Abrupt Impacts of Climate Change: Anticipating Surprises

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SUMMARY

Levels of carbon dioxide and other greenhouse gases in Earth's atmosphere are exceeding levels recorded in the past millions of years, and thus climate is being forced beyond the range of the recent geological era. Lacking concerted action by the world's nations, it is clear that the future climate will be warmer, sea levels will rise, global rainfall patterns will change, and ecosystems will be altered.

However, there is still uncertainty about *how* we will arrive at that future climate state. Although many projections of future climatic conditions have predicted steadily changing conditions giving the impression that communities have time to gradually adapt, for example, by adopting new agricultural practices to maintain productivity in hotter and drier conditions, or by organizing the relocation of coastal communities as sea level rises, the scientific community has been paying increasing attention to the possibility that at least some changes will be abrupt, perhaps crossing a threshold or "tipping point" to change so quickly that there will be little time to react. This concern is reasonable because such abrupt changes—which can occur over periods as short as decades, or even years—have been a natural part of the climate system throughout Earth's history. The paleoclimate record—information on past climate gathered from sources such as fossils, sediment cores, and ice cores—contains ample evidence of abrupt changes in Earth's ancient past, including sudden changes in ocean and air circulation, or abrupt extreme extinction events. One such abrupt change was at the end of the Younger Dryas, a period of cold climatic conditions and drought in the north that occurred about 12,000 years ago. Following a millennium-long cold period, the Younger Dryas abruptly terminated in a few decades or less and is associated with the extinction of 72 percent of the large-bodied mammals in North America.

Some abrupt climate changes are already underway, including the rapid decline of Arctic sea ice over the past decade due to warmer polar temperatures. In addition there are many parts of the climate system that have been thought to be possibly prone to near-future abrupt change that would trigger significant impacts at the regional and global scale. For some of these potential changes, current scientific understanding is insufficient to say with certainty how significant the threat is. In other cases, scientific research has advanced sufficiently that it is possible to assess the likelihood, for example the probability of a rapid shutdown of the Atlantic Meridional Overturning Circulation (AMOC) within this century is now understood to be low.

In addition to abrupt changes within the climate system itself, gradual climate changes can cross thresholds in both natural systems and human systems. For example, as air and water temperatures rise, some species, such as the mountain pika or some ocean corals, will no longer be able to survive in their current habitats and will be forced to relocate or rapidly adapt. Those populations that cannot do so quickly enough will be in danger of extinction. In addition, human infrastructure is built with certain expectations of useful life expectancy, but even gradual climate changes may trigger abrupt thresholds in their utility, such as rising sea levels surpassing sea walls or thawing permafrost destabilizing pipelines, buildings, and roads.

Climate is not the only stressor on the Earth system—other factors, including resource depletion and ever-growing human consumption and population, are exerting enormous pressure on nature's and society's resilience to sudden changes. Understanding the

potential risks posed by both abrupt climate changes and the abrupt impacts resulting from gradual climate change is a crucial piece in advancing the ability of society to cope with changes in the Earth system. Better scientific understanding and improved ability to simulate the abrupt impacts of climate change would help researchers and policymakers with a comprehensive risk assessment. This report, sponsored by the U.S. intelligence community, the National Oceanic and Atmospheric Administration, the National Science Foundation, and the National Academies, examines current knowledge about the likelihood and timing of potential abrupt changes, discusses the need for developing an abrupt change early warning system to help anticipate major changes before they occur, and identifies the gaps in the scientific understanding and monitoring capabilities (the full Statement of task can be found in Chapter 1).

STATE OF KNOWLEDGE ON ABRUPT IMPACTS OF CLIMATE CHANGE

This study differs from previous treatments of abrupt changes by discussing both the abrupt changes in the physical climate system (hereafter called "abrupt climate change"), as well as the abrupt changes in the physical, biological, or human systems that result from steadily changing aspects of the climate system (hereafter referred to as "abrupt climate impacts"). This report focuses on abrupt climate changes and abrupt climate impacts that have (or were thought to possibly have) the potential to severely affect the physical climate system, natural systems, or humans systems, often affecting multiple interconnected areas of concern. The primary timescale of concern is years to decades. A key characteristic of these changes is that they can come faster than expected, planned, or budgeted for, forcing more reactive, rather than proactive, modes of behavior.

Careful and vigilant monitoring, combined with a constantly improving scientific understanding of the climate system, would help society anticipate major changes before they occur. With this goal in mind, the report's authoring committee summarized the state of knowledge about potential abrupt changes in Table S.1. This table includes potential abrupt changes to the ocean, atmosphere, ecosystems, and to high latitude regions that are judged to meet the above criteria. For each abrupt change, the Committee examined the available evidence of potential impact and likelihood. Some abrupt changes are likely to occur within this century—making these changes of most concern for near-term societal decision making and a priority for research. In other cases, there are still large scientific uncertainties about the likelihood of a potential abrupt change, highlighting the need for further research in these areas. Finally, recent data has revealed that some abrupt changes, widely discussed in the scientific literature because they were once identified as possible threats, are no longer considered likely during this century. This illustrates how focused efforts to study critical climate change mechanisms can also assuage societal concern about potential abrupt changes, in addition to identifying them.

