1.** A Map of Arctic Climate Scenarios

## 5.7 Arctic climate change scenarios

### 5.7.1 Scenario 1: Gradual climate change, manageable adaptations

#### The Scenario Story: “Manageable Adaptations”

This scenario is described by the first region in the Arctic climate scenario map near the origin. Physical changes may be a surprising reversal of expected trends, the steady climate change currently forecast by many including the IPCC report, or an equally surprising dominance of natural variation. In all physical cases in this scenario, the change is relatively slow and adaptation is manageable.

In Arctic regions, this scenario translates to continued but slow changes in permafrost, sea ice extent, and coastal erosion. Adaptation is manageable since we assumed that energy costs do not force imposition of hard (or impossible) choices in infrastructure.

In this scenario, better understanding and measurements of the critical climate feedback processes will be essential. These feedback processes are surface reflectivity, ocean circulation, and greenhouse gas emissions.

Surface reflectivity changes will occur with changes in sea ice extent (ice vs. a dark ocean), snow cover (snow vs. tundra), forest extent, and soot deposits from sources outside the Arctic. Ocean circulation changes will occur with changes in thermohaline circulation caused by changes in sea ice, glacial ice, and river flows into the Arctic. Greenhouse gas emissions, as described in an earlier section, are projected to continue increase rapidly, in line with current IPCC emission scenarios and with expected changes in permafrost and methane-trapping tundra.

Two of the Arctic climate events that we identified prior to our scenarios development are possible under this scenario. They are:

- Ice-free Arctic summers: Shipping, resources, Arctic ports in Siberia, oil and gas, minerals, and
- Accelerated ice loss from Greenland, sea level rise, increased numbers of icebergs.

#### National Security Implications:

In this scenario, changes caused by climate change in the Arctic will either reverse or will occur at a pace that is sufficiently slow to make them manageable. The race to claim and develop Arctic energy resources will continue even if the current warming trend slows or reverses. International agreement on a revised Law of the Sea will likely be possible. If changes continue, retreating sea ice will open new sea routes and allow increased access to national borders, such as the Alaskan coast, that were formerly protected by land-fast ice.

From the CNAS report

*“National security implications include: heightened internal and cross-border tensions caused by large-scale migrations; conflict sparked by resource scarcity, particularly in the weak and failing states of Africa; increased disease proliferation, which will have economic consequences; and some geopolitical reordering as nations adjust to shifts in resources and prevalence of disease. Across the board, the ways in which societies react to climate change will refract through underlying social, political, and economic factors.”*

#### Leading Indicators and Signposts for this Scenario:

The geophysical equivalents of “canaries in the coal mine” will provide early indicators of change. These include:

- Arctic sea ice volume and extent;
- Glacial extents;
- Greenland ice sheet volume;
- Permafrost extent and depths;
- Ocean salinity and circulation, particularly at high latitudes.



#### Science and Technology Challenges for Sandia:

- Long-term monitoring of key indicators and resources to better monitor key indicators including satellite sensors and unmanned aerial and terrestrial vehicles;
- Better understanding of critical Arctic climate feedback processes and sensitivities;
- Better climate models including regional climate models and Arctic systems models that include socio-economic impacts.

### **5.7.2 Scenario 2: Gradual changes with sudden shocks, extreme weather events, frequent conflicts involving energy resource ownership.**

#### The Scenario Story: “Weather Spikes, Climate Shocks”

Climate spikes characterize this scenario. The physical basis for this scenario is the hypothesis that warmer surface temperatures can increase the intensity of storm events.

Periods of rapid climate variation are evident in paleoclimate records.

In this scenario, coastal erosion and damage to infrastructure are significant. Late-summer or autumn storms that strike ice-free shorelines will damage energy, defense, and other critical infrastructure. Large variation in precipitation and river flow will have large impacts on human and animal populations, forest extent, and may alter ocean circulations.

#### National Security Implications:

A primary driver in this scenario is the uncertainty regarding the design requirements for infrastructure. The criteria for the “hundred-year storm” change in this scenario. Existing infrastructure is inadequate to handle the increasing numbers of severe storms. New infrastructure is significantly more expensive.

In this scenario, intense Arctic storms will surge past ice-free coastlines on a frequent basis. Storm surge will accelerate coastal erosion. Energy and defense infrastructure will be vulnerable to storm damage or will require expensive modification.

Since the permafrost that supports much of this infrastructure in the Arctic is thawing, infrastructure vulnerability is increasing with time.

#### Leading Indicators and Signposts for this Scenario:

- Number and frequency of Arctic storm events;
- Observed changes in key climate parameters and statistical weather information;
- Physical observations of Arctic climate feedback processes and comparison to regional-scale models;
- Changes in weather patterns from radically-altered hydrological cycle completely changes storm patterns and make some potential ports or bases inaccessible.

#### Science and Technology Challenges for Sandia:

- High-resolution monitoring of key areas using satellites, airborne sensors, unmanned aerial vehicles;
- Improved weather forecasts and emergency response for the Arctic region;
- Better integration of synoptic scale models (Weather Research and Forecasting Model) with regional and global climate models;
- Capability to model extreme weather events, uncertainty quantification for these events, and incorporate into climate modeling.

### **5.7.3 Scenario 3: Toward a climate threshold--rapid climate change and cascading events advancing toward a climate tipping point**

#### The Scenario Story: “On the Brink”

A current credible estimate of the amount of atmospheric greenhouse gas in carbon dioxide equivalent that is required to exceed a stability threshold or tipping point is 500 ppm. There remain large uncertainties in this estimate and conservative engineering risk assessment would assume it could be significantly lower. The amount of time required to reach that point depends on future greenhouse gas emissions, estimated through emission scenarios for the IPCC report. The A2 and B2 emission scenarios used in the Arctic Climate Impacts Assessment report correspond to 500 ppm CO<sub>2</sub> equivalent by dates between 2040 and 2060. Beyond this estimated “tipping point,” one anticipates the possibility of runaway greenhouse gas concentrations and resulting negative consequences.

A recent article in the New York Times (Revkin, Sept 26, 2008)<sup>33</sup> notes that carbon emissions appear to be accelerating.

