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Global Situational Awareness and Early Warning of High-Consequence Climate Change

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Abstract

Global monitoring systems that have high spatial and temporal resolution, with long observational baselines, are needed to provide situational awareness of the Earth's climate system. Continuous monitoring is required for early warning of high-consequence climate change and to help anticipate and minimize the threat. Global climate has changed abruptly in the past and will almost certainly do so again, even in the absence of anthropogenic interference. It is possible that the Earth's climate could change dramatically and suddenly within a few years. An unexpected loss of climate stability would be equivalent to the failure of an engineered system on a grand scale, and would affect billions of people by causing agricultural, economic, and environmental collapses that would cascade throughout the world. The probability of such an abrupt change happening in the near future may be small, but it is nonzero. Because the consequences would be catastrophic, we argue that the problem should be treated with science-informed engineering conservatism, which focuses on various ways a system can fail and emphasizes inspection and early detection. Such an approach will require high-fidelity continuous global monitoring, informed by scientific modeling.

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1 Introduction

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 (GHGs, mainly CO₂). A significant fraction of the thermal energy from Earth that would otherwise pass through the atmosphere and be radiated into space is instead absorbed by the higher concentration of molecules that interact with infrared radiation. Part of this energy is re-radiated back to the surface, resulting in higher temperatures. There are large 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. Because of these insurmountable uncertainties, it is unrealistic to expect that precise quantitative forecasts will ever be possible. However, there is no known set of feedback mechanisms by which the atmospheric radiative imbalance will be compensated. In the unlikely event that such globally-compensating feedbacks actually 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, it is virtually certain that climate change will accelerate and global warming in the next 100 years will be exacerbated by increases in GHGs. If there are stability thresholds in this nonlinear system, these atmospheric changes may increase the probability that such tipping points will be crossed. The severity and consequences of climate change are open questions that will always have some degree of uncertainty.

The most useful measurement of the 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.

The purpose of this white paper is to compare the complex dynamic climate system to engineered systems that can fail, and to make a case for increased situational awareness using global monitoring systems that have high spatial and temporal resolution. Continuously monitoring the state of the Earth's climate can provide early warning of high-consequence climate change to help anticipate and minimize the severity of the threat.

2 Climate Change and its Consequences

The increasing mean global surface temperature is due to energy imbalance between incoming short-wave radiation (sunlight) and outgoing long-wave radiation (thermal emission). The global time-averaged imbalance in radiative flux is defined as climate forcing. The best estimate of the imbalance as of 2005 includes effects from other human activities, and is 1.6 W/m^2 , with an uncertainty range between 0.6 and 2.4, according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4)¹. The uncertainty is dominated by the radiative effects of aerosol pollution.

The only physically possible way for the Earth to respond to this energy imbalance is to warm up, but feedbacks and partitioning into various subsystems (atmosphere, ocean, cryosphere) and forms of heat (latent or sensible) are uncertain. Climate researchers have defined climate sensitivity as the increase in mean global surface temperature to an effective doubling of CO_2 relative to the pre-industrial concentration of 280 ppm. Sensitivity is an idealized concept that provides a grossly incomplete description of the response of a nonlinear, multi-dimensional, complex system, but nevertheless provides a useful one-variable means of characterizing global climate change as “global warming”. Calculated sensitivity estimates range from less than $2 \text{ }^\circ\text{C}$ to greater than $8 \text{ }^\circ\text{C}$, with a mean of about $3.5 \text{ }^\circ\text{C}$. The primary sources of sensitivity uncertainty are lack of knowledge associated with feedbacks, and uncertainty in current forcing. Ice core paleoclimate data and 20th century temperature measurements provide the empirical validation that sensitivity is within the calculated range for climate states that are not too different from the present.

Uncertainty in projected future climate is much greater than the range of uncertainties in forcing and sensitivity, because it critically depends on the unknown future GHG concentration. The growth rate depends on energy policy, human behavior, and economics, as well as on the Earth’s biogeochemical cycle. The uncertainty in future climate also includes unknown, unanticipated feedbacks that could lead to a cascading sequence of stability failures, such as the complete loss of Arctic sea ice, rapid collapse of the Greenland or West Antarctic ice sheet, sudden reorganization of thermohaline circulation, or abrupt volatilization of methane hydrates. New ice core data provide strong evidence that extremely abrupt and strong responses to relatively small forcings have happened in the recent geologic past. The existence of such thresholds in the climate system is not easily accommodated by the concept of sensitivity.

The potential human costs of climate change are undoubtedly a strong function of sensitivity. The resulting asymmetry in the relative importance of uncertainty means that the high-sensitivity tail of a probability density function has a disproportionate influence on the magnitude of the total climate change threat. We argue for a science-informed engineering approach to quantification of the potential human cost of climate change, which requires stronger focus on the high-consequence, “catastrophic climate change” tail in the distribution of possible future climate states. Moreover, early-warning systems

¹ IPCC AR4 available at <http://www.ipcc.ch>

must be developed that are capable of identifying the onset of unexpected climate change and anticipating its evolution so that consequences can be minimized.

3 Climate is a Nonlinear Dynamic System

The Earth's climate is a complex system. Greenland ice core evidence shows that when the climate system is left to itself and the variability of natural forces, it tends to be wildly erratic. Looking from the perspective of the past several million years, climate change is the norm, and long-term stability is the exception. Moreover, major shifts in climate over large areas can be remarkably fast.

One example of such an abrupt climate change took place over the north Atlantic at the end of the last ice age. About half the warming associated with the end of the glacial period occurred within a decade, and the changes had global effects. A graph of the temperature of central Greenland over the past 100,000 years demonstrates that until about 11,000 years ago, such climate convulsions happened all the time (Figure 1). Since then, an extraordinarily stable condition has prevailed (this time series strongly correlates with other paleoclimate proxy records from throughout the northern hemisphere). Modern humans have been blessed with 11,000 years of climate constancy (relative to any equally-long period known from Greenland ice cores).

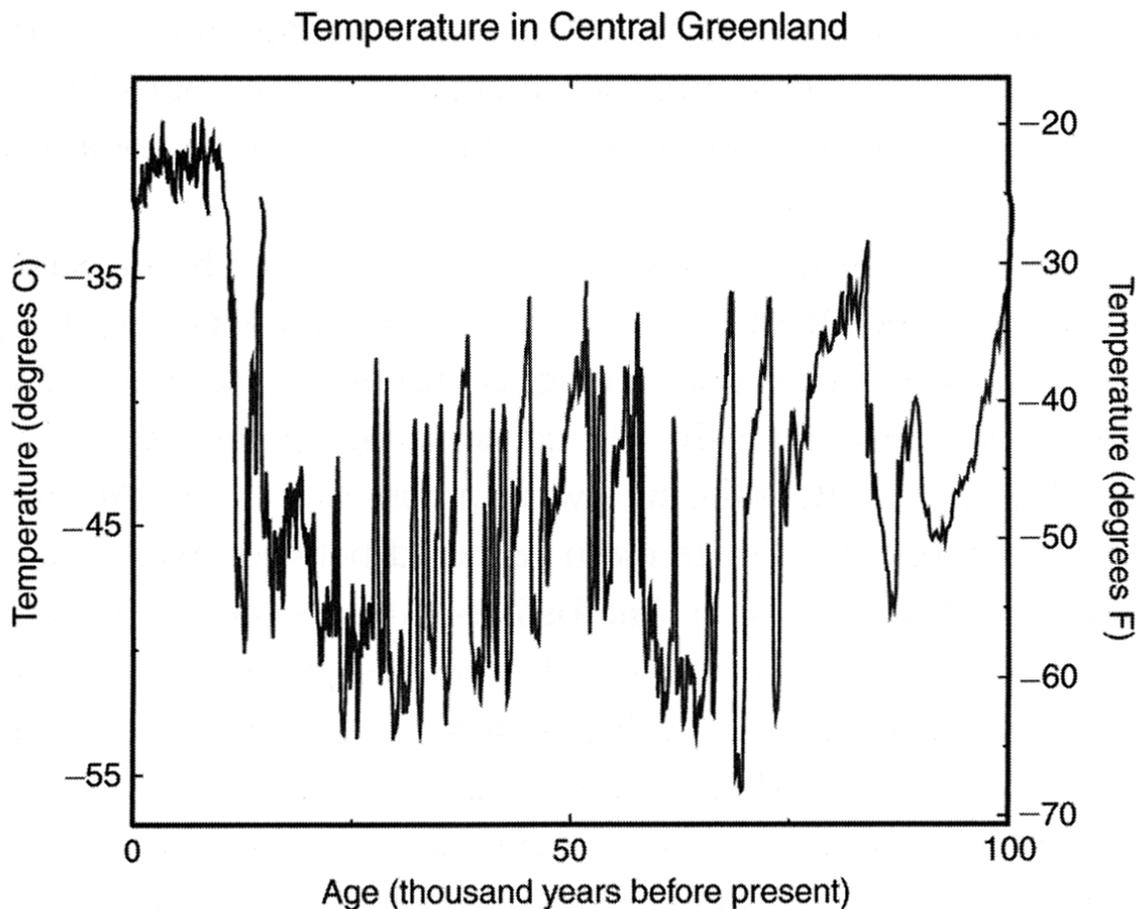


Figure 1. Temperature record from ice-core oxygen isotope record in central Greenland (Cuffey & Clow, 1997).