Abrupt Changes Already Underway

The abrupt changes that are already underway are of most immediate concern for societal decisions. These include the disappearance of late-summer Arctic sea ice and increases in extinction rates of marine and terrestrial species.

Disappearance of Late-Summer Arctic Sea Ice

Recent dramatic changes in the extent and thickness of the ice that covers the Arctic sea have been well documented. Satellite data for late summer (September) sea ice extent show natural variability around a clearly declining long-term trend (Figure S.1). This rapid

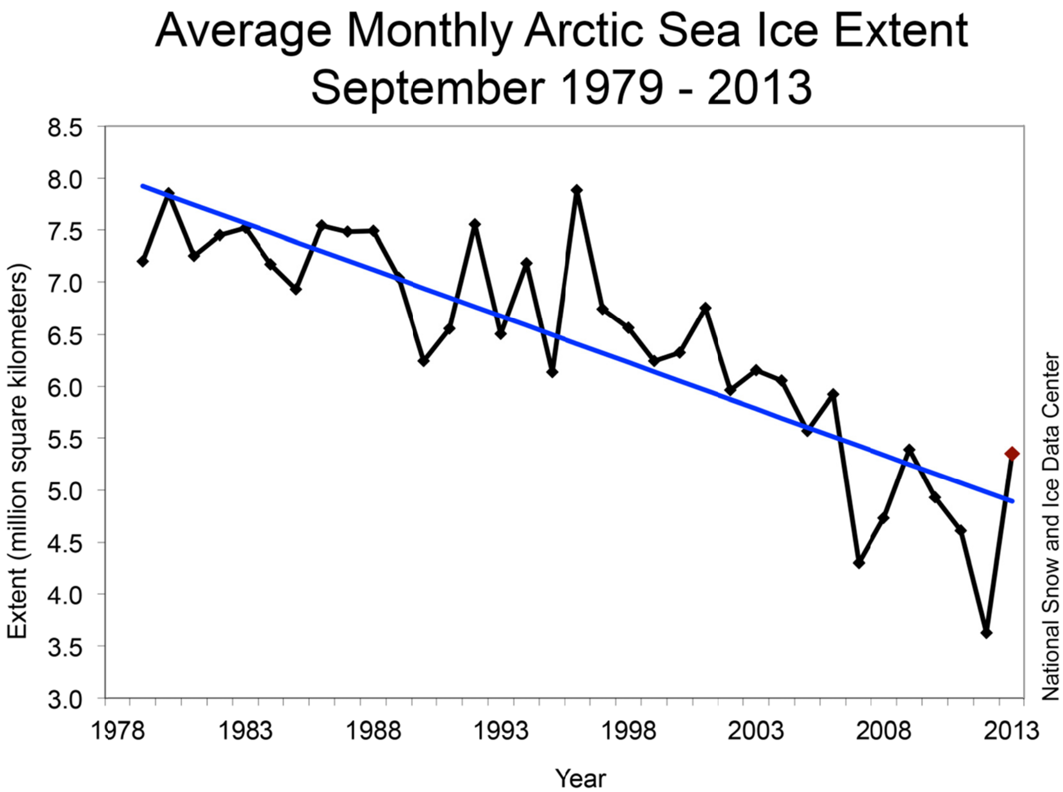

FIGURE S.1 The chart above shows the time series of Arctic sea ice extent each September from 1979 to 2013 derived from satellite data. Late summer Arctic sea ice extent has shown a substantial decrease since the satellite data record began in 1979, in particular the most recent seven summers have shown much lower sea ice cover. Source: National Snow and Ice Data Center, http://nsidc.org/arcticseaicenews/.

reduction in Arctic sea ice already qualifies as an abrupt change with substantial decreases in ice extent occurring within the past several decades. Projections from climate models suggest that ice loss will continue in the future, with the full disappearance of late-summer Arctic sea ice possible in the coming decades.

The impacts of rapid decreases in Arctic sea ice are likely to be considerable. More open water conditions during summer would have potentially large and irreversible effects on various components of the Arctic ecosystem, including disruptions in the marine food web, shifts in the habitats of some marine mammals, and erosion of vulnerable coastlines. Because the Arctic region interacts with the large-scale circulation systems of the ocean and atmosphere, changes in the extent of sea ice could cause shifts in climate and weather around the northern hemisphere. The Arctic is also a region of increasing economic importance for a diverse range of stakeholders, and reductions in Arctic sea ice will bring new legal and political challenges as navigation routes for commercial shipping open and marine access to the region increases for offshore oil and gas development, tourism, fishing and other activities.

Understanding and predicting future changes in Arctic sea ice will require maintained and expanded observations of sea ice thickness and extent, including satellite-based measurements. Information on Arctic Ocean conditions may provide insight on the potential for rapid sea ice loss, yet only limited observations of Arctic Ocean conditions currently exist. In addition to observations, improved modeling of sea ice, including within global and regional climate models, is needed to better forecast Arctic sea ice changes and their impacts.