*“Overnight the [Global Carbon Project](#), a network of scientists tracking emissions of carbon dioxide, released its latest update, and it shows that emissions are accelerating and are close to the highest scenarios considered by the [Intergovernmental Panel on Climate Change](#) last year.*

*Seth Borenstein of The Associated Press has written a [summary of the carbon dioxide findings](#), with some input from experts who express surprise that a slowing of economic growth in some places hasn’t blunted the growth in CO<sub>2</sub> output.*

*More than half of global emissions, which totaled more than 34 billion tons of CO<sub>2</sub> in 2007, are now from developing countries, the report said. Their dominance reflects explosive growth in the burning of coal and manufacturing cement, another big source of the heat-trapping gas.*

*The project scientists also said that the absorptive power of oceans, forests, and other “sinks” for carbon dioxide, which typically suck in more than half of the gas emitted each year, has not kept pace with the rising emissions. In 2007, the report said, these sinks took in 54 percent of the emissions, but that is a drop of 3 percent from the long-term average rate from 1959 to 2000.*

*In a news release from the Global Carbon Project, Corinne Le Quéré from British Antarctic Survey and the University of East Anglia said that drop in the efficacy of the carbon sinks could mean even more warming in the end. ‘If this trend continues and the natural sinks weaken, we are on track towards the highest projections of climate change,’ Dr. Le Quéré said.”*

In his recent book Six Degrees, Mark Lynas surveyed the current science literature on climate change and summarized changes that could be expected based on the average global temperature increase. Table 4.1 below, from Six Degrees, lists expected average global temperature increases with CO<sub>2</sub> emissions. Table 4.2 is from the Times Online. It lists global-scale consequences expected for up to six degrees of average temperature increase with a Europe-centered focus.

**Table 5.1: Global temperature change and CO<sub>2</sub> targets (Lynas, 2008)**

<b>Temp Change, °C</b>	<b>Action Needed</b>	<b>CO<sub>2</sub> Target (Current = 380 ppm)</b>
0 – 1	Avoidance probably not possible	350 ppm
1 – 2	Peak global emissions by 2015	400 ppm
2 – 3	Peak global emissions by 2030	450 ppm
3 – 4	Peak global emissions by 2050	550 ppm
4 – 5	Allow constantly rising emissions	650 ppm
5 – 6	Allow very high emissions	800 ppm

**Table 5.2: Average Global Temperature Rise versus Consequences, adapted from Six Degrees by Mark Lynas**

Temperature Rise, °C	Expected Consequences, Europe-Centered
1	Ice-free sea absorbs more heat and accelerates global warming; fresh water lost from a third of the world's surface; low-lying coastlines flooded.
2	Europeans [and other residents of the Northern Hemisphere] dying of heatstroke; forests ravaged by fire; stressed plants beginning to emit carbon rather than absorbing it; a third of all species face extinction.
3	Carbon release from vegetation and soils speeds global warming; death of the Amazon rainforest; super-hurricanes hit coastal cities; starvation in Africa.
4	Runaway thaw of permafrost makes global warming unstoppable; much of Britain made uninhabitable by severe flooding; Mediterranean region abandoned.
5	Methane from ocean floor accelerates global warming; ice gone from both poles; humans migrate in search of food and try vainly to live like animals off the land.
6	Life on Earth ends with apocalyptic storms, flash floods, hydrogen sulfide gas and methane released to atmosphere, only fungi survive.

#### National Security Implications:

International conflict would be likely as nations struggle to adapt with large-scale change and disruptions. Along with this conflict, border security would be difficult since millions of refugees would seek refuge from coastal areas. Borders would become difficult to patrol and monitor with extreme weather events that accompany this scenario. Changes in precipitation patterns would alter food production and availability. Energy demands worldwide would surge. As energy prices escalate, tensions would likely increase and the race for Arctic energy resources would accelerate.

#### From the CNAS report

*“In this scenario, addressed in Chapter IV, nations around the world will be overwhelmed by the scale of change and pernicious challenges, such as pandemic disease. The internal cohesion of nations will be under great stress, including in the United States, both as a result of a dramatic rise in migration and changes in agricultural patterns and water availability. The flooding of coastal communities around the world, especially in the Netherlands, the United States, South Asia, and China, has the potential to challenge regional and even national identities. Armed conflict between nations over resources, such as the Nile and its tributaries, is likely and nuclear war is possible. The social consequences range from increased religious fervor to outright chaos. In this scenario, climate change provokes a permanent shift in the relationship of humankind to nature.”*

#### Leading Indicators and Signposts for this Scenario:

- Number and frequency of Arctic storm events;
- Observed changes in key climate parameters and statistical weather information;
- Physical observations of Arctic climate feedback processes and comparison to regional-scale models;
- Rate of sea-level rise;
- Rate of Greenland ice-sheet volume decrease.

#### Science and Technology Challenges for Sandia:

Estimations of trends and regional-scale climate modeling results will be needed on a much-accelerated basis to provide timely information to the policy, the intelligence, and the defense communities. The crucial questions are where is the tipping point, how quickly are we approaching it, what is the uncertainty and safety margin, and what mitigation methods will be effective to avoid reaching that point?

### **5.7.4 Scenario 4: Abrupt collapse of the Arctic environment, global conflicts, and chaos**

#### The Scenario Story: “Collapse and Chaos”

Recent data indicate that the Arctic is changing at a rate that significantly exceeds the most dramatic IPCC scenario. Recognition of the vast and possibly vulnerable methane hydrate deposits and the potential for extreme weather to release carbon from the Yedoma permafrost implies the possibility of extremely rapid and dramatic changes. Precedents exist in the paleoclimate record for changes of 8° C or more within a few decades. Such a scenario would bring into question the ability of governments to adequately respond to the resulting widespread humanitarian crises.

The CSIS-CNAS report casts this catastrophic scenario in terms of energy and compared it with the current threat of terrorism. Because of the abruptness of climate change in this scenario, it appears unlikely that sufficient resources exist to mount large scale adaptation efforts. Limited defensive responses are more likely.