Our sense of climate stability is comforting but it is illusory because the entire history of human civilization is so short. It is probably no accident that agriculture, cities, and civilization itself arose during this extended time of climate quiescence. Because the entire human experience is associated with anomalous climate stability, we are inclined to continue to expect more of the same. Our political boundaries, trade systems, infrastructure, transportation networks, alliances, energy policies, agricultural practices, supply chains, military deployments, investments, and economics have always been based on an implicit assumption that the climate will not be significantly different in a decade from what it is now. It can be argued that our current high level of prosperity is attributable to an implicit wager that we have been making. Every time we plan for the future, the unspoken supposition has been that tomorrow's climate will be much like today's climate. The paleoclimate records show that we have (so far) consistently won this bet.

We have been on a long winning streak, but the most prudent course of action is to anticipate the end of climate stability when we place our next bets about the future. Our approach in this white paper is to compare the Earth system to an engineered system which is designed and optimized to support a stable human civilization. In reality it is the other way around. Because of the time scale of the Holocene stability, starting about 11,700 years ago, and slow advance of human culture, we have gradually adapted to the boundary conditions provided by climate. The fact that the Earth system was not actually designed for the purposes for which we use it is immaterial, but looking at it that way allows us to adopt language and concepts of engineering. Paleoclimate and paleoceanographic records demonstrate that there is nothing special about the present temperature or sea level, other than the remarkable stability. However, we have adapted to and invested in the present conditions with our infrastructure and agriculture. Changing conditions will require costly re-adaptations.

The way we have used the Earth system to our advantage has depended on its stability. A stable climate is therefore analogous to a properly-functioning engineered system. An abrupt climate change is analogous to the failure of an engineered system. An unstable climate will no longer sustain human life as it is accustomed to being sustained. Those who have the best ability to anticipate changes will be those whose bets allow them to survive and prosper in the long run. We expect the lucky streak to eventually run out for those who continue to make the longstanding default wager that climate will never return to its more typical unstable behavior. This outlook is analogous to assuming the stock market or real estate prices will always go up, or that fire insurance is not necessary. It is usually right, but when it is wrong the consequences can be devastating.

Climate is a complex system, so failure of climate stability will be difficult to forecast. Nevertheless, it is in our interest to anticipate, adapt to, or even exploit the shifting boundary conditions due to abrupt climate change when it happens.

4 Climate is a Heterogeneous Multi-Variable System of Systems

There is no debate within the scientific community about the reality of climate change. The ongoing and contentious political and social debate revolves mainly around issues of attribution, mitigation, adaptation, economics, statistics, policy, funding, and the scientific method, but the Earth is undoubtedly getting warmer as measured by global mean surface temperature. Figure 2 is a time series showing the combined land and marine surface temperature from 1850 to 2008, based on data compiled by the Climate Research Unit (CRU) of the University of East Anglia and the UK Met Office Hadley Center². This sharp increase in global temperature since the beginning of the 20th century is the primary observational evidence for global warming, onto which short-term natural variability and changes caused by other forcings (such as aerosols from volcanic eruptions and air pollution) are superimposed. Global mean surface temperature is a very convenient metric for which multi-year averages can be used to determine whether or not climate is changing, and to assess the rate of change, but it does not provide a measure of the actual state of the Earth. Because climate is a complex system, global mean surface temperature represents only a fraction of the warming. Heat is partitioned into the oceans and cryosphere in addition to the atmosphere, but the rates fluctuate due to natural cycles such as the El Nino/Southern Oscillation, so the rise is not expected or observed to be monotonic. Global mean surface temperature is only one of a multitude of variables that can be used to describe the climate.

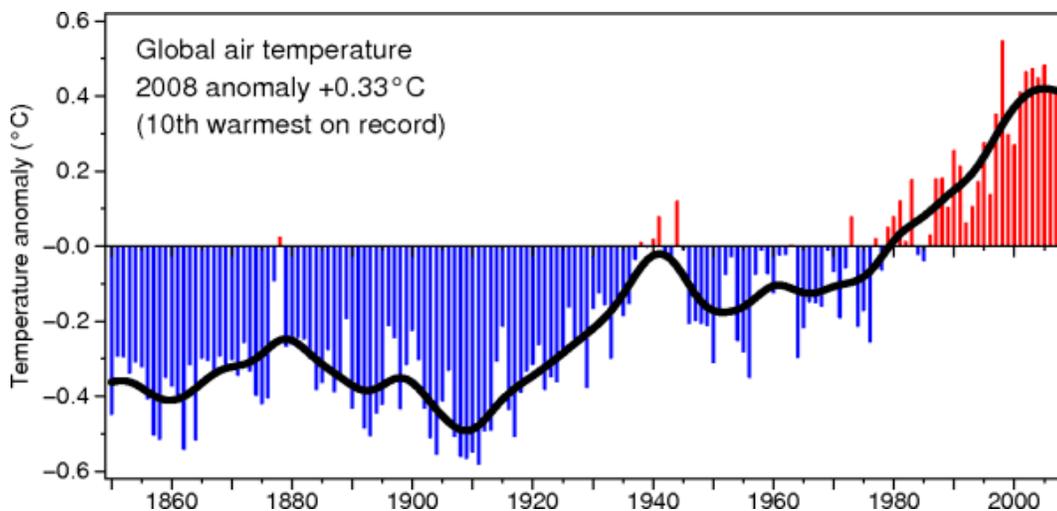


Figure 2. Instrumental global temperature data based on analysis methods described by Brohan, *et al.*, (2006).

Figure 2 does not tell us anything about Arctic sea ice, the mean pH of the oceans, the likelihood of severe heat waves in Europe, the desertification of the African Sahel, the rate of sea level rise, the average intensity of the South Asian monsoon, or the probability

² Link to CRU: <http://www.cru.uea.ac.uk/cru/info/warming>

of a category 5 hurricane landfall on US territory. It does not tell us what will happen in the future, nor does it tell us whether the changes since the beginning of the 20th century are reversible. The term “global warming” is therefore merely a description of one aspect of climate change. It is also a variable that feeds back into the climate itself, causing glaciers to melt, storm tracks to shift, and ocean currents to speed up or slow down. Global temperature is at once a cause, a feedback, an effect, and a measurable diagnostic variable of the complex system.

The term “climate change” also creates an oversimplified picture. The word “change” often suggests a transition from one state to another. Melting causes ice to “change” into water, going from one well-defined and well-understood state to another by a controlled and reversible path. This is not a realistic view of climate change. Graphs of projected sea level, mean surface temperature, and Arctic sea ice show monotonic changes, just like a graph of expected returns from the stock market. The actual changes occur in fits and starts, with large fluctuations in a chaotic two-steps-forward-one-step-back pattern over multiple time scales. This is a characteristic of the complex climate system that is often misunderstood by lay commentators who think that deviations from uniform and monotonic change provide a reason to ignore the potential threat.

The term “climate instability” is still an incomplete description, but more accurately represents the history and expected future of the system. From the Earth’s perspective, climate instability is not necessarily bad, wrong, or unnatural. From the human perspective—because of our civilization-long dependence on climate *stability*—climate instability can be considered a “failure” of the system. From the human perspective, an abrupt shift from stable to unstable climate has the potential to be calamitous.

Society and its institutions represent a second complex system that depends on the first one. Systems engineers understand that failure of one complex system can cascade into another—amplifying failures that initially appear to be small and turning them into catastrophes. It goes without saying that as climate stability begins to fail, the integrity of our national security will increasingly depend on global situational awareness, early warning, and our ability to identify potential cascading mechanisms.

5 Cascading Failures in Engineered and Natural Systems

Concepts from accident theory for engineered systems can be extrapolated to natural and human complex systems. A complex system is characterized by the potential occurrences of an unfamiliar or unexpected series of events that may not be observable in real time or immediately comprehensible. Complex systems exhibit nonlinear responses to external forcings, and have branching responses with feedback loops. Failures of complex systems can jump across subsystem boundaries.

A failure of the climate/human coupled system can unfold like an accident. Failure of one part can coincide with the failure of another part creating a combination that leads to further failures. Such failures can accelerate out of control. Like accidents, climate failures are inevitable, but continuous situational awareness and effective early warning can prevent them from cascading to catastrophic human system failures.

Because complex systems exhibit emergent behavior (*i.e.*, phenomena that are not necessarily predictable from first principles or intuition), high fidelity modeling and simulation is an important component of any attempt to anticipate potential failure chains. To illustrate cascading failures and the analogy between engineered systems and Earth systems, we provide an example of each. The catastrophic implosion of thousands of photomultiplier tubes at the Super-Kamiokande neutrino lab is a classic example of such a failure in a human-engineered system. The paleoclimate phenomena known as Heinrich events (though not normally considered to be a “failure”) are similarly catastrophic cascades of events in the Earth system.