Increases in Extinction Threat for Marine and Terrestrial Species

The rate of climate change now underway is probably as fast as any warming event in the past 65 million years, and it is projected that its pace over the next 30 to 80 years will continue to be faster and more intense. These rapidly changing conditions make survival difficult for many species. Biologically important climatic attributes—such as number of frost-free days, length and timing of growing seasons, and the frequency and intensity of extreme events (such as number of extremely hot days or severe storms)—are changing so rapidly that some species can neither move nor adapt fast enough (Figure S.2).

Specific examples of species at risk for physiological reasons include mountain species such as pikas and endemic Hawaiian silverswords, which are restricted to cool temperatures at high altitudes. Species like polar bears are at risk because they depend on sea ice to facilitate their hunting of seals and Arctic sea ice conditions are changing rapidly. Other species are prone to extinction as changing climate causes their habitats to alter such that growth, development, or reproduction of constituent individuals are inhibited.

The distinct risks of climate change exacerbate other widely recognized and severe extinction pressures, especially habitat destruction, competition from invasive species, and unsustainable exploitation of species for economic gain, which have already elevated extinction rates to many times above background rates. If unchecked, habitat destruction, fragmentation, and over-exploitation, even without climate change, could result in a mass extinction within the next few centuries equivalent in magnitude to the one that wiped out the dinosaurs. With the ongoing pressures of climate change, comparable levels of extinction conceivably could occur before the year 2100; indeed, some models show a crash of coral reefs from climate change alone as early as 2060 under certain scenarios.

Loss of a species is permanent and irreversible, and has both economic impacts and ethical implications. The economic impacts derive from loss of ecosystem services, revenue, and jobs, for example in the fishing, forestry, and ecotourism industries. Ethical implications include the permanent loss of irreplaceable species and ecosystems as the current generation's legacy to the next generation.

Research on species extinctions is in many ways still at a nascent stage of discovery. Prominent research questions at this time include identifying which species in which ecosystems are most at risk, identifying which species extinctions would precipitate inordinately large ecological cascades that would lead to further extinctions, and assessing the impact of climate-induced changes in seasonal timing and species interactions on extinction rates.

Abrupt Changes of Unknown Probability

Destabilization of the West Antarctic Ice Sheet

The volume of ice sheets is controlled by the net balance between mass gained (from snowfall that turns to ice) and mass lost (from iceberg calving and the runoff of meltwater from the ice sheet). Scientists know with high confidence from paleo-climate records that during the planet's cooling phase, water from the ocean is traded for ice on land, lowering sea level by tens of meters or more, and during warming phases, land ice is traded for ocean water, raising sea level, again by tens of meters and more. The rates of ice and water