#### Implications for National Security:

Under this scenario, we expect

- A chaotic rush for Arctic energy resources;
- Military conflict in the Arctic;
- Collapse of Arctic ecology and infrastructure;
- Extreme stresses on Arctic energy and transportation infrastructure leading to frequent outages;
- Defensive responses to extreme climate stresses;
- International conflict.

From the CNAS report.

*“This catastrophic-scenario would pose almost inconceivable challenges as human society struggled to adapt. It is by far the most difficult future to visualize without straining credulity. The scenario notes that understanding climate change in light of the other great threat of our age, terrorism, can be illuminating. Although distinct in nature, both threats are linked to energy use in the industrialized world, and, indeed, the solutions to both depend on transforming the world’s energy economy—America’s energy economy in particular. The security community must come to grips with these linkages, because dealing with only one of these threats in isolation is likely to exacerbate the other, while dealing with them together can provide important synergies.”*

#### Leading Indicators and Signposts:

Leading indicators and signposts are similar to those of the more benign first scenario. In this scenario, identification of the “canaries” or critical points in these geophysical systems will be crucial.

- Arctic sea ice volume and extent;
- Glacial extents;
- Greenland ice sheet;
- Permafrost extent and depths;
- Ocean salinity and circulation, particularly at high latitudes.

#### Science and Technology Challenges for Sandia:

The challenge in this scenario will be to deliver credible information to Sandia customers in time for that information to be useful. Change will be extremely rapid in this scenario. It may be possible to perform an analysis on whether and how society could adapt to and survive such a change.

## **5.8 Conclusions from these scenarios**

### **5.8.1 Scenario 1: Manageable Adaptations**

The scenario map with physical climate cases plotted against rates of change is a means to visualize possible changes or system trajectories in the Earth climate system. Although we consider the first two physical climate cases used in Scenario 1 to be unlikely given current trends in greenhouse gas emission, Scenario 1 tells a hopeful story. Mitigation and adaptation are possible in this scenario for three physical climate cases. For all three, a crucial requirement is measurement of key Arctic climate indicators and use of these measurements in regional scale models. Accurate measurements and credible regional scale models are the key to understanding the location and trajectory of the Arctic climate system.

### **5.8.2 Scenario 2: Weather Spikes, Climate Shocks**

Scenario 2 includes an acceleration of change and conflict. The climate spikes and extreme weather of Scenario 2 will incur large economic costs. Mitigation and adaptation are possible but will be complicated by international conflict that impedes cooperation. Extreme weather in the Arctic will have a significant impact on energy and mineral exploration and production there. There will be both winners and losers in this scenario as new shipping routes and access to Arctic resources opens with reductions in sea ice.

### **5.8.3 Scenario 3: On the Brink**

Of these four scenarios, Scenario 3 is the most plausible, although it includes a measure of uncertainty associated with the range of temperature increase. This increase will be linked to future greenhouse gas emissions. At present, there is little evidence that growth in emissions, particularly carbon dioxide, will slow. As shown in the ACIA report, Arctic temperatures will likely increase faster than global averages. The dire consequences forecast for the high end of the chart from Six Degrees would occur earlier for Arctic regions. IPCC estimates for emissions and temperature change may well prove to be too conservative, resulting in Scenario 4.

### **5.8.4 Scenario 4: Collapse and Chaos**

Scenario 4 is our worst case. This scenario assumes irreversible climate change and transition to a new and chaotic climate regime. The CNAS report cited earlier compares this scenario with widespread terrorism in that both drivers are linked to energy.

### **5.8.5 Common threads, common future assessment needs**

We concur with the Arctic Climate Impacts Assessment (ACIA) report regarding seven key areas in which attention and work are needed to improve future climate impacts assessment. These needs cut across the four climate scenarios given in the preceding section. They are: (ACIA, pg. 1019)

#### **1. Regional Impacts and Climate Models**

Better regional-scale modeling is an essential requirement for improved assessments. It is currently receiving attention as a climate-modeling research priority. Improvements in regional scale modeling will facilitate better assessments of economic impacts and will enable better decision making.

## 2. Economic Impacts

Economic impacts of climate change are difficult to quantify, especially without needed regional information. Credible economic impacts are needed by policy and governmental decision makers, and assessments of these impacts will require regional-scale modeling that is arguable accurate. The Stern Report and other similar parallel efforts are recent steps toward assessing economic impacts.

## 3. Assessing Vulnerabilities

Climate impacts on interdependent, coupled systems are difficult to assess and require additional research. For the present study, systems of importance to national security were considered. However, these systems may be indirectly affected by climate change through couplings that include human interactions.

## 4. Observations and Process Studies

The recent under-prediction of changes in Arctic sea ice extent makes it clear that important climate processes are not well understood or captured in models. Poorly understood processes range from physical systems such as cloud-aerosol-forcing interactions to human health and biota changes. Because of the strong ice-albedo feedbacks, and teleconnections, the faulty prediction of the rate of retreat of the sea ice extent raises questions about other climate-related predictions.

## 5. Long-Term Monitoring

There are very few measurement sites in the Arctic from which reliable, climate-scale records are available. The National Science Foundation, the US Department of Energy, NOAA, and international science agencies have recently placed a priority on long-term monitoring in the Arctic. This current research emphasis must be sustained over coming decades in order for science and climate-modeling needs to be met.

## 6. Climate Modeling

High-resolution coupled regional models are needed for the Arctic region. An initiative spearheaded by the University of Alaska Fairbanks/International Arctic Research Center for development and refinement of Arctic system models is attempting to improve on the current situation. A suite of available models for the Arctic that can be interconnected and run with minimal customization is needed.

## 7. Analysis of Impacts on Society

A better understanding of likely impacts of Arctic climate change on global society and the uncertainty associated with these impacts are needed for decision makers. The development and use of scenarios similar to those presented here but with expanded detail is one tool that can help decision makers allocate economic resources.



## 6. Approaches for Arctic Modeling

Climate change in the Arctic has become indisputable, with many dramatic and unexpected changes. Understanding this change and predicting future change will require a greatly improved Arctic modeling capability. A recent Nature editorial (2008) mentioned several reasons why the climate change community needs to expand its Arctic modeling effort: the surprising and unpredicted rate of Arctic sea ice decline in the past few summers, the unknown future of the Greenland ice sheet, and the repercussions of a very different Arctic on the rest of the Earth system.