Engineering Case: Super-Kamiokande Accident

There are many examples of cascading failures in aviation and engineering. The Super-Kamiokande accident is noteworthy because it involved an emergent phenomenon based on very simple physics, but was not anticipated by some of the most brilliant physicists in the world. This Japanese laboratory is the premier neutrino laboratory and consists of over 11,000 photomultiplier tubes in an underground array. According to the accident report, the disaster was triggered by the implosion of a single photomultiplier tube, creating a shock wave that imploded adjacent tubes, setting off a chain reaction (analogous to a chemical or thermal detonation). Post-accident simulations showed that shock wave pulse durations and magnitudes were sufficient, under the circumstances, to sustain the chain reaction. There is no reason that such simulations could not have been done prior to the accident, and measures taken to prevent it. However, such a scenario was entirely unexpected and may have been considered too “far-fetched” and improbable if it had been suggested.

The accident caused over \$20 million in damage and it took nearly five years to restore the facility to its pre-accident configuration.

Natural Case: Heinrich Events

When icebergs calve into the ocean, they usually carry some bedrock from beneath the ice sheet that spawned them. When the icebergs melt, the rocks drop to the sea floor as “ice-rafted debris”. North Atlantic sediment from the last ice age contains more of this debris than recent sediment, because there were more icebergs at that time. Earlier cold times also have more debris than warmer times, as expected. There are six remarkably thick layers of rocks that were deposited over the past 100,000 years, suggesting that there were six catastrophic ice breakup events that completely inundated the north Atlantic with icebergs. Events are separated by between 5 and 15 thousand years. The most recent was about 12 thousand years ago. Geochemical signatures in rocks from these debris layers show that they came from Hudson Bay.

Hudson Bay is a large basin, and during times of cold climate it gradually fills up with snow, which turns to ice as it is packed down by subsequent snow. As the ice sheet thickens, it traps more geothermal heat at its base. The deposition of mass leads to a steady increase in stress at the bottom of the stack, while the accumulation of heat slowly decreases its shear strength. Eventually, the stability threshold is crossed and the ice sheet collapses in a cascading failure involving mechanisms that are not fully understood. Because of the normal atmospheric lapse rate, loss of ice at higher altitudes exposes previously-buried ice to warm air at an altitude that is lower than it was when it was deposited. This accelerates the process in subsequent cascades, quickly purging the basin of ice that had built up over millennia of mechanical stability.

The abrupt flushing of ice into the north Atlantic leads to the next step of the cascade. The icebergs melt rapidly in the warmer water, forming a low-density layer of fresh water that suddenly stops the “conveyor belt” that circulates warm water northward from the tropics, plunging Europe and North America into a deep freeze. If an event of this magnitude were to occur today, there would be subsequent cascades of failure involving human systems of agriculture, trade, and economics, which would undoubtedly lead to conflict.

Hudson Bay does not currently contain an ice sheet, so there is no possibility of a modern Heinrich event. Nevertheless, the paleoclimate record shows that other abrupt climate change events—many of which are less well understood—take place with regularity. Like the Super-Kamiokande accident, abrupt cascading failures of the climate system may seem “far fetched”, and might even be rejected as impossible if they hadn’t already been observed in the geological record. However, the last Heinrich event took place before the dawn of human civilization. From our vantage point, it is still easy to believe that Earth’s climate is rock-stable. The time series shown in Figure 1 demonstrates that this view is dangerously incorrect.

6 Engineered and Natural Stability

Most complex engineered systems are designed to be stable when operated within certain specified conditions. Fixed-wing aircraft provide a familiar example of engineered dynamic stability. A slight displacement of the control surfaces of properly trimmed airplane will generate forces and moments that tend to restore the original flight condition. When an aircraft is flown “outside the envelope” of its specifications it can become unstable. Nonlinear effects can take over, and the small negative feedbacks that served to stabilize the aircraft can be replaced with strong positive feedbacks that lead to abrupt or erratic changes in attitude. This can force the aircraft into a chaotic state, or a different self-sustaining state—such as a flat spin—from which recovery to safe flight may be impossible.

The Earth system is infinitely more complex than any engineered system, and it is not known whether its current stability is an emergent property or an illusion. Both positive and negative feedbacks operate over a large range of time scales and geographic ranges, and they are not linearly independent. Ice albedo feedback is an example of a destabilizing force. Increasing temperature melts Arctic ice, exposing darker water which absorbs more sunlight, accelerating the temperature increase. On the other hand, temperature increases also accelerate evaporation which can lead to more reflective clouds which tend to lower the temperature. Both feedbacks may take place on different time scales, during different seasons, over different regions of the Earth along with many other positive and negative feedbacks. This can create differential temperatures that change the air circulation and ocean currents that transport heat, humidity, and salinity, leading to a cascading effect. Because of the degree of complexity, it is unrealistic to expect a prediction of whether the system would return to its original quasi-equilibrium, enter a chaotic state, or go into the climate equivalent of a flat spin.

A stable aircraft will oscillate when perturbed from straight and level flight, because of the tendency of aerodynamic restoring forces to overshoot. The phugoid “porpoising” oscillation is the most familiar. Because the system is damped, the amplitude of the oscillations will decrease, returning the aircraft to a stable trajectory unless an inexperienced pilot overcorrects in phase with the oscillations, inadvertently amplifying them.

Because an aircraft has fixed characteristics (e.g. weight, airfoil shape, center of mass), and few degrees of freedom, it is straightforward to predict its future state. The climate system is analogous to an aircraft whose characteristics change as a function of time, airspeed, attitude, and altitude, in a nonlinear, coupled, irreversible, and incompletely known way. Such an aircraft might be capable of straight and level flight for an extended period of time. Any stability is perilous at best, and might be completely illusory. Moreover, any expectation that complete prediction of its future state would be misplaced.

Natural Case: The “Stable” Holocene

The beginning of the Holocene, about 11,500 years ago, coincides with end of the last ice age, and was quickly followed by the dawn of agriculture and rise of civilization. Ice core data shown in Figure 1 suggest that the Earth’s climate was rock-stable during the Holocene compared to the previous 90 thousand years. That may be true in a relative sense, but recent research has demonstrated that what appear to be tiny fluctuations in Figure 1 coincide with rise and fall of great civilizations. Moreover, it was not the temperature changes associated with climate change that caused problems, but the pattern of temperature change that led to reorganization of the climate system, causing a redistribution of precipitation. The historical record, taken together with regional paleoclimate records, demonstrates a recurring pattern of cascading failures of societies, triggered by abrupt climate change. Civilization is yet another complex system dominated by feedbacks and nonlinearities. The way it responds to climate change is not deterministic, but the correlation between environmental stress and conflict in the past is undeniable.

The most catastrophic of these collapses wiped out Bronze Age civilization across North Africa, the Nile Valley, southern Europe, Mesopotamia and south Asia. Recent research using a variety of paleoclimatic data has shown, for example, that the heart of the Akkadian empire experienced a severe 300-year drought at the time it disappeared. Evidence suggests that refugees flooded southward, forcing the Akkadians to construct a 100-mile long defensive wall that proved futile. Simultaneously, the Nile River nearly dried up and Ancient Egyptians suffered an extreme famine, ending a long period of stability. Thousands of miles to the east, flow of the Indus River abruptly shut down at the same time, causing the Harappan people of the Indus Valley to abandon their cities and migrate northward.

As was done for the Super-Kamiokande accident, modelers have been able to recreate the conditions of this cascading failure after the fact. It was long suspected that the transformation of North Africa from a grassy, fertile savannah to the bone-dry Sahara Desert was related to the gradual change in the orientation of the Earth in its orbit. The explanation for the abruptness and severity of the change, however, turns out to be due to a strong positive feedback associated vegetation loss. Once desertification crossed a threshold, it accelerated, and was not reversible.

Many Americans look back on our own experience with desertification as an anomaly. The Dust Bowl of the 1930s was caused by combination of severe regional drought and poor agricultural practices, exacerbating economic depression and leading to the largest migration (2.5 million) in American history. Paleoclimate records from lake sediments in North Dakota, however, demonstrate the sobering reality that there have been many other droughts in the past 2000 years that were both longer and more severe. The remarkable global Holocene stability is only steady when compared to the last ice age. The relative global stability is no guarantee of regional stability, and may even be nothing more than an illusion.

A false stability can be created when a system appears to be in a dynamic balance, but in fact is not. A dynamic balance is one in which negative feedbacks create restoring forces, whereas a false stability is one where two unrelated forces just happen to be balanced by coincidence. False stabilities can abruptly disappear, leading to a situation where an apparently small change can generate an abrupt and unexpected response. There is no fundamental theory or empirical evidence to suggest that the stability of the Holocene is real, or that it should continue.

7 Abrupt Change in Engineered and Natural Systems

In a complex system, abrupt change can take many forms. A system in which two large forces are in balance can rapidly lurch if one of the forces changes. This can jolt the system into an entirely different dynamic state. Such an event can happen in an engineered system, as illustrated by an incident involving a commercial DC-4 flight from Dallas to Los Angeles in 1947.

Engineering Case: Airplane Trajectory

A senior captain, sitting in a jump seat of a DC-4 at cruise altitude over Mt. Riley, New Mexico, engaged the pitch control gust lock without the knowledge of the pilot. Because the aircraft had already been trimmed for straight and level flight, the captain thought that the elevator was stabilized by the balance between the aerodynamic forces of the trim tab and the opposite force of airflow over the control surface itself. In reality, it was rigidly held in place by a pin.

The pilot began to make minor trim adjustments to accommodate a slight drift in pitch angle of the aircraft. This increased the force on the control surface, which was exactly balanced by the lock. It appeared to the pilot that the aircraft was close to the dynamic equilibrium he wanted, needing only small adjustments, when it was actually in a dangerous false balance. By continuing to make adjustments, he was effectively winding up a spring.