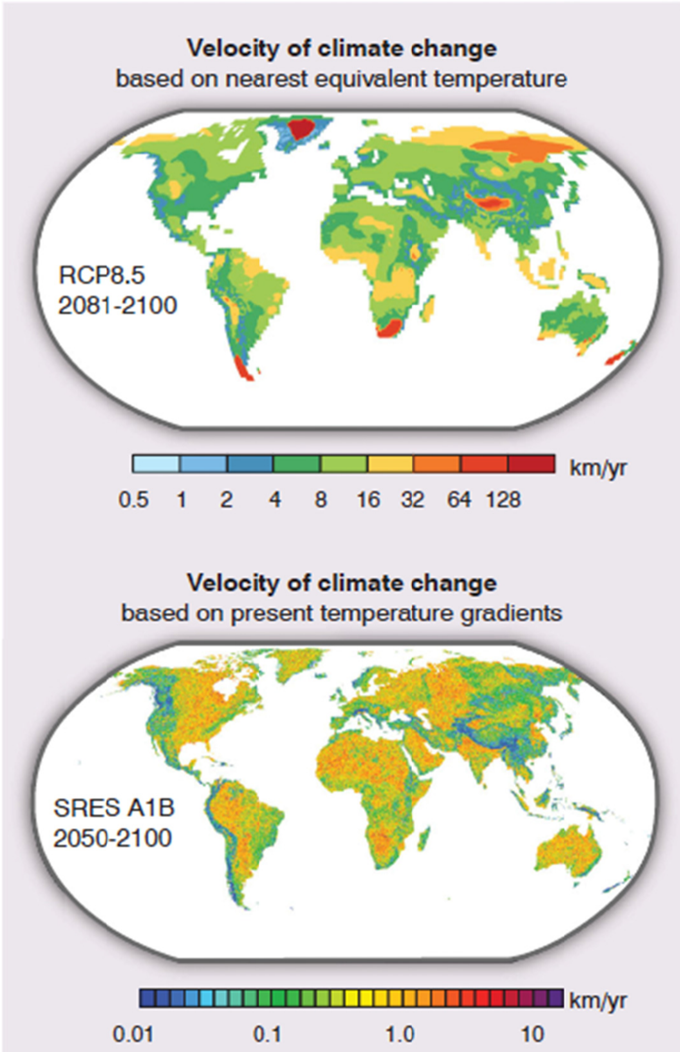

FIGURE S.2. As temperatures rise, populations of many species will have to move to new habitats to find suitable food, water, and shelter. The colors on these maps show how fast individuals in a species will have to move across the landscape in order to track the mean temperature that now characterizes the places where they live. The figure shows two methods of calculating the velocity of climate change for different time periods at the end of this century. The top panel shows the velocity in terms of nearest equivalent temperature, i.e., the climate change velocity in the CMIP5 RCP8.5 ensemble, calculated by identifying the closest location (to each grid point) with a future annual temperature that is similar to the baseline annual temperature. The lower panel expresses velocity as change in present temperature gradients calculated by using the present temperature gradient at each location and the trend in temperature projected by the CMIP3 ensemble in the SRES A1B scenario. Source: Diffenbaugh and Field, 2013.

loss from ice stored on land directly affect the speed of sea level rise, which in turn directly affects coastal communities. Of greatest concern among the stocks of land ice are those glaciers whose bases are well below sea level, which includes most of West Antarctica, as well as smaller parts of East Antarctica and Greenland. These glaciers are sensitive to warming oceans, which help to thermally erode their base, as well as rising sea level, which helps to float the ice, further destabilizing them. Accelerated sea level rise from the destabilization of these glaciers, with sea level rise rates several times faster than those observed today, is a scenario that has the potential for very serious consequences for coastal populations, but the probability is currently not well known, but probably low.

Research to understand ice sheet dynamics is particularly focused on the boundary between the floating ice and the grounded ice, usually called the grounding line (see Figure S.3). The exposed surfaces of ice sheets are generally warmest on ice shelves, because these sections of ice are at the lowest elevation, furthest from the cold central region of the ice mass and closest to the relatively warmer ocean water. Locations where meltwater forms on the ice shelf surface can wedge open crevasses and cause ice-shelf disintegration—in some cases, very rapidly.

Because air carries much less heat than an equivalent volume of water, physical understanding indicates that the most rapid melting of ice leading to abrupt sea-level rise is restricted to ice sheets flowing rapidly into deeper water capable of melting ice rapidly and carrying away large volumes of icebergs. In Greenland, such deep water contact with ice is restricted to narrow bedrock troughs where friction between ice and fjord walls limits discharge. Thus, the Greenland ice sheet is not expected to destabilize rapidly within this century. However, a large part of the West Antarctic Ice Sheet (WAIS), representing 3-4 m of potential sea-level rise, is capable of flowing rapidly into deep ocean basins. Because the full suite of physical processes occurring where ice meets ocean is not included in comprehensive ice-sheet models, it remains possible that future rates of sea-level rise from the WAIS are underestimated, perhaps substantially. Improved understanding of key physical processes and inclusion of them in models, together with improved projections of changes in the surrounding ocean, are required to notably reduce uncertainties and to better quantify worst-case scenarios. Because large uncertainties remain, the Committee judges an abrupt change in the WAIS within this century to be plausible, with an unknown although probably low probability.

Abrupt Changes Unlikely to Occur This Century

Some abrupt changes that have been widely discussed in the literature because they were previously considered to be potential threats with poorly known probability. More recent research findings have shown that they may be less likely to occur within this century than previously considered possible. These include disruption to the Atlantic Meridional Overturning Circulation (AMOC) and potential abrupt changes of high-latitude methane sources (permafrost soil carbon and ocean methane hydrates). Although the Committee judges the likelihood of an abrupt change within this century to be low for these processes, should they occur even next century or beyond, there would likely be severe impacts. Furthermore, gradual changes associated with these processes can still lead to consequential changes. Thus, they merit further study.

Disruption to the Atlantic Meridional Overturning Circulation (AMOC)

The AMOC is the ocean circulation pattern that involves the northward flow of warm near-surface waters into the northern North Atlantic and Nordic Seas, and the southward flow at depth of the cold dense waters formed in those high latitude regions. This circulation pattern plays a critical role in the global transport of oceanic heat, salt, and carbon. Paleoclimate evidence of temperature and other changes recorded in North Atlantic Ocean sediments, Greenland ice cores and other archives suggest that the AMOC abruptly shut down and restarted in the past—possibly triggered by large pulses of glacial meltwater or gradual meltwater supplies crossing a threshold—raising questions about the potential for abrupt change in the future.