In this section we describe several approaches to Arctic climate modeling. We will outline some of the approaches that have been used to model Arctic specific questions. We focus on first-principle models as opposed to statistical correlation models. First-principle models rely on developing equations which approximate the physical processes responsible for climate, which are then solved on modern high performance computers. For most modeling work, the community relies on two types of models: global climate models (AOGCMs: Atmosphere-Ocean General Circulation Models) which simulate as much as possible of the entire Earth system and regional climate models (RCMs) which focus on a limited area and can thus achieve much higher resolution with the same computational resources.

### 6.1 AOGCMs

AOGCMs consist of 4 major model components: Atmosphere, ocean, land, and sea ice. The components are developed by separate teams and can usually run in a “stand-alone” mode where they are driven by initial conditions from observational data sets or idealized climates and specified greenhouse gas emission scenarios. In an AOGCM, components are coupled together and run concurrently. Significant computing resources are required to run these large models. A typical climate simulation can take a month or longer running full time on several hundred processors. The scalability of current AOGCMs is limited by the atmospheric component making it difficult to exploit the latest massively parallel computers with tens of thousands of processors. This lack of scalability limits current AOGCMs to horizontal resolutions of about 100 km. However, next generation AOGCMs with more scalable components are expected to be much improved, allowing for long climate simulations at resolutions closer to 10 km.

The strengths and limitations of both AOGCMs and RCMs were recently assessed in great detail by (Bader, *et al.*, 2008). They discuss the ability of modern AOGCMs to reproduce a wide range of features of the Earth’s climate, such as statistical properties and trends of the global mean temperature, tropical and extra-tropical storms, monsoons, the Madden-Julian and El Nino southern oscillations (ENSO), sea ice, ocean circulation, and extreme events. Here we summarize their well-referenced findings, focusing on how these results apply to Arctic modeling.

Modern AOGCMs do a remarkable job at reproducing many aspects of the Earth's climate and they continue to improve. Quantities well-modeled by AOGCMs include mean surface temperature and precipitation at the continental scales, including trends such as the twentieth century mean-surface-temperature warming. Models also do a good job at capturing statistical properties such as the frequency of heat waves and variability of mid-latitude winds. That quantity is a measure of how well the models capture the Pacific and Atlantic mean storm tracks. The ability of models to capture details of these tracks further improves as the models increase horizontal and vertical resolution and improve their representation of tropical precipitation. In the Arctic, most of the interannual variability is contained in the Arctic Oscillation. AOGCMs do a fair job of capturing this oscillation.

Quantities not well modeled in AOGCMs include finer details of both temperature and precipitation. For precipitation, the errors are largest in the tropics. There are also large errors in the day-night cycle and the separation between light, medium, and heavy rains. Of more direct interest to us, the errors in the seasonal mean temperatures in the CCSM3 AOGCM are quite large (up to 12° C too warm) in the Arctic. Most AOGCMs have difficulty capturing frequency and amplitude of North Atlantic blocking events, which leads to an incorrect tilt in the Atlantic storm track. Tropical storms are not simulated very well in today's AOGCMs due in part to their low spatial resolution. Bader *et al.* (2008) suggest that AOGCMs running at 20 km global resolution will be adequate for models to represent many aspects of tropical storms except for storm intensity. For past Arctic warming events, the climate shifts simulated by AOGCMs are considerably slower than the observed ones (Flückiger, 2008), which could be due to "missing feedbacks, the wrong forcing of the abrupt shifts, or a misguided focus on changes in ocean circulation or temperature," rather than other aspects of the climate system like atmospheric wind patterns.

For Arctic modeling, Bader *et al.* (2008) identify several areas in AOGCMs which can be improved: model resolution, snow, permafrost and soil freeze/thaw models, and the incorporation of land ice sheet models.

## **6.2 Improved resolution with RCMs**

There are many reasons to perform climate simulations at higher resolutions than can be obtained by current AOGCMs. Aspects of AOGCM simulations which are improved with resolution mentioned above included mid-latitude storm track structure, tropical cyclones and details of Arctic climate change. In addition, Bader *et al.* (2008) also attribute part of climate modeling community's progress in improved simulations of ENSO variability to increased resolution within the ocean model component of AOGCMs. Note of course that resolution by itself does not improve all aspects of a simulation. There will always be physical processes that must be parameterized, and many gains in simulation quality will be obtained through improving these parameterizations.

One can obtain resolutions on the order of 10 km with only moderate computer resources by using RCMs. High resolution is made possible because the models work with a much smaller computational domain such as the western U.S. Because they are not global, they require boundary conditions at the edges of their computational domain. For future climate simulations, these lateral boundary conditions must be obtained from AOGCM simulations. These types of simulations are an example of downscaling. The requirement of using lateral boundary conditions from AOGCM simulations does present some difficulties. RCM results have been shown to be particularly sensitive to the large scale atmospheric circulation patterns in the driving AOGCM (Stephenson and Pavan, 2003). For example, the poor representation of North Atlantic blocking in AOGCMs mentioned above suggests that a regional model of Europe driven by such an AOGCM will fail to reproduce many important regional features of the European climate (van Ulden and van Oldenborgh, 2006). Another current difficulty with RCMs is that there is no good mechanism for feeding regional effects back to the global scale for RCM downscaling. Influence flows only from global to regional scale.

Despite these difficulties, the increased resolution made possible by RCMs improves many aspects of climate simulations. One of the biggest improvements to be had with the increased RCM resolution is in the simulations of precipitation patterns and heavy precipitation events. Recent work has shown that downscaling with an RCM running at 18 km resolution can obtain reasonable simulations of Atlantic hurricane frequency including the increasing frequency trend of the last 30 years (Knutson, *et al.*, 2007). Another recent example of the usefulness of RCMs comes from (Evans, 2008), who showed that for the middle east, AOGCMs with O(150 km) resolution were predicting a loss of about 170,000 km<sup>2</sup> due to drought, but when an RCM with 27-km resolution was used (which could include the effects of the Zagros Mountains on the moisture-bearing winds) the same region was predicted to see an 50% increase in annual rainfall.