When the senior captain released the gust lock, the elevator sprung downward due to the accumulated trim. This abruptly pitched the nose of the aircraft downward, putting it beyond a vertical dive into inverted half-loop. The pilot and senior captain were not wearing seat belts. The sudden acceleration lifted them out of their seats and slammed their heads against three of the propeller feather controls, immediately reducing thrust and preventing a power dive into the ground. The strapped-in copilot managed to roll the plane upright only 400 feet above the desert surface.

In this case, the failure cascade was interrupted by a lucky negative feedback (the inadvertent propeller feathering). A complex system that started in an apparently stable state (straight and level westbound flight at cruise altitude and speed) unexpectedly and abruptly switched to a new state (eastbound flight at 400 feet and red-line speed).

A dynamically stable system can also become unstable if a threshold is crossed. A classic example from aviation is the stall. Increasing back pressure on the elevator increases lift, causing the nose of an airplane to pitch up. However, there is a lower limit to the airspeed that is required to maintain lift. Once that threshold is crossed, the aircraft will stall, and increasing back pressure only prevents recovery. In a complex system of systems, such as Earth's climate, such a threshold crossing can lead to a cascade of subsequent threshold crossings in subsystems.

We are just beginning to understand abrupt climate change related to past threshold crossings, such as Heinrich events. About 14,000 years ago, orbital forces on the Earth caused summers at high northern latitudes to be warmer and longer, and the ice that had slowly accumulated over previous millennia began to disappear. Large freshwater lakes appeared as the Laurentide ice sheet melted over Canada. Most of the water drained southward into the Gulf of Mexico, because a large mass of ice prevented it from flowing eastward into the Atlantic. As melting continued the ice dam diminished until about 11,400 years ago, when a threshold was crossed, and the dam burst. A massive flood of fresh water flooded down the St. Lawrence Valley into the North Atlantic, leading to the crossing of a second threshold and stopping the circulation of the Atlantic current that transported heat from the tropics to Europe. In a cascade of subsequent threshold crossings, the atmospheric circulation reorganized, plunging the planet back into another 1300 years of ice age climate called the Younger Dryas. Ecosystems, as well as early human social systems, collapsed as the climate "failure" cascaded throughout the northern hemisphere.

The Younger Dryas ended as abruptly as it began, ushering in the unprecedented period of steady climate upon which human civilization could thrive. Current evidence suggests that we have already re-entered an era of rapid climate change. Our understanding is insufficient to know whether it will be a short-term transient change, a long-term reorganization, or a fundamental return to the chaos of the last ice age. Any failure of the current (seemingly stable) climate on which we depend will undoubtedly cascade through society, at all levels. It is not unreasonable to ask if the Holocene is dynamically stable like an airplane is designed to fly, or if it is falsely stable like an airplane with a gust lock in place. Computational modeling coupled with long baseline, high fidelity measurements can begin to address whether we are on the threshold of a tipping point, and identify data that should be collected as the most sensitive precursor to the next abrupt change. Science-informed global situational awareness has the potential to provide the means to anticipate both short-term and long-term national security implications of high-consequence climate change.

8 Situational Awareness and Early Warning

The Earth's climate system behaves like many other nonlinear dynamic systems that are dominated by complexity, heterogeneities, and fluctuations. The stock market is a good example. The Dow Jones Industrial Average, over the long run, has had a predictable pattern of exponential growth. It is said to have grown at a high rate for some period of time (usually chosen to maximize the number), and most analysts expect the future rate of return to remain high. One can project a future "expectation value" of this parameter for different scenarios (e.g. 5% or 10% annual growth) and plot a smooth, monotonically increasing curve. This would not be a forecast, only a projection of a long-term average. The nature of the chaotic system means that there will be fluctuations. Sometimes there will be catastrophic collapses that cannot be predicted. Individual stocks that make up the composite will fluctuate more than the average. In some cases they will move in the opposite direction, and in other cases they will disappear altogether. These temporal and spatial heterogeneities are not inconsistent with scenario projections of long-term averages, just as temporal and spatial heterogeneities in the climate system are not inconsistent with scenario projections published by the IPCC. However, it is the fluctuations and heterogeneities that are responsible for the major short-term consequences.

We suggest that IPCC (Figure 3) and similar graphs are misleading representations for assessing the consequences of climate change, because they appear to imply a smoothly increasing and uniform trajectory of warming. By analogy with other complex systems, we argue that the greatest short-term threat will be due to sudden, unpredictable, and local changes. For this reason, there is a critical need for an early warning system consisting of high-resolution, time-resolved sensor systems with long observational baselines.

Another analogy might be the earthquake hazard. We can use what we know about plate tectonics, the strength of rocks, and solid mechanics to create sophisticated science-based models of fault zones, but we still cannot predict when an earthquake will occur because the complexity of the Earth's crust contains too many unknowns. We can create an early-warning system to reduce the hazard from the inevitable "big one" in California, even though we cannot forecast when it will occur, where and how the fault will break, or the pattern of strong ground motion.

Coupled general circulation models (GCMs) have a similar relationship to the climate-change hazard that mantle convection models have to the earthquake hazard. Climate sensitivity and projections of global mean surface temperature are useful global-scale and averaged parameters, just as plate motion can be used to describe global-scale tectonics. The proximal seismic threat isn't the mantle circulation or the plate tectonics, but the regional and local response to these forcings by sudden releases of energy in the form of earthquakes. The elastic energy is converted to ground motion, with cascading consequences such as collapsing bridges, burning buildings, and looting. Likewise the proximal climate threat isn't from the atmospheric circulation or macroscopic quantities like GHG concentration, radiative imbalance, climate sensitivity, or mean global surface

temperature. The actual threat is dominated by regional and local responses to these forcings, in the form of drought, heat waves, severe weather events, changes in precipitation patterns, desertification, loss of critical habitat, ice loss, and the cascading consequences such as agricultural collapse, wildfires, and conflict.

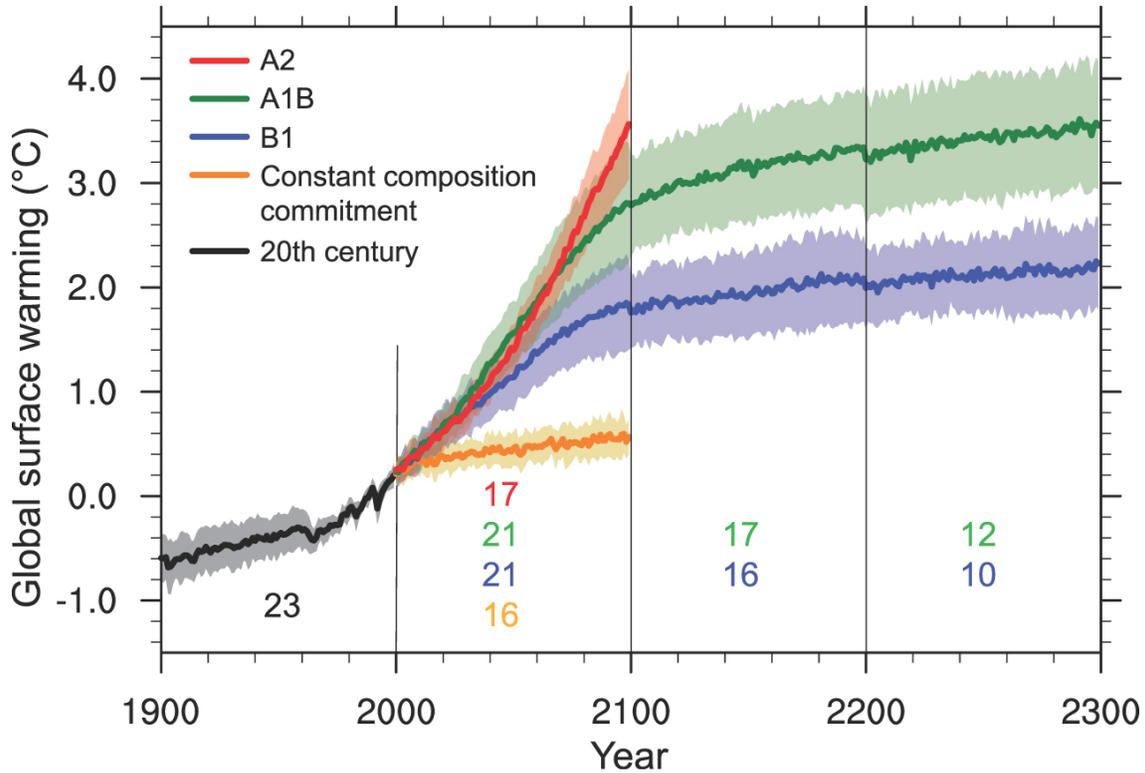


Figure 3. IPCC multi-model projections of mean global surface temperatures for various GHG stabilization scenarios.