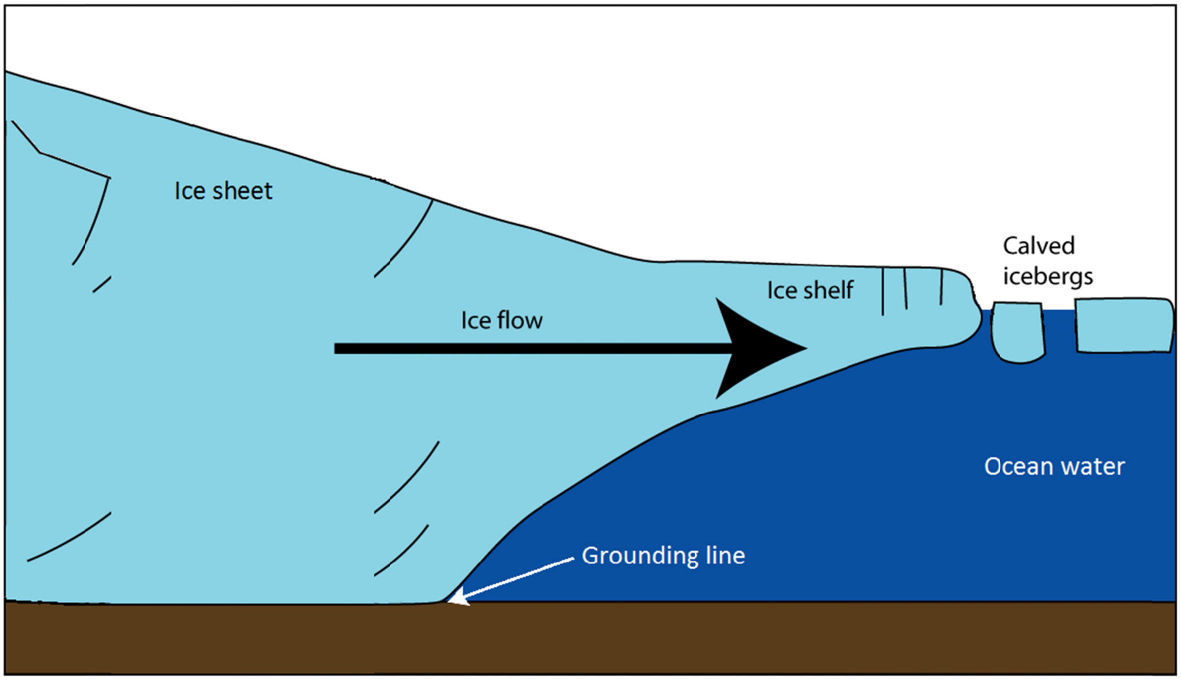

FIGURE S.3. The grounding line is the boundary between floating ice and grounded ice. SOURCE: Adapted from *www.AntarcticGlaciers.org* by Bethan Davies. Used with permission.

Despite these concerns, recent climate and Earth system model simulations indicate that the AMOC is currently stable in the face of likely perturbations, and that an abrupt change will not occur in this century. This is a robust result across many different models, and one that eases some of the concerns about future climate change.

However, it is important keep a close watch on this system, to make observations of the North Atlantic to monitor how the AMOC responds to a changing climate, for reasons including the likelihood that slow changes will have real impacts, and to update the understanding of the slight possibility of a major event. One example of a monitoring effort began in 2004 when the U.K./U.S. RAPID/MOCHA array (Rapid Climate Change – Meridional Overturning Circulation and Heatflux Array) was deployed at 26.5^{0}N to provide the first continuous measurement of the AMOC in the North Atlantic. Data from this array, which consists of instruments deployed from the North American continent to the west coast of Africa, has revealed key features of the AMOC and its variability. However, to understand the linkage between high latitude climate change and AMOC variability, investigate the differences between South and North Atlantic AMOC variability, and to ground truth models of the AMOC system, measurements at other latitudes (currently being planned) are needed. Finally, to make a clear assessment of the AMOC's response to anthropogenic climate change, it is expected that a multi-decadal observing system will be necessary.

Potential Abrupt Changes due to High-Latitude Methane

Large amounts of carbon are stored at high latitudes in potentially labile reservoirs such as permafrost soils and methane-containing ices called methane hydrate or clathrate, especially offshore in ocean marginal sediments. Owing to their sheer size, these carbon stocks have the potential to massively affect Earth's climate should they somehow be released to the atmosphere. An abrupt release of methane is particularly worrisome because methane is many times more potent than carbon dioxide as a greenhouse gas over short time scales. Furthermore, methane is oxidized to carbon dioxide in the atmosphere, representing another carbon dioxide pathway from the biosphere to the atmosphere.

According to current scientific understanding, Arctic carbon stores are poised to play a significant amplifying role in the century-scale buildup of carbon dioxide and methane in the atmosphere, but are unlikely to do so abruptly, i.e., on a timescale of one or a few decades. Although comforting, this conclusion is based on immature science and sparse monitoring capabilities. Basic research is required to assess the long-term stability of currently frozen Arctic and sub-Arctic soil stocks, and of the possibility of increasing the release of methane gas bubbles from currently frozen marine and terrestrial sediments, as temperatures rise.

Summary of Abrupt Climate Changes and Abrupt Climate Impacts

In addition to the abrupt changes described in the sections above, the Committee examined a number of other possible changes. These included sea level rise due to thermal expansion or ice sheet melting (except WAIS—see above), decrease in ocean oxygen (expansion in oxygen minimum zones (OMZs)), changes to patterns of climate variability, changes in heat waves and extreme precipitation events (droughts / floods / hurricanes / major storms), disappearance of winter Arctic sea ice (distinct from late-summer Arctic sea ice—see above), and rapid state changes in ecosystems, species range shifts, and species boundary changes. Table S.1 summarizes the current knowledge of these various processes and identifies key future research and monitoring needs. This research promises to continue to help distinguish the more serious threats from the less likely ones.