The need for regional climate modeling was further explained in recent Congressional testimony (Avissar, 2007): “Simulations produced with AOGCMs miss significant processes that drive the climate response in somewhat unexpected ways. As an example to demonstrate this issue, simulations of deforestation of the Amazon Basin are produced with a state-of-the-art regional climate model, namely the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University. By using much better resolution than that typically adopted in AOGCMs, land-atmosphere interactions (including clouds and precipitation) are simulated more accurately with regional models.”

For the application of RCMs to the Arctic, we quote (Dethloff, *et al.*, 2004): “A high-resolution regional climate model (RCM) is a powerful tool for improving the simulation of regional effects of the Arctic climate as a result of finer resolved orography and land- sea contrasts, better resolved nonlinear interactions between the large- and meso-scales, improved simulations of hydrodynamic instabilities and synoptic cyclones, and improved description of hydrological and precipitation processes”

### 6.3 Local mesh refinement for downscaling

One approach which will probably see more use in the future is AOGCMs which allow for local mesh refinement, resulting in much higher resolution over key regions of interest within a single AOGCM. One popular approach has been the stretched grid, where the grid in the atmospheric component is smooth stretched to focus additional resolution in a single regional area of interest. Next-generation models will most likely be capable of using full unstructured grids. In fact, Sandia's work in support of the DOE Climate Change Prediction Program involves the integration of a spectral element atmospheric model into the NCAR Community Climate System Model (one of the two U.S. flagship AOGCMs used for climate change research). This atmospheric model has not yet been used for downscaling with local mesh refinement within an AOGCM setting, but in idealized settings, it has been shown to work well even with grids where the finest resolution is 10 times finer than the coarsest resolution (Fournier, *et al.*, 2004; Jablonowski, *et al.*, 2008).

### 6.4 Approaches to Arctic modeling

The vast majority of Arctic modeling studies rely on AOGCMs running at relatively low resolution. Some recent examples include (Min, *et al.*, 2008), who showed a human-induced moistening in the Arctic from greenhouse gases and surface aerosols. They studied both observations and compared AOGCM output collected by the CMIP3 (Coupled Model Intercomparison Project phase 3). (Holland, *et al.*, 2006) used AOGCM ensembles at 140 km resolution to study abrupt reductions in the summer Arctic sea ice. (Sewall and Sloan, 2004) used an AOGCM running at 300 km to study future Arctic sea surface temperature and sea ice extent distribution, showing that a reduction in sea ice thickness results in a significant drying of western North America. (Zhang, *et al.*, 2008) used a global ocean model and sea-ice model, forced by NCEP/NCAR reanalysis data, to identify the main causes of the unprecedented retreat of Arctic sea ice in 2007. Very long AOGCM simulations were used by (Hall and Stouffer, 2001) to find that abrupt climate change events near Greenland are triggered solely by the model's internal variability. Two AOGCMs were used to study the Arctic oscillation by (Zorita and Gonzalez-Rouco, 2000) who showed that models disagreed on long-term trends of the Arctic oscillation intensity.

RCMs have also been used to study the Arctic. (Dethloff, *et al.*, 2004) used an RCM running at 50 km resolution and driven by an AOGCM to study the impact of deglaciation of Greenland on the Arctic circulation and storm tracks. A similar model configuration was used to show how “Arctic processes can feed back on the global climate system via an atmospheric wave bridge between the energy source in the tropics and the energy sink in the polar regions” by (Dethloff, *et al.*, 2006). The same approach was also used to study the significant climate effect of Arctic Haze by (Rinke, *et al.*, 2004) and to look at future climate changes in frequency and intensity of extreme temperature and precipitation in the Arctic by (Saha, *et al.*, 2006). An RCM land model, driven by an 1940-1998 observational data set was used by (Stieglitz, *et al.*, 2003) to study how future changes in snow cover will impact warming below ground, which in turn can result in the loss of terrestrial carbon.

## 6.5 Sandia capabilities

As shown above, most Arctic climate simulations to date have been made at very low resolutions with AOGCM models, or at moderate resolutions on the order of 20 km with RCMs. With the advent of petascale computers currently being acquired by the DOE and NSF, the climate community will soon have the ability and resources to make routine AOGCM simulations at 10 km resolutions. Sandia has made a key contribution to this goal. For our part of the DOE SciDAC Earth System Modeling project, we have been working to eliminate the largest roadblock to the petascale-readiness of modern AOGCMs: the ability of the atmospheric component model to show increased performance commensurate with increases in computer resources, i.e., “scale.” Our work integrating the spectral element method into the NCAR CCSM has allowed the CCSM to use true two-dimensional domain decomposition for the first time, leading to unprecedented scalability demonstrated on LLNL’s BG/L computer system. The new model scales well out to 96,000 processors with an average grid spacing of 25 km. Even better scalability will be possible when computing with a global resolution of 10 km, allowing us to obtain realistic climate integration rates at 10 km resolution on the upcoming petascale machines. For our initial simulations, we used prescribed surface temperatures and without the CCSM land and ice models. Coupling with the other CCSM component models is in progress now.

This will represent a new regime for AOGCMs. Work will be required to understand how to most make effective use of such a dramatic increase in resolution. Many subgrid parameterizations will have to be replaced or updated. As Sandia is playing a key roll in making this work possible, we should also use our modeling expertise and computational resources to create a state-of-the-art Arctic modeling capability that will allow us to address the important issues in Arctic climate change outlined in our previous sections.



## 7. Roles for Sandia and Emerging Opportunities

We believe that Sandia has the capability to contribute to understanding of climate change and its near-term national security impacts. Most climate research focuses on “best estimate” projections, or most-probable expectations. This approach is the most conservative from the perspective of scientific understanding, but tends to err on the side of optimism from the perspective of potential consequences. By contrast, we believe that Sandia’s role, as a national laboratory, should be to focus on high-consequence, less probable scenarios. This focus is more conservative from an engineering perspective because it asks the question: “What is the worst thing that can happen, and what would be the national security consequences?” In this section, we list the areas in which Sandia has the most to offer to help evaluate this question.