Scientific understanding of mantle convection physics, quantification of macroscopic parameters like mean plate boundary motion, geomechanical modeling, and analysis of empirical data on seismicity and historical recurrence intervals are not sufficient to predict actual earthquakes. However, the science is indispensable for *informing* the types of data, development of sensors, locations of placement of instruments such as seismometers, geodetic surveys, monitors of water well levels, and a host of sensor systems that have the potential to provide early warning of imminent hazardous earthquakes. The model-driven scientific understanding is also a crucial component of probabilistic risk assessments for conservative engineering of structures such as buildings and bridges. We assert that this science-informed conservative engineering and early warning approach is precisely what is needed to reduce the severity of the consequences of climate change.

9 Science-Informed Engineering Conservatism

The convection of Earth's mantle does not directly threaten humans, but generates conditions and supplies the energy that, when abruptly released in the form of earthquakes or volcanic eruptions, can be dangerous. Likewise, the circulation of earth's ocean and atmosphere creates conditions and transport energy that can lead to severe storms, droughts, and other climate-related phenomena and conditions that can be dangerous. Schneider and Lane (2006) proposed metrics for dangerous climate change, which span the sustainability measures of water, energy, health, agriculture, and biodiversity, and included risks associated with extreme weather events and irreversible cascading chains of events beyond "tipping points". They listed proposed numerical values of temperature increase, starting at 1 °C for disintegration of the Greenland ice sheet, but emphasized the idea that single-metric aggregations "probably underestimate the seriousness of climate impacts." From an engineering perspective, worst-case scenarios are assumed for earthquakes and volcanic eruptions. Conservatism requires engineers to focus on metrics associated with *high-consequence* events, and we argue that conservative engineering practice should be applied to hazards associated with climate changes as well.

We call upon the framework of probabilistic risk assessment used for safety engineering, acknowledging the fact that no complex system can be guaranteed to be 100% safe. For purposes of this report, we do not think it is realistic to adopt the typical definition from the safety engineering literature: "A safe situation is one where risks of injury or property damage are low and manageable levels". We accept as conclusive the evidence that populations of the most heavily impacted regions are already exposed to dangerous climate change, with unmanageable risks; this threshold has already been crossed. For example, Sir John Holmes, the UN undersecretary for humanitarian affairs has stated that 12 out of first 13 emergency relief operations in 2007 were climate related³.

By treating climate-related hazards more like volcanic or earthquake hazards, we believe risks can be better anticipated, managed, and mitigated. Such an effort requires basic science, modeling, and extensive real-time monitoring. Science and model-informed sensitivity analysis can provide guidance about where to look and what to look for. For example, volcano monitoring does not benefit Louisiana nor does hurricane monitoring benefit Alaska. Likewise climate observations must be tuned to the hazard associated with specific geographic locations, and this selection is informed by the science and the models.

9.1 Probabilistic Risk Assessment

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

³ <http://www.guardian.co.uk/environment/2007/oct/05/climatechange>

applying physically-sound theory, empirical observations, and validated models. The scientifically conservative estimates are the ones that minimize deviation from prior expectations. Scientific conservatism, when applied to climate change, tends to downplay the degree of change, and virtually all the climate change literature uses the term “conservative” in the opposite sense from that of safety engineers. For complex, non-deterministic, chaotic systems such as Earth’s climate, reliable prediction of the future is not possible. The best approach is to generate probability distribution functions (PDFs) which encapsulate the best estimate of the future, plus some bounds on its uncertainty. The lower bound on expected climate change is the “scientifically 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 Figure 4 tend to be of the most interest to decision makers because they are the most probable. Unfortunately, they are often treated as “forecasts”. Palmer (2002) makes the argument that policy or planning should not be based on best estimates, but on probabilistic weather and climate ensemble forecasts: “commercial decisions are often made, not on the basis of events which are likely to occur, but on the basis of events which are unlikely to occur, but which, if they did occur, would involve serious financial loss”.

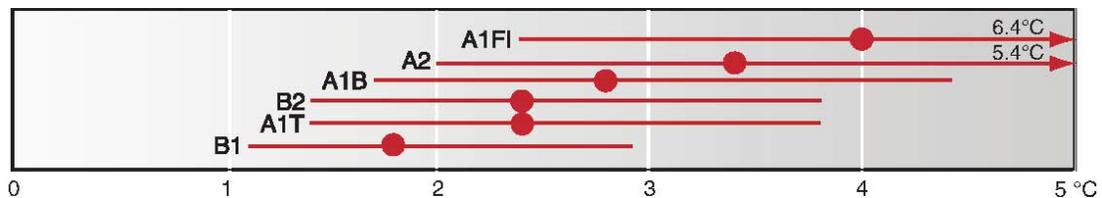


Figure 4. Estimated temperature bands for various emissions scenarios from IPCC AR4 Synthesis Report. Dots and bars show best estimates and “likely” ranges of warming for the 2090s relative to the 1980s and 1990s.

Two occurrences that can lead to even greater catastrophe than a nuclear war 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 can provide some guidance. 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 dominated by scientists and is focused on the most probable scenarios. We prefer to apply the safety engineering-oriented risk approach, which requires more

emphasis on uncertainty quantification, especially to characterize the high end of the range of the projections with a focus on failure mechanisms, and on continuous monitoring to provide global situational awareness and early warning.

Ongoing research is quantifying the uncertainty in climate sensitivity. Some assessments result in the generation of PDFs rather than the simple “likelihood bounds” as provided by the IPCC. 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 with a distribution that 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 expected, 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. Andronova and Schlesinger (2001) calculated a distribution with a 10% probability of climate sensitivity greater than 6.8 °C. The skewed distribution with a high-sensitivity tail is characteristic of sensitivity PDFs, and is shown by Roe and Baker (2007) to be an inevitable consequence of the nature of the climate system and the inherent uncertainty in the feedbacks. This interpretation further suggests the need for a safety engineering approach to characterize the mechanisms that can lead to high sensitivity.

Murphy, *et al.*, (2004) 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. This sophisticated analysis 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. We have chosen to use the Murphy, *et al.*, (2004) probability distribution function to illustrate the importance of the oft-neglected high-end tail to estimate the climate change threat.

9.2 Risk is Equal to Probability Multiplied by Consequences

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 (WHO)⁴ which estimated in 2005 that 150,000 deaths per year were attributable to anthropogenic climate change. It can be argued 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” or more for a period of months (Covey, *et al.*, 1990) to as

⁴ Link to WHO report: <http://www.who.int/globalchange/news/fsclimandhealth/en/index.html>

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 CO₂. 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.

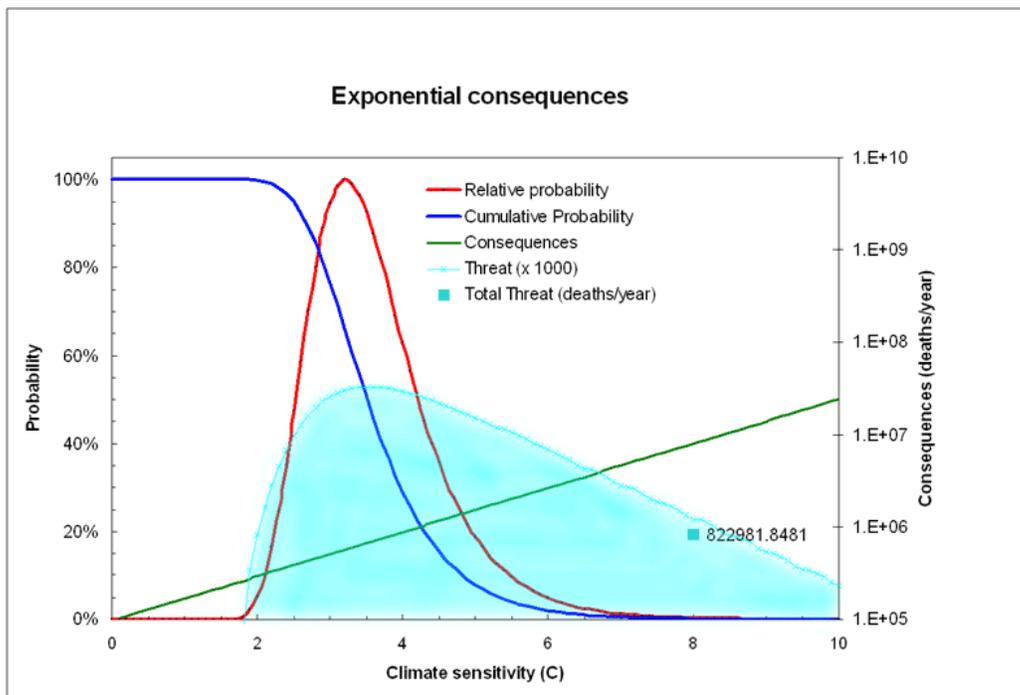


Figure 5. Using the probability distribution of Murphy, *et al.*, (2004) (red) a cumulative probability is derived (blue). The consequence curve (green) assumes an exponential increase of fatalities from the current WHO estimate at 0.8 °C to a global extinction event at 20 °C.

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. For purposes of illustration we used the WHO estimate of current climate-change fatalities/year of 150,000 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. 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.