ANTICIPATING SURPRISES

The abrupt climate changes and abrupt climate impacts discussed here present substantial risks to society and nature. The ability to anticipate what would otherwise be "surprises" in the climate system requires careful monitoring of climate conditions, improved models for projecting changes, and the interpretation and synthesis of scientific data using novel analysis techniques. In light of the importance of actionable information about the occurrence and impacts of abrupt changes, it is the Committee's judgment that action is urgently needed to improve society's ability to anticipate abrupt climate changes and impacts.

To address these needs the Committee recommends development of an Abrupt Change Early Warning System (ACEWS). Surprises in the climate system are inevitable: an early warning system could allow for the prediction and possible mitigation of such changes before their societal impacts are severe. Identifying key vulnerabilities can help guide efforts to increase resiliency and avoid large damages from abrupt change in the climate system, or in abrupt impacts of gradual changes in the climate system, and facilitate more informed decisions on the proper balance between mitigation and adaptation. With adequate scientific monitoring and study of these potential changes to the climate system, the probability that society can anticipate future abrupt climate changes and impacts will be substantially increased.

An ACEWS would be part of an overall risk management strategy, providing required information for hazard identification and risk assessment. In general, an ACEWS system would (1) identify and quantify social and natural vulnerabilities and ensure long-term, stable observations of key environmental and economic parameters through enhanced and targeted monitoring; (2) integrate new knowledge into numerical models for enhanced understanding and predictive capability; and (3) synthesize new learning and advance the understanding of the Earth system, taking advantage of collaborations and new analysis tools. The improved information could help identify vulnerabilities to assist in tailoring risk mitigation and preparedness efforts to ensure warnings result in the appropriate protective actions, with the ultimate goal to preempt catastrophes. Planning an ACEWS would benefit from leveraging the experience and knowledge gained as part of existing early warning programs such as the National Integrated Drought Information System (NIDIS) and Famine Early Warning System Network (FEWS NET). The Committee described several important aspects of a strategy to provide an effective Abrupt Change Early Warning System (ACEWS):

- ***Monitor key variables of abrupt change:*** Monitoring for an ACEWS should expand upon existing monitoring networks, protect and/or augment important networks that are currently in place, and develop new ones as needed (examples of specific monitoring needs are listed in Table S.1).
- ***Modeling to project future abrupt changes:*** A successful and adaptive ACEWS must consistently iterate between data collection, model testing and improvement, and model predictions that suggest better data collection (examples of future modeling needs are listed in Table S.1).
- ***Synthesis of existing knowledge:*** A necessary part of an ACEWS is synthesizing knowledge to avoid the trap of data collection without continuing and evolving data analysis and model integration. This will require dedicated teams of researchers, improved collaborative networks, enhanced educational activities, and innovative tools for data analysis and modeling techniques.

To implement an ACEWS, it will be important to integrate the various components of the project, pay attention to stakeholder priorities, and build the ability to be flexible and adaptive. Thus, designing and implementing an ACEWS will need to be an iterative process that is revisited and refined as understanding of abrupt climate change, impacts, and social vulnerabilities evolves.

The organizational structure of an ACEWS could capitalize on existing programs, but there will be a need to capture the interconnectedness of climate and human systems. An ACEWS could eventually be run as a large, overarching program, but might better be started through coordination, integration, and expansion of existing and planned smaller programs. One possible mechanism to achieve this would be with a steering group that could provide efficient guidance. Such a steering committee could be made up of representatives of funding agencies, scientists, representatives of various user communities (including national security and interested businesses), and international partners, to name a subset of the possibilities. Subgroups or working groups may be able to bring focus to specific issues that require more attention as needed, e.g., water, food, or ecosystem services. A number of other interagency coordinating mechanisms exist that could assist in the planning and implementation of such a warning system. Whatever the mechanism, the committee does stress that coordination—to reduce duplication of efforts, maximize resources, and facilitate data and information sharing—is key to a successful ACEWS. The development of an ACEWS will need to be an ongoing process, one that goes beyond the scope of this report, and one that needs to include multiple stakeholders.

THE WAY FORWARD

Scientific understanding of abrupt changes in the physical climate system and abrupt impacts of climate change has steadily advanced over the past couple of decades. Owing to these scientific advances, some of the possible abrupt climate change mechanisms whose probability of occurrence was previously poorly known are now understood to be unlikely during this century—these include a sudden shutdown of the Atlantic Meridional Overturning Circulation, and a large and abrupt release of methane from thawing Arctic permafrost. However, concerns over the likelihood of other potential abrupt impacts of climate change—such as destabilization of the West Antarctic Ice Sheet and rapid increases in already-high rates of species extinctions—have intensified. It is important to note that such abrupt impacts can be suddenly triggered simply by continuing the present climate-change trajectory that humans are driving until "tipping points" are reached, as opposed to an abrupt change in the climate system itself.