Arctic hydrological cycle. With several million square km of ice-free open water, there will be much more evaporation. Where will all this water vapor go? Will there be major storms of an unprecedented magnitude somewhere? Will there be major changes in accumulation on Greenland or other land masses? Will some areas become inaccessible? Will Siberia become a temperate rainforest? SNL should run high-resolution global models with regional refinement in the Arctic to seek robust emergent weather phenomena associated with these new conditions.

Global ocean circulation. With an uncapped Arctic Ocean, the sea surface boundary conditions will change. Evaporation will change temperature and salinity of Arctic surface waters. Will the patterns of sea ice converge on some new equilibrium? Will “flushing” locations of thermohaline circulation migrate from the north Atlantic into the Arctic? Will increased freshwater from the Siberian and North American rivers create a freshwater cap? Will a new wind-driven circumpolar surface current emerge in the Arctic that couples to the Atlantic and Pacific in a way that “wags the global dog”? Sandia should run a series of exploratory high-resolution coupled simulations in an attempt to discover new phenomena before they are observed.

Permafrost stability. Permafrost is rapidly deteriorating. How much longer will it survive? How should structures be designed so they have sufficiently long lifetimes, regardless of what happens to the permafrost? Can the feedbacks due to rapid release of permafrost-bound methane be quantified? Sandia should develop the capability to model the stability of permafrost with focus on volatilization of methane, ecosystem stability, and engineering for infrastructure (military, industrial, and domestic). This is a multi-disciplinary problem that requires expertise in fields as diverse as solid mechanics and soil ecology.

Greenland ice sheet stability. The net loss of ice from Greenland is accelerating. Is the Greenland ice sheet reaching its own tipping point? What is the worst-case scenario that is physically viable? What are the early-warning signs of tipping, and can changes be predicted? Can a full-physics high-fidelity model be developed? Sandia should employ multiscale, multi-phase 3D high-fidelity solid dynamics with radiation and heat transport to model the mobilization of the Greenland ice sheet and consequent global sea level rise. Sandia already has many tools that can be applied to this problem.

Coastal erosion. The loss of sea ice has led to erosion of coastlines that had formerly been protected. The cost of shoring up structures, building barriers, and relocating entire villages and towns worldwide is staggering. Depending on how the relocation is implemented, these solutions may only be temporary. Coastal erosion is affected not only by loss of sea ice but by sea level rise as well. Are other, currently-protected coasts likely to become vulnerable? How can structures be designed for 100-year events when there is no record that relates to current (or future) conditions? Sandia should apply a high-resolution coupled regional Arctic model to predict frequencies and locations of severe storms that dominate coastal erosion.

Thresholds and sensitivity. Many scientists are suggesting that the Arctic sea ice is reaching a point of no return. Are there other unanticipated thresholds in the Arctic system? Can the rapid change in one subsystem (e.g. sea ice) cascade into other subsystems in a downward spiral that leads to an abrupt collapse? Sandia should identify candidate system "tipping points"<sup>34</sup> in the Arctic and use regional models to seek precursory phenomena associated with runaway effects of climate change. Modeling and simulation groups should work with satellite and instrumentation groups to develop advanced monitoring or "early warning" systems for notifying decision makers when accelerating effects of climate change are imminent.

Socio-economic Consequence Models. Governments and multinational corporations have noted the vast resources the Arctic offers and the dramatic reduction in shipping costs that ice-free passages afford. Successful claims of sovereignty in the area will reap huge economic and geopolitical benefits. Will critical paths for the northern hemisphere's supply chains tend to overlap or mesh in the Arctic? Through its NISAC capability and other behavioral/socio-economic modeling efforts, Sandia can address the tensions and consequence of Arctic exploitation. Sandia should utilize its infrastructure and supply-chain expertise to determine the risk to U.S. strategic resources and the options to protect national security interests in the region.

Uncertainty quantification. Decisions associated with mitigation or adaptation will be made under conditions of uncertainty because the Arctic system is nonlinear and complex, so perfect knowledge is unattainable. Can the uncertainty in future loss of sea ice, Greenland ice sheet melting rates, permafrost disintegration, and coastal erosion be rigorously quantified? Uncertainties are highly asymmetric with respect to consequences. Erring on the optimistic side (as was the case for sea-ice loss predictions) is much more dangerous than erring on the cautious side. Sandia should pay special attention to quantifying uncertainty associated with the high-consequence scenarios.

Arctic observations. Any modeling effort needs to be backed up by observations to ascertain how well the evolving model actually performs. The observations provide feedback for development of the model to assure continual improvement. Through the DOE/Atmospheric Radiation Measurement (ARM) program, Sandia already has a robust foothold in Arctic observations – a climate research station on the North Slope of Alaska<sup>35</sup>, and participation in the research community making *in situ* measurements throughout the circumpolar Arctic, as well as the communities using satellite remote sensing and unmanned (and manned) aircraft systems for making both remotely-sensed



and *in situ* measurements there. Use of multi-spectral satellite and aircraft-based remote sensors is particularly valuable when coordinated with ground facilities that provide measurement validation (see Appendix A1). Fixed ground level observation stations provide the most reliable measurements, but the costs are such that there can never be enough such stations to meet model verification needs.

Arctic System Model. The need to understand the Arctic as an integrated system is well recognized within the research community. In May of 2008, a planning workshop hosted by the University of Alaska Fairbanks and held at the National Center for Atmospheric Research in Boulder focused on needs for the Community Arctic System Model Project and the high-resolution modeling resources needed to achieve that integrated model. An Arctic System Model, analogous to community global circulation models, would provide a common high-performance computing environment for linking regional ocean-ice, atmospheric, terrestrial, ecosystem, glacier, and social-dimension models. Efforts to build a Community Arctic System Model are still in an early stage and it is possible for Sandia to effectively engage in that effort. The Arctic System Model links to current work at Sandia in the area of Complex Adaptive Systems of Systems (e.g. Glass, *et al.*, 2007).

Science and Technology Needs for Improved Arctic Observations and Atmospheric Measurements. Climate-related measurements are sparse or simply not available for large regions of the Arctic. Precipitation measurements, thermodynamic parameters of the atmosphere, cloud extent and type, ice volume, and many other geophysical parameters of importance to climate modelers are needed at higher temporal and geographical resolutions to facilitate regional-scale modeling of the Arctic. Sandia can contribute to improved observation through better sensors and sensing platforms. These include Unmanned Vehicles (aerial and surface), satellite sensing capabilities, atmospheric sensors, lightweight Synthetic Aperture Radar (for UAV applications), and hyper-spectral and multi-spectral sensors for UAVs and satellites.