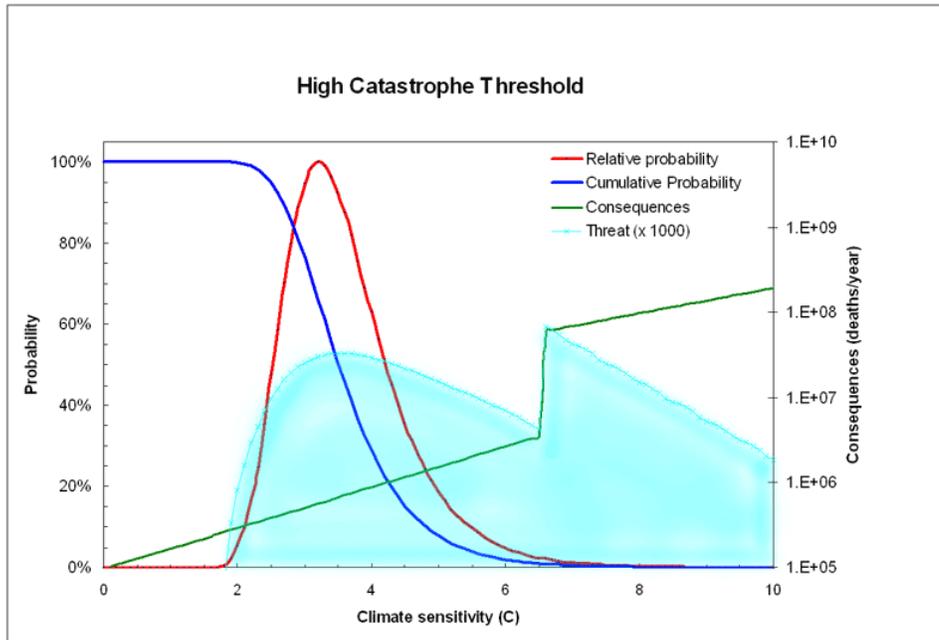


Figure 6. The low range of the consequence curve (green) is the same as for Fig. 2, but assumes that 6.5 °C causes a global environmental collapse that kills about ¼ of the world’s population over 25 years.

It is the area under the threat curve that is equal to the expected loss of life for a given assumed consequence function, and 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 as opposed the current best estimate of 80 deaths/year from the asteroid hazard (Harris, 2008). The climate sensitivity PDFs are not symmetric in terms of their contribution to the total risk. From an engineering safety perspective, it is much more important to quantify the high-end (right-hand side in the figures) 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. On the other hand, the conditions on this tail are likely to be most sensitive to monitoring and early warning.

This concept is generalized and illustrated schematically in Figure 7, 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). 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”.

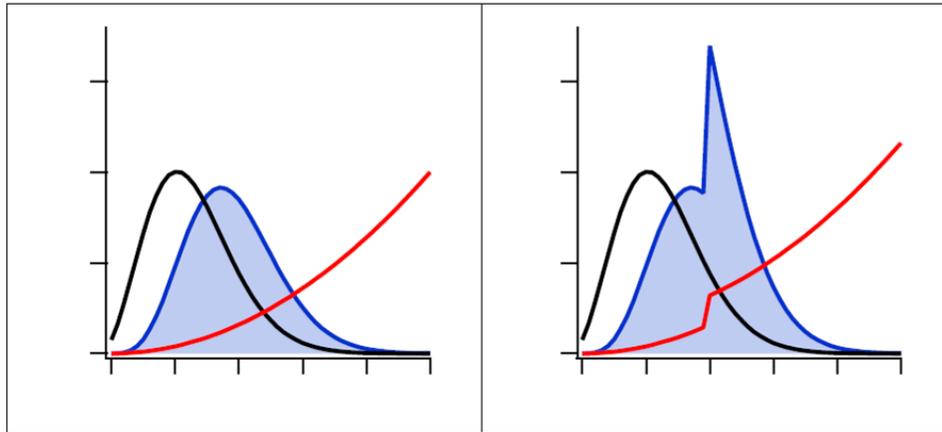


Figure 7. Schematic of probability, consequence and risk, from the IPCC Workshop Report on Uncertainty and Risk (Manning, *et al.*, 2004).

We argue that appropriate global situational awareness should focus resources on the high-consequence, “catastrophic climate change” tail in the distribution of possible future climate states. 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.

9.3 Physical Changes in the Arctic

An example germane to security consequences of Arctic climate change is illustrated in Figure 8, which is based on Figure 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.

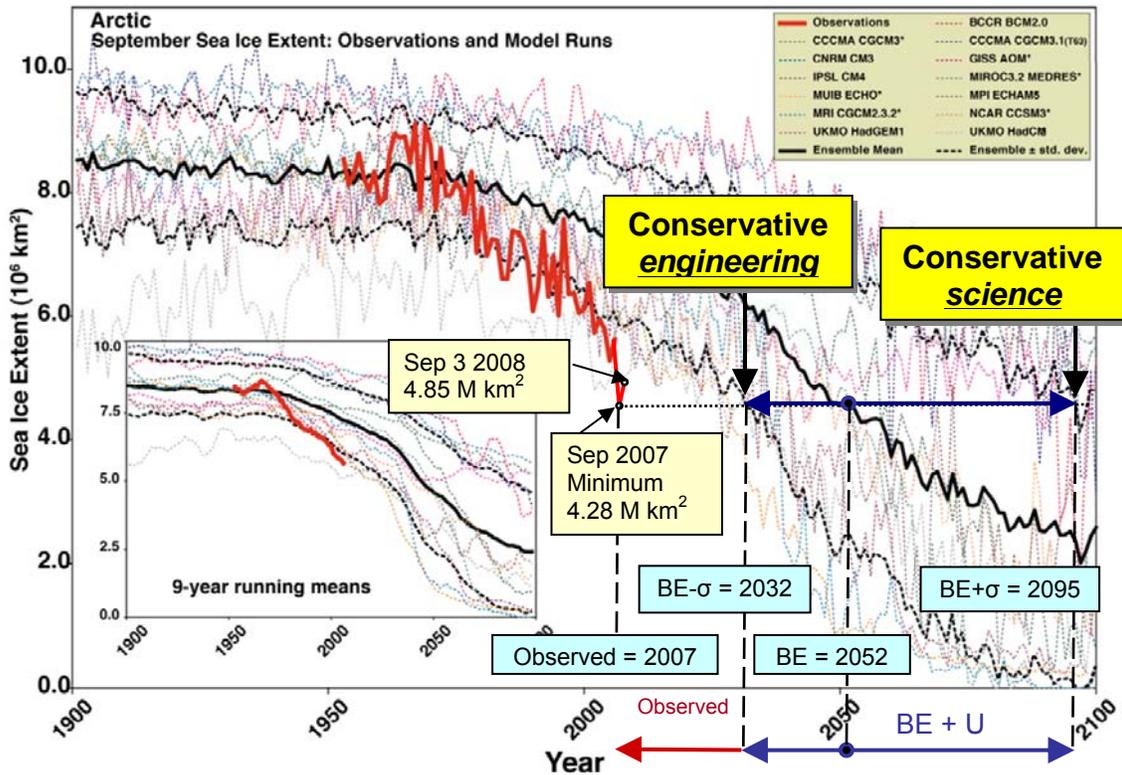


Figure 8. Observed September Arctic sea ice extent (red) and predictions, based on Figure 1 of (Stroeve, *et al.*, 2007).

In Figure 8, 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 safety, which is more appropriate for informing decision makers. For illustration purposes, consider what might have been reasonable questions for decision makers to ask several years ago.

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 km²?
2. What is the uncertainty in this estimate?

Using only 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, 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 safety engineering 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 and critical data to enable better estimates of the high-consequence tails in the probability distribution functions of future climate change. Moreover, the models suggest that Arctic sea ice extent is extremely sensitive to assumptions and scenarios. Geopolitical considerations suggest that the rate of sea ice loss is highly consequential. Highly-resolved, continuous monitoring of Arctic sea ice extent would be an example of science-informed global situational awareness.

9.4 Duel-use of Monitoring Data: Atmospheric Explosions and Bolides

We already discussed the danger from asteroid impacts as an example of how a threat can be quantified in terms of probability and consequences. It is noteworthy that this probability component of this assessment is critically dependant on data from DoD satellites (Brown, *et al.*, 2002). Formerly classified data were made available to scientists, and our best assessment of the population of small asteroids that explode in the atmosphere comes from this data.⁵ As more of the larger asteroids are discovered and monitored, the smaller airbursts are a growing fraction of the total threat (Boslough and Crawford, 2008). Real-time availability of such data to researchers has created opportunities for rapid and important discoveries. A notable recent example is the observation of asteroid 2008 TC3 which exploded as a bolide in the atmosphere over northern Sudan in October, 2008 (Jenniskens, *et al.*, 2009). In Figure 9, the size distribution of asteroids in Earth-crossing orbits is shown to be heavily constrained by observations of bolides by instruments designed to detect nuclear explosions (Brown, *et al.*, 2002). These observations provide statistical constraint on the probability of impact, as well as global situational awareness associated with the impact threat. We believe there are other sets of data that may be equally useful for characterizing climate change as well as global situational awareness associated with the climate-change threat.