The Committee believes strongly that actions are needed to develop an ACEWS that serves to anticipate the possibilities of future abrupt changes and helps to reduce the potential consequences from such abrupt changes. Knowledge in this field is continuously advancing, and the implementation of such an early warning system will require additional collaborative research targeted at how to synthesize the various components in the most effective way. The proper design and implementation of an ACEWS will need to be an ongoing process and will require expertise from many different disciplines beyond just the physical sciences, as well as input from many different stakeholder groups. Providing a complete roadmap to a successful ACEWS was beyond the scope of this report, but the committee has outlined its initial thoughts on what would make such a system successful above. Much is known about the design, implementation, and sustainability of early warning systems that can be leveraged in addition what is described in this report.

Although there is still much to learn about abrupt climate change and abrupt climate impacts, to willfully ignore the threat of abrupt change could lead to more costs, loss of life, suffering, and environmental degradation. The time is here to be serious about the threat of tipping points so as to better anticipate and prepare ourselves for the inevitable surprises.

TABLE S.1– State of knowledge on potential candidate processes that might undergo abrupt change. These include both abrupt climate changes in the physical climate system and abrupt climate impacts of ongoing changes that, when certain thresholds are crossed, can cause abrupt impacts for society and ecosystems. The near term outlook for this century is highlighted as being of particular relevance for decision makers generally.

	Potential Abrupt Climate Change or Impact and Key Examples of Consequences	Current Trend	Near Term Outlook (for an Abrupt Change within This Century)	Long Term Outlook (for a Significant Change[1] after 2100)	Level of Scientific Understanding	Critical Needs (Research, Monitoring, etc.)
Abrupt Changes in the Ocean	**Disruption to Atlantic Meridional Overturning Circulation (AMOC)** • Up to 80 cm sea level rise in North Atlantic • Southward shift of tropical rain belts • Large disruptions to local marine ecosystems • Ocean and atmospheric temperature and circulation changes • Changes in ocean's ability to store heat and carbon	Trend not clearly detected	**Low**	High	Moderate	• Enhanced understanding of changes at high latitudes in the North Atlantic (e.g., warming and/or freshening of surface waters) • Monitoring of overturning at other latitudes • Enhanced understanding of drivers of AMOC variability
Abrupt Changes in the Ocean	**Sea level rise (SLR) from ocean thermal expansion** • Coastal inundation • Storm surges more likely to cause severe impacts	Moderate increase in sea level rise	**Low**[2]	High	High	• Maintenance and expansion of monitoring of sea level (tide gauges and satellite data), ocean temperature at depth, local coastal motions, and dynamic effects on sea level
Abrupt Changes in the Ocean	**Sea level rise from destabilization of WAIS ice sheets** • 3-4 m of potential sea level rise • Coastal inundation • Storm surges more likely to cause severe impacts	Losing ice to raise sea level	**Unknown but Probably Low**	Unknown	Low	• Extensive needs, including broad field, remote-sensing, and modeling research
Abrupt Changes in the Ocean	**Sea level rise from other ice sheets (including Greenland and all others, but not including WAIS loss)** • As much as 60m of potential sea level rise from all ice sheets • Coastal inundation • Storm surges more likely to cause severe impacts	Losing ice to raise sea level	**Low**	High	High for some aspects, low for others	• Maintenance and expansion of satellite, airborne, and surface monitoring capacity, process studies, and modeling research

TableS-1-page1.eps

TABLE S.1 continued

	Potential Abrupt Climate Change or Impact and Key Examples of Consequences	Current Trend	Near Term Outlook (for an Abrupt Change within This Century)	Long Term Outlook (for a Significant Change[1] after 2100)	Level of Scientific Understanding	Critical Needs (Research, Monitoring, etc.)
...in the Ocean (cont.)	**Decrease in ocean oxygen (expansion in oxygen minimum zones (OMZs))** • Threats to aerobic marine life • Release of nitrous oxide gas—a potent green house gas—to the atmosphere	Trend not clearly detected	**Moderate**	High	Low to Moderate	• Expanded and standardized monitoring of ocean oxygen content, pH, and temperature • Improved understanding and modeling of ocean mixing • Improved understanding of microbial processes in OMZs
Abrupt Changes in the Atmosphere	**Changes to patterns of climate variability (e.g., ENSO, annular modes)** • Substantial surface weather changes throughout much of extratropics if the extratropical jetstreams were to shift abruptly	Trends not detectable for most patterns of climate variability Exception is southern annular mode—detectable poleward shift of middle latitude jetstream	**Low**	Moderate	Low to Moderate	• Maintaining continuous records of atmospheric pressure and temperatures from both in-situ and remotely sensed sources • Assessing robustness of circulation shifts in individual ensemble members in climate change simulations • Developing theory on circulation response to anthropogenic forcing
Abrupt Changes in the Atmosphere	**Increase in intensity, frequency, and duration of heat waves** • Increased mortality • Decreased labor capacity • Threats to food and water security	Detectable trends in increasing intensity, frequency, and duration of heat waves	**Moderate** (Regionally variable, dependent on soil moisture)	High	High	• Continued progress on understanding climate dynamics • Increased focus on risk assessment and resilience
Abrupt Changes in the Atmosphere	**Increase in frequency and intensity of extreme precipitation events (droughts/floods/ hurricanes/major storms)** • Mortality risks • Infrastructure damage • Threats to food and water security • Potential for increased conflict	Increasing trends for floods Trends for drought and hurricanes not clear	**Moderate**	Moderate / High	Low to Moderate	• Continued progress on understanding climate dynamics • Increased focus on risk assessment and resilience