## 8. Conclusions

The Arctic region is already experiencing the rapid climate change that had been predicted, and the changes are accelerating. These changes include increases in surface air temperatures, loss of sea ice, coastal erosion, permafrost degradation, melting of the Greenland ice sheet, changes in clouds and aerosols and their radiative properties, changes in weather and precipitation patterns, and possible long-term atmospheric and ocean circulation changes. Evidence from Greenland ice cores and other sources suggest that the Arctic climate has changed very abruptly in the past, and there is no *a priori* reason to believe that it cannot change just as quickly and erratically in response to the present rapid increases in radiative forcing from inadvertent human modification of the atmospheric composition.

Consequences of Arctic climate change are already evident. Future consequences depend on the degree and nature of future changes, which are highly uncertain with regard to timing. The reduction in sea ice is already opening up shipping routes and increasing the opportunities for oil, gas, and mineral exploration and exploitation. This is creating territorial disputes and increasing international tensions, leading to an increased militarization of the Arctic. Coastal erosion and permafrost loss has caused damage to infrastructure, and increased engineering costs. Ecosystems are suffering from the rapid changes, with cascading consequences for fisheries and indigenous populations. The net loss of ice from Greenland is leading to increases in sea level rise, which has a global impact.

Anticipation of future consequences requires the best possible projections of future climate changes, with uncertainty quantification. Because consequences are a strong function of the degree and speed of change, more attention needs to be given to the high-consequence scenarios. Sandia has wide-ranging competencies and an engineering and systems outlook that can be applied to this problem. High performance computing resources can be used to run regional circulation models to define the range of possible changes to the Arctic hydrological cycle and circulation, which will have global consequences. Multi-disciplinary models using Sandia's expertise ranging from soil ecology to solid mechanics and multi-phase flow can be applied to analysis of permafrost stability, Greenland ice sheet dynamics, and coastal erosion. We can apply Sandia's special optimization know-how to quantify uncertainty and better understand sensitivities and thresholds. At the human interface, we can use systems dynamics and microeconomic models, coupled with physical models, to characterize socioeconomic consequences. Finally, because Sandia is already actively engaged in observational studies of the Arctic, we can expand and integrate observational studies with modeling and simulation, providing model validation as well as guidance for future observational work.

From a systems perspective, we believe that the best approach is one that treats risks associated with climate change much like a complex, nonlinear, dynamic engineering problem. We start by examining the worst case(s) that could reasonably be expected, and what the consequences would be for those cases. For the modeling, we are particularly interested in discovery of emergent, robust, high-consequence phenomena. By running simulations at unprecedented high resolution—updated with the latest data—we intend to focus on finding emergent phenomena or patterns that would not be predicted by first principles reasoning or intuition. We are primarily interested in phenomena that are robust, i.e. are independent of the details of the simulations (specific parameterizations, tunings, or resolution) so that we can have confidence that they are real. Finally, as a national laboratory, our focus should be on those phenomena that have the greatest potential for national security consequences.

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# Appendices

## A1. Sandia Participation in Satellite and Aircraft Measurements in the Arctic

In 2000, the Multi-Spectral Thermal Imager (MTI)<sup>36</sup> was launched with DOE support. Sandia, Los Alamos and Savannah River were involved in the joint MTI program. It was to be a three year demonstration program for application to the DOE non-proliferation effort. MTI has an imaging system with 5 m resolution in its visible bands, and 20 m resolution in its IR bands (nadir-pointing; 15 bands in all). However, MTI continued to be functional long after the 3 year demo program was over. Subsequently, Sandia inherited the sole operating responsibility for MTI, but at a much lower level of support.

MTI has been used on an as-available basis for imaging the North Slope of Alaska (NSA) ARM Climate Research Facility (ACRF) since mid 2002. As the Arctic sea ice recedes, there is great interest in using satellite remote sensing resources not only for geophysical monitoring, but for potential Homeland Security monitoring as well. In particular, it appears that, given an adequate thermal gradient at the water surface, ships leave thermal wakes behind that are detectable by satellite for a substantial period of time after their passage. MTI has been used to investigate this phenomenon in the Arctic. MTI also has been seen to provide interesting insights regarding sea ice, especially the refreezing of leads (breaks in the ice).

The NSA ACRF has also been used routinely to provide validation data for other satellite remote sensors.

With regard to aircraft measurements in the Arctic, Sandia has participated in a number of field campaigns centered on the North Slope of Alaska ACRF. Looking forward, Sandia is developing for DOE an unmanned aircraft hosting capability at Oliktok Point as part of the NSA ACRF. Oliktok Point is the location of a USAF Long Range Radar Station on the shore of the Arctic Ocean at which an earlier ARM field campaign was based. We anticipate that it will provide ideal access for unmanned aircraft to the Arctic Ocean. Through Sandia, DOE has acquired FAA restricted airspace at Oliktok Point that will be useful in connection with hosting unmanned aircraft there.

## A2. Arctic Climate Scenarios Development and Selection

### A. From Schwartz, Peter. *The Art of the Long View*. Doubleday. New York. 1991 – Appendix, Steps to Developing Scenarios

Step One: Identify The Focal Issue Or Decision.

- Begin with a specific decision or issue and then build out toward the environment.
- Develop scenarios from ‘the inside out’ rather than ‘the outside in.’
- What is keeping you awake at night (or will be keeping you awake at night)?

Step Two: Identify The Key Forces In The Local Environment.

- What will decision-makers want to know when making key choices?
- What will be seen as success or failure?
- What are the considerations that will shape these outcomes?

#### Step Three: Identify Driving Forces.

- What are the macro forces behind the forces listed in step two?
- What are the major trends and the trend breaks?
- This step tends to be research intensive; this is where we inform our future stories.