⁵ According to Nature News (June 12, 2009) scientists have now lost access to this data (see <http://www.nature.com/news/2009/090612/full/459897a.html>)

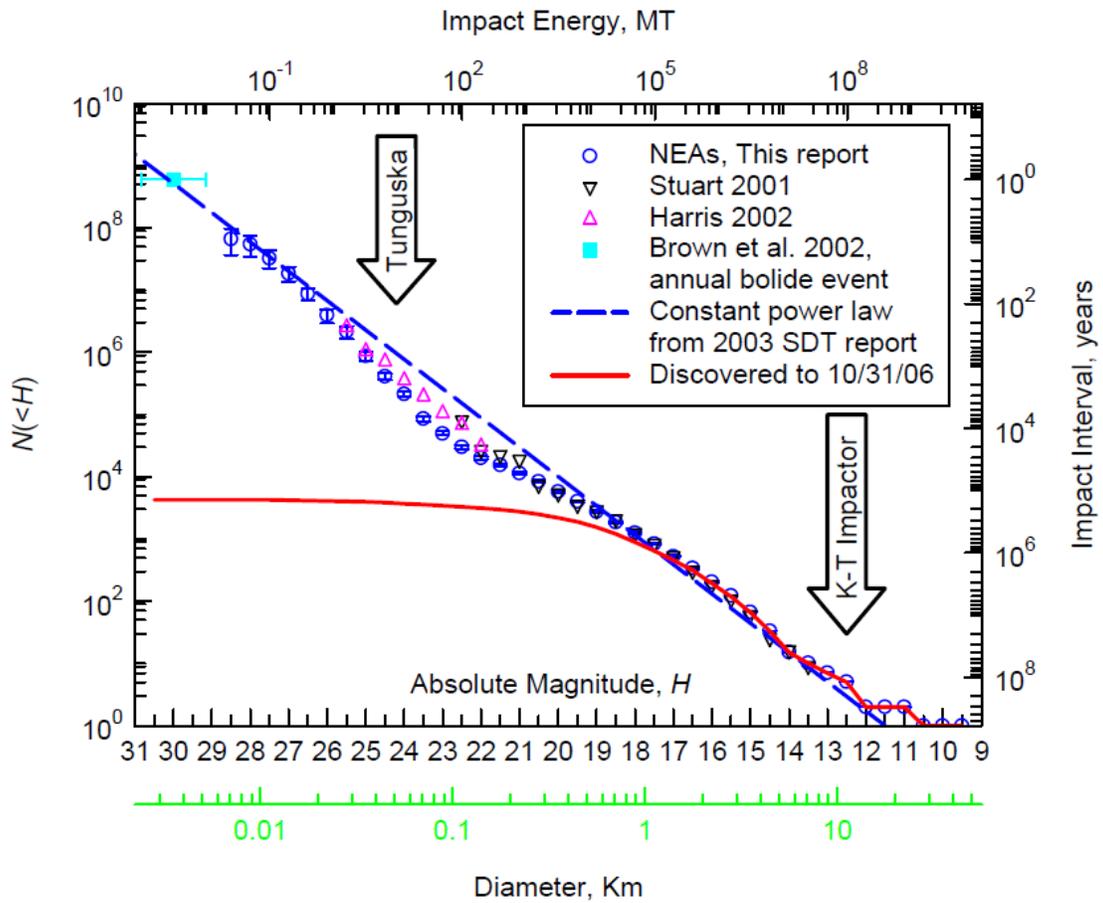


Figure 9. Population of Earth-crossing asteroids of as a function of size (Harris, 2009). Brown, *et al.*, (2002) provide constraint on risk from small asteroids using formerly classified DoD satellite data on superbolide frequency (light blue square, upper left).

10 What Else can go Wrong?

There is significant variability among the IPCC models which contributes to uncertainty in the degree of future climate change. The results of these models were aggregated into best estimates and uncertainties by the IPCC's Summary for Policymakers (SPM) which focused primarily on global averages such as radiative forcing, sea level rise, and mean global surface temperature as the most important metrics for quantifying climate change. We suggest that such global aggregations are inadequate because climate shares features with many nonlinear dynamic physical systems for which temporal and spatial fluctuations can be proportionately much greater on local and regional scales. For example, there are regions of the Earth—such as the African Sahel—for which climate change has already contributed to agricultural collapse and chaos. Other regions—such as the Arctic—are much more sensitive than the global average and are currently changing very rapidly in a way that will have enormous impact on society and national security (Backus and Strickland, 2008). Climate change is likely to continue manifesting itself in the most sensitive regions before serious global consequences are experienced.

We expect the acute short-term consequences to be associated with *regional* climate change. Regional metrics for climate change span sustainability measures of water, energy, health, agriculture, and biodiversity, and include risks associated with extreme weather events and irreversible cascading chains of events associated with “tipping points”. We argue that global situational awareness must focus on regional climate change as well as global climate change.

Smith, *et al.*, (2009) list five of “reasons for concern” that include both global and regional climate change. We propose that comprehensive monitoring for high-consequence climate change must take these concerns into account:

- Risk to unique and threatened systems (e.g. coral reefs, tropical glaciers, endangered species, unique ecosystems, biodiversity hotspots, small island states, and indigenous communities).
- Risk of extreme weather events (e.g. frequency, intensity, or consequences of heat waves, floods, droughts, wildfires, or tropical cyclones).
- Disparities of impacts and vulnerabilities (e.g. disparities of impacts, with some regions suffering more than others, and disproportionate harm to populations with the least ability to adapt).
- Aggregate damages (comprehensive measures of impacts such as cost, lives affected, or lives lost).
- Risks of large-scale discontinuities (tipping points and thresholds, such as rapid sea-level rise, ocean acidification, and strong feedbacks).

11 Vulnerability Scenario Cases

Different parts of the world have different physical as well as different geopolitical sensitivities to climate change. Some areas are highly sensitive to sea-level rise (e.g. island nations, China, Bangladesh, Florida), some to changes in seasonal monsoon patterns (e.g. South Asia, Indonesia), and others to the melting of glaciers (e.g. China, South Asia, South American highlands). We have chosen two regions—the Arctic and the African Sahel—to illustrate the complexity of interactions between physical climate change and its geopolitical consequences. The Arctic is more sensitive to climate change than any other region, and even though its population density is extremely low, the geopolitical consequences are enormous because of competition for resources, potential for conflict among developed nations, and effects that can have globally cascading consequences (e.g. increased Arctic shipping can reduce traffic in the Panama Canal, potentially destabilizing Central America). Our discussion here is extracted from a more comprehensive report, “The Arctic as a Test Case for an Assessment of Climate Impacts on National Security,” (Boslough, *et al.*, 2008). The African Sahel is a transition zone that is vulnerable to drought and desertification, and is characterized by failed states and ethnic conflict. Because it is already on the margin, any climate change is likely to have a disproportionate effect on its population. We argue that for global situational awareness, the potential geopolitical consequences must be taken into account as well as the likelihood of regional climate change.

11.1 The Arctic

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.

It has long been known that the Arctic is a critical component in the Earth’s geophysical 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. This represents a dire scenario because of the enormous ecological and

human consequences arising from powerful positive feedbacks whose possibility has not been eliminated by researchers.

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).

For a very complete review of the impact of climate change on the Arctic region, we recommend the Arctic Climate Impact Assessment - Scientific Report, published by Cambridge University Press (ACIA)⁶. 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)⁷, 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.

Our brief snapshot of the current state of Arctic change and its ramifications highlights the most noteworthy recent observations and lists a subset of possible consequences (Boslough, *et al.*, 2008). We used scenarios as a framework for planning and discussion, and described approaches for Arctic modeling and how models can be improved and used to guide observations and global situational awareness. We concluded that exploratory simulations should be used 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. There is a critical need for 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.

⁶ Full ACIA reports are available at <http://www.acia.uaf.edu/> or <http://www.amap.no/acia/>

⁷ IPCC TAR available at <http://www.ipcc.ch>

11.2 The African Sahel

The Sahel is the politically and environmentally unstable transition region between the Sahara Desert to the north and the tropical savanna to the south. It consists of arid to semi-arid grasslands, savanna, and steppes, and is highly variable in agricultural productivity because of extreme seasonal and geographic precipitation differences, and intermittent droughts. These droughts have led to famines and conflict throughout history. Climate change and other factors have created conditions that led to the enduring crisis and genocide in Darfur in the 21st century.

The Darfur crisis demonstrates the connection between climate-change-induced environmental scarcity and conflict. It is a connection that is not simple, but is rather one that has many causes that are exacerbated by the changes in climate. The United Nations has called the current crisis the worst humanitarian disaster in the world. The crisis erupted in February 2003 when two loosely allied rebel groups, the Sudan Liberation Army and the Justice Equality Movement launched attacks on government posts in Darfur. The rebels had a few victories in the initial months of the conflict, but then the government “turned loose” the Janjaweed militias, backed by its regular forces, on civilians who were thought to support the insurgency. The Janjaweed militias are made up of Arab nomadic shepherds and have been described as a civilian terrorist group. The Janjaweed have been accused of major human rights violations, mass killings of civilians, rape and other forms of sexual violence, forced displacement, and burning of villages. The Janjaweed have also been accused of intentionally destroying irrigation systems and food stores so that the civilian populations do not return to the burned-out villages.

The International Crisis Group states that there were multiple causes for the insurgency in Darfur in 2003, including economic and political marginalization, underdevelopment, and the government’s policy (longstanding) of supporting the Janjaweed militias against the primarily African farming communities. According to several sources, the roots of the current violence can be traced to traditional clashes between nomadic (pastoral) Arab herders and sedentary African farmers. Such clashes occurred as Arab herders from the north migrated south in the dry season in search of water sources and grazing for their cattle and camels and trampled the fields of the African farmers. Some sources say the conflicts in Darfur have been going on for several decades, while others say centuries. Traditionally, such conflicts were resolved by negotiation, but the conflicts intensified during the 1980s and 1990s because of drought and also the government’s policy of arming the Arab herders and removing the weapons of the farmers.