TableS-1-page2.eps

TABLE S.1 continued

	Potential Abrupt Climate Change or Impact and Key Examples of Consequences	Current Trend	Near Term Outlook (for an Abrupt Change within This Century)	Long Term Outlook (for a Significant Change[1] after 2100)	Level of Scientific Understanding	Critical Needs (Research, Monitoring, etc.)
Abrupt Changes at High Latitudes	**Increasing release of carbon stored in soils and permafrost** • Amplification of human-induced climate change[3]	Neutral trend to small trend in increasing soil carbon release	**Low**	High	Moderate[4]	• Improved models of hydrology/cryosphere interaction and ecosystem response • Greater study of role of fires in rapid carbon release • Expanded borehole temperature monitoring networks • Enhanced satellite and ground-based monitoring of atmospheric methane concentrations at high latitudes
	Increasing release of methane from ocean methane hydrates • Amplification of human-induced climate change	Trend not clearly detected	**Low[5]**	Moderate	Moderate[6]	• Field and model based characterization of the sediment column • Enhanced satellite and ground-based monitoring of atmospheric methane concentrations at high latitudes
	Late-summer Arctic sea ice disappearance • Large and irreversible effects on various components of the Arctic ecosystem • Impacts on human society and economic development in coastal polar regions • Implications for Arctic shipping and resource extraction • Potential to alter large-scale atmospheric circulation and its variability	Strong trend in decreasing sea ice cover	**High**	Very high	High	• Enhanced Arctic observations, including atmosphere, sea ice and ocean characteristics • Better monitoring and census studies of marine ecosystems • Improved large-scale models that incorporate the evolving state of knowledge
	Winter Arctic sea ice disappearance • Same as late summer Arctic sea ice disappearance above, but more pronounced due to year-round lack of sea ice	Small trend (Decreasing but not disappearing)	**Low**	Moderate	High	• Same as late summer Arctic sea ice disappearance above

TableS-1-page3.eps

TABLE S.1 continued

	Potential Abrupt Climate Change or Impact and Key Examples of Consequences	Current Trend	Near Term Outlook (for an Abrupt Change within This Century)	Long Term Outlook (for a Significant Change[1] after 2100)	Level of Scientific Understanding	Critical Needs (Research, Monitoring, etc.)
Abrupt Changes in Ecosystems	**Rapid state changes in ecosystems, species range shifts, and species boundary changes** • Extensive habitat loss • Loss of ecosystem services • Threats to food and water supplies	Species range shifts significant; others not clearly detected	**Moderate**	High	Moderate	• Long term remote sensing and in situ studies of key systems • Improved hydrological and ecological models
Abrupt Changes in Ecosystems	**Increases in extinctions of marine and terrestrial species** • Loss of high percentage of coral reef ecosystems (already underway) • Significant percentage of land mammal, bird, and amphibian species extinct or endangered[7]	Species and population losses accelerating (Portion attributable to climate is uncertain)	**High**	Very high	Moderate	• Better understanding of how species interactions and ecological cascades might magnify extinctions intensity • Better understanding of how interactions between climate-caused extinctions and other extinction drivers (habitat fragmentation, overexploitation, etc.) multiply extinction intensity • Improved monitoring of key species

[1] Change could be either abrupt or non-abrupt
[2] To clarify, the Committee assesses the near-term outlook that sea level will rise abruptly before the end of this century as Low; this is not in contradiction to the assessment that sea level will continue to rise steadily with estimates of between 0.26 and 0.82m by the end of this century (IPCC, 2013).
[3] Methane is a powerful but short-lived greenhouse gas
[4] Limited by ability to predict methane production from thawing organic carbon
[5] No mechanism proposed would lead to abrupt release of substantial amounts of methane from ocean methane hydrates this century
[6] Limited by uncertainty in hydrate abundance in near-surface sediments, and fate of CH_4 once released
[7] Species distribution models (Thuiller et al., 2006) indicate between 10–40% of mammals now found in African protected areas will be extinct or critically endangered by 2080 as a result of modeled climate change. Analyses by Foden et al.(2013) and Ricke et al. (Ricke et al., 2013) suggest 41% of bird species, 66% of amphibian species, and between 61% and 100% of corals that are not now considered threatened with extinction will become threatened due to climate change sometime between now and 2100.

TableS-1-page4.eps