#### Step Four: Rank By Importance And Uncertainty.

- Rank the key factors and driving trends on the basis of two criteria:
  1. The degree of importance for the success of the focal issue or decision identified in Step One and
  2. The degree of uncertainty surrounding those factors and trends.
- The point is to identify the two or three factors or trends that are most important and most uncertain.
- This step determines the axes along which the scenarios will differ.

#### Step Five: Selecting Scenario Logics

- When the axes of crucial uncertainties have been identified, present them as a spectrum (one axis), matrix (two axes), or volume (three axes).
- Attempt to identify the basic scenario logics to the point where stories emerge.
- Identify the logic of challenges and responses.

#### Step Six: Flesh Out The Scenarios

- Use the key factors and trends to add substance to the basic scenarios.
- Attempt to answer who, what why, where, when, and how for each scenario.
- Build narratives.

#### Step Seven: Identify the Implications

- How does the decision look in each scenario?
- What vulnerabilities have been revealed?
- Is the decision or strategy good in all scenarios, just one scenario, a few? If it is good in only one or two of several scenarios, it should be considered high risk.

#### Step Eight: Selection of Leading Indicators and Signposts

- “It is important to know as soon as possible which of several scenarios is closest to the course of history as it actually unfolds.”
- Select key leading indicators, signposts, and points to monitor
- Build adjustment plans

#### Additional Considerations for Creating Scenarios

(1) Beware of ending up with three scenarios since it will be tempting to pick the “middle” or most likely scenario. Also, avoid too many scenarios.

- (2) In general, avoid assigning probabilities to different scenarios because it will bias choices towards most probable scenarios.
- (3) Choose scenario names carefully. Names should telegraph the scenario logics and should be vivid.
- (4) Ideally, scenario development teams should include
  - a. management who make and implement decisions;
  - b. a broad range of functions and divisions;
  - c. “imaginative people who work well together as a team.”
- (5) “You can tell you have good scenarios when they are both plausible and surprising.”

## **B. From Arctic Climate Impact Assessment - Scientific Report, Cambridge University Press, 2005.**

“Selection of climate scenarios for impact assessments is always controversial and vulnerable to criticism (Smith, *et al.*, 1998). The following criteria are suggested (Mearns, *et al.*, 2001) for climate scenarios to be most useful to impact assessors and policy makers:

- (1) consistency with global warming projections over the period 1990 to 2100 ranging from 1.4 to 5.8 °C (IPCC, 2001a);
- (2) physical plausibility;
- (3) applicability in impact assessments, providing a sufficient number of variables across relevant temporal and spatial scales;
- (4) representativeness, reflecting the potential range of future regional climate change; and
- (5) accessibility. It is preferable for impact researchers to use several climate scenarios, generated by different models where possible, in order to evaluate a greater range of possible futures. Practical limitations, however, typically mean researchers can only work with a small number of climate scenarios.”

## **C. Future collaborations for scenario building**

We have many colleagues throughout the climate science community who would be willing to participate in a multi-day workshop leading to detailed climate scenario development concentrating on national security impacts. A few of these possible participants stand out.

Our colleagues at the University of Alaska, Fairbanks, were heavily involved with development of the often-cited Arctic Climate Impacts Assessment Report (2005).

Research and academic centers with relevant expertise in climate impacts include the International Arctic Research Center, the Institute of Northern Engineering, and the Geophysical Institute.

At the University of Washington, the Climate Impacts Group, the Joint Institute for the Study of the Atmosphere and Ocean, and the Atmospheric Sciences Department all have strong research interests and field campaign experience in Arctic regions. Sandia has collaborated with key personnel from these centers in the past.

Sandia staff members have collaborative ties to researchers from NOAA, the Naval Postgraduate School, NCAR, and other federally-sponsored organizations with active research interests and capabilities in Arctic regions.

## End Notes

- <sup>1</sup> Full IPCC reports are available for viewing or download at <http://www.ipcc.ch/>
- <sup>2</sup> Full ACIA reports are available at <http://www.acia.uaf.edu/> or <http://www.amap.no/acia/>
- <sup>3</sup> IPCC Third Assessment Report (TAR) available at [www.grida.no/climate/ipcc\\_tar/](http://www.grida.no/climate/ipcc_tar/)
- <sup>4</sup> Described in the IPCC Special Report on Emissions Scenarios, [www.grida.no/climate/ipcc/emission/](http://www.grida.no/climate/ipcc/emission/)
- <sup>5</sup> [http://nsidc.org/news/press/20021207\\_seaice.html](http://nsidc.org/news/press/20021207_seaice.html)
- <sup>6</sup> [http://nsidc.org/news/press/20021207\\_seaice.html](http://nsidc.org/news/press/20021207_seaice.html)
- <sup>7</sup> <http://www.natice.noaa.gov/icefree/FinalArcticReport.pdf>
- <sup>8</sup> [http://nsidc.org/news/press/20081002\\_seaice\\_pressrelease.html](http://nsidc.org/news/press/20081002_seaice_pressrelease.html)
- <sup>9</sup> <http://epic.awi.de/Publications/BerPolarforsch2005506.pdf>
- <sup>10</sup> <http://www.arctic.gov/files/PermafrostForWeb.pdf>
- <sup>11</sup> <http://www.iarc.uaf.edu/expeditions/?cat=8>
- <sup>12</sup> <http://www.independent.co.uk/environment/climate-change/exclusive-the-methane-time-bomb-938932.html>
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- <sup>21</sup> [http://www.csis.org/media/isis/events/080723\\_arctic\\_event\\_summary.pdf](http://www.csis.org/media/isis/events/080723_arctic_event_summary.pdf)
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- <sup>31</sup> <http://www.who.int/globalchange/news/fsclimandhealth/en/index.html>
- <sup>32</sup> [http://ipcc-wg1.ucar.edu/meeting/URW/product/URW\\_Report\\_v2.pdf](http://ipcc-wg1.ucar.edu/meeting/URW/product/URW_Report_v2.pdf)
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- <sup>34</sup> <http://www.pnas.org/content/105/38/14308.abstract>
- <sup>35</sup> [www.arm.gov/sites/nsa.stm](http://www.arm.gov/sites/nsa.stm)
- <sup>36</sup> <http://www.fas.org/spp/military/program/masint/mti.htm>



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