Climate change since the 1970s has accelerated the pace of desertification, putting pressure on those who live in the northern part of Darfur to move southward and thus contributing to the historic struggle for land between the herders and the farmers. Desertification is defined as “land degradation in arid, semi-arid and dry subhumid areas resulting from various factors, including climatic variations and human activities”. Examples of such human activities are overcultivation, deforestation, and poor irrigation practices, which reduce the amount of arable land.

Though the rainy season came to Darfur in 2004, civilians had to flee the land to escape the conflict and thus were unable to plant their crops, contributing to a shortage of food in the region. The rains also spur flash floods, which make the roads impassable, restrict the delivery of assistance, and increase the risk of disease. In addition, there has been concern that locusts currently threatening northern Africa would swarm to Darfur, where locust-control efforts would be impossible. Locusts eat their weight in food every day.

As part of a project to understand climate change effects on international stability, we began to develop a concept map (Figure 10) for understanding the Darfur crisis (Boslough, *et al.*, 2004). We combined several of the graphical components from the set of systems dynamics tools to show the interaction of important elements of the conflict. These elements were taken from our review of the current literature and international media sources on the current crisis.

In Figure 10, we use several symbols:

- A box represents a quantitative element (*i.e.*, factor or condition) that has a causal relationship with another element and that can increase or decrease over time.
- An arrow denotes that one element is affecting another element. The “+” and “-” symbols that are associated with an arrow indicate the effect of the influence of one element on the other element.
- In general, a “+” means that both elements move in the same direction, *i.e.*, an increase in the first element is expected to cause an increase in the second element, or a decrease in the first element is expected to cause a decrease in the second element.
- In general, a “-” means that both elements move in the opposite direction, *i.e.*, an increase in the first element is expected to cause a decrease in the second element, or a decrease in the first element is expected to cause an increase in the second element.

Taking a small piece of the map, we can explain how the elements interact and influence each other. In the upper left, we have the element of drought, which is related to human land-use patterns as well as climate change. Drought affects the movement of refugees (the Fur farmers). There is a + symbol on the arrow connecting the drought to the movement of refugees. This indicates that as the drought increases, the movement of refugees is expected to increase (or conversely, if the drought decreases, the refugees will move less). The movement of refugees has a similar relationship to the expansion of agricultural activity and competition over arable and pastoral land. For example, as the movement of refugees increases, agricultural activity will increase as the refugees find new areas to farm and also there will be competition for these new areas to farm.

We chose the Darfur conflict to illustrate the extreme complexity of climate-coupled geopolitical systems, and to emphasize the need for monitoring systems that are informed by human consequences in addition to probabilities of physical changes. There may be a significant change in the climate of the Sahara Desert, for example, but it may not have

serious social or geopolitical consequences due to the fact that it is already uninhabitable and changes would affect small populations. In a transition region such as the Sahel, however, small changes in the timing or quantity of precipitation can have disproportionate human consequences, so data collection in this region is much more important. Global situational awareness must be informed not only by the science of climate change, but by geopolitical assessments.

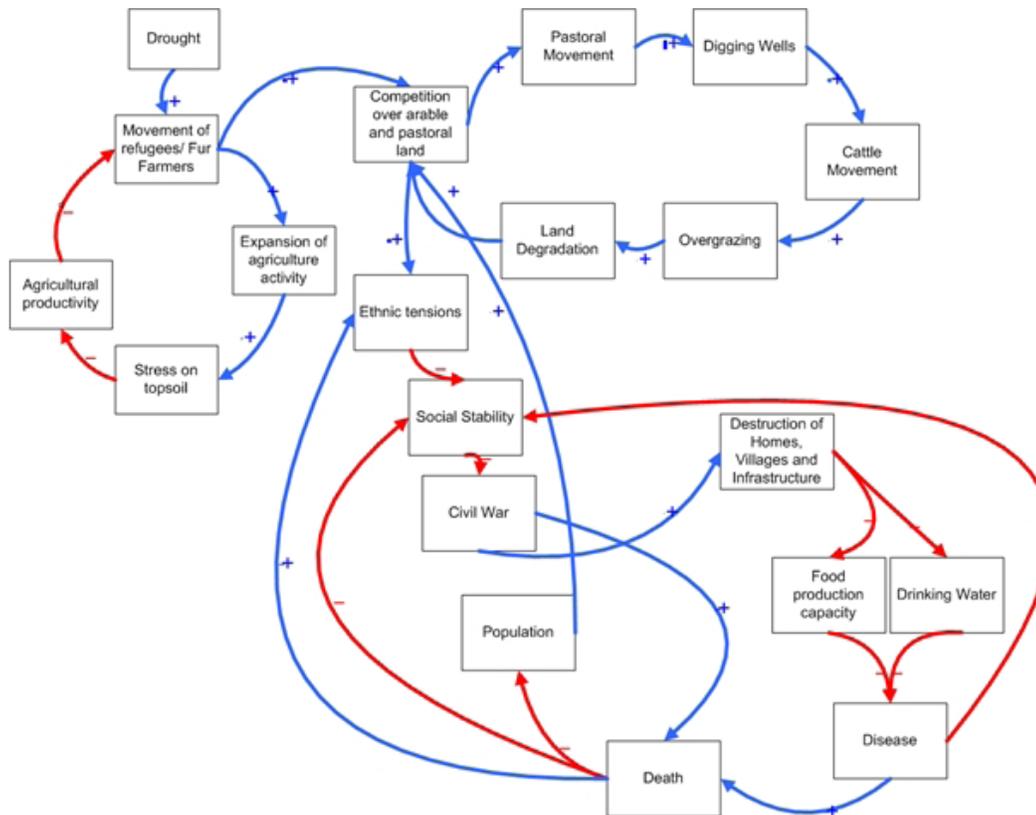


Figure 10. Concept map that deconstructs the Darfur crisis (Boslough, *et al.*, 2004).

12 Anticipating Conflict over Geoengineering

There is growing interest in the idea of geoengineering, the attempt to manipulate the Earth's climate to counteract the effects of excess greenhouse gas pollution. Most of this discussion has been theoretical and only considered to be a last-resort solution if warming becomes extreme or if runaway climate change becomes a reality due to strong positive feedbacks. Experiments to test geoengineering concepts by intentionally releasing iron into the ocean to create carbon-absorbing blooms of algae have met with enormous international resistance, but recent comments by President Obama's science advisor, John Holdren, suggest that geoengineering has become a serious topic of policy discussion⁸. The strong negative reaction illustrates how controversial the subject is.

It seems unrealistic to assume that geoengineering is going to be sanctioned by the international community, regardless of the severity of climate change, because measures that may have a net global benefit will never be free of risk. One such risk has been discussed for geoengineering concepts based on production of stratospheric aerosols ("artificial smog") to offset the radiative forcing due to excess GHG concentrations. This would allow GHGs to build up gradually without a significant response, analogous to the way that small but continuous adjustments of a trim tab can allow stress to build up on a locked airplane control surface. Like the gust lock in the DC-4 incident (see sidebar in Section 7), a layer of artificial aerosol would provide a dangerously unstable compensation. If the geoengineering effort were abruptly discontinued due to a war or economic failure, the aerosol would rapidly dissipate, whereas the GHG forcing would remain. The likely outcome would be a strong radiative imbalance leading to a sudden but unpredictable change in climate.

The burden of unintended negative consequences may be borne by populations other than those who are intended to benefit. It is possible that unauthorized "wildcat" geoengineering projects could create conflict among nations. Under extreme climate-change scenarios, such conflict could unfold in a way that is analogous to levee sabotage that has taken place during Mississippi floods (in which residents of one side of the river cause the levees on the other side to fail in order to lower the water level to save their own property). Monitoring for effective global situational awareness should anticipate the possibility of unauthorized attempts at self-interested geoengineering.

⁸ "It's got to be looked at," he said. "We don't have the luxury ... of ruling any approach off the table." <http://www.guardian.co.uk/world/feedarticle/8448106>

13 Conclusions

Situational awareness of the Earth's climate system can be improved by using global monitoring systems that have high spatial and temporal resolution. Continuously monitoring the state of the Earth's climate can provide early warning of high-consequence climate change to help anticipate and minimize the threat. Global climate has changed abruptly in the past and will almost certainly do so again, even in the absence of anthropogenic interference. We cannot assume that climate will continue to be stable, even on time scales of a few years. Moreover, the sudden collapse of regional or global climate stability would not necessarily be triggered by a mechanism we understand or could predict, regardless of how sophisticated and highly-resolved our climate models become. Increasing recognition that climate models have such limitations underscores the need for high-fidelity continuous global monitoring.

Our scientific understanding of the processes driving climate change will continue to improve regardless of the ability of political and social debates to shed light on foreseeable consequences or courses of action. Climate change is moving beyond a scientific problem to the realm of engineering, policy, economics, and national security. A conservative engineering approach requires us to focus on metrics associated with *high-consequence* events, and we have adopted this perspective in our assessment of hazards due to climate change and our recommendations for global situational awareness.

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