CCSP Synthesis and Assessment Product 1.2

SAP-1.2

Prospectus for

Past Climate Variability and Change in the Arctic and at High Latitudes

U.S. Climate Change Science Program

Lead Agency
U.S. Geological Survey

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National Aeronautics and Space Administration
National Oceanic and Atmospheric Administration
National Science Foundation

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Past Climate Variability and Change in the Arctic and at High Latitudes

1. OVERVIEW: DESCRIPTION OF TOPIC, AUDIENCE, INTENDED USE, AND QUESTIONS TO BE ADDRESSED

1.1. Description of Topic

Pa·leo·cli·ma·tol·o·gy – The study of Earth's climate prior to the widespread availability of instrumental records (>150 years ago); the study of climatic conditions, and their causes and effects, in the geologic past.

Paleoclimate records play a key role in understanding the Earth's past and present climate system and in predicting future climate changes. This role is recognized, for example, by inclusion of paleoclimate as Chapter 6 of the 11-chapter Fourth Assessment Report of Working Group I (AR4-I) of the Intergovernmental Panel on Climate Change, and by the extensive references to paleoclimatic data in climate change reports of the U.S. National Research Council, such as *Climate Change Science: An Analysis of Some Key Questions* (2001). The perspective provided by paleoclimate records plays several roles in the effort to understand and predict the climate system by helping to elucidate past and present active mechanisms, by placing the short instrumental record in a longer term context, and by permitting model testing beyond the time-limited period of instrumental records. Paleo-records provide quantitative estimates of the magnitude of the polar amplification of climate change, and these estimates can also be used to evaluate polar amplification derived from model simulations of past and future climate changes.

The pre-instrumental context of the Earth's climate system provided by paleo-data is also used to strengthen the interlocking web of evidence supporting scientific results regarding climate change. For example, in considering whether fossil-fuel burning is an important contributor to the recent rise in atmospheric carbon dioxide concentrations, it is important to determine and quantify global sources and sinks of carbon in the Earth's overall carbon budget. But one can also legitimately ask whether the change of atmospheric carbon dioxide concentrations observed in the instrumental record for the past 100 years falls inside or outside the range of natural variability as revealed in the paleo-record, and if inside, whether the timing of changes in carbon dioxide levels matches any known natural cycles that can explain them. Answers to such questions must come from paleoclimate data, because the instrumental record is much too short to characterize the range of natural fluctuations.

Testing and validation of climate models involves several techniques, as described in Chapter 8 of IPCC AR4-I. The specific role of paleoclimate information is described there: "Simulations of climate states from the more distant past allow models to be evaluated in regimes that are significantly different from the present. Such tests complement the 'present climate' and 'instrumental period climate' evaluations, since 20th century climate variations have been small compared with the anticipated future changes under forcing scenarios derived from the IPCC *Special Report on Emission Scenarios* (SRES)."

Paleoclimate records are typically developed through analysis of sediment, broadly defined, including ice, mud, trees, cave formations, and other deposits (e.g., Crowley and North, 1991). The sediment (e.g., in a lake or in the ocean) must preserve a record of the conditions when it formed, the record must be interpretable in terms of climate (e.g., geochemistry, texture, fossil content, etc.), and there must be some way to determine age of formation (or geochronology). Some paleoclimate indicators are easy to read and understand. For example, the grass-covered dunes of the Sand Hills of northwestern Nebraska document formerly more arid conditions than exist today. Similarly, the unique glacial erosional and depositional features found in parts of New York, Ohio, and the northern New England states which now lack glaciers demonstrate the existence of a previous cold ice age. Evidence of the colder temperatures of this ice age is still preserved in the Greenland ice sheet in several ways. For example, the depths of the ice sheet in Greenland have not finished warming from that ice age, with warmer ice both above and below a cold zone in the middle of the ice sheet. Analyses of this temperature profile of the Greenland ice sheet shows that ice-age cooling in central Greenland was more than 20°C (Cuffey and Clow, 1997).

Many paleoclimate records are based on biotic indicators; for instance, tundra plants are recognizably different from plants of the mid-latitudes, and a time sequence of pollen or macro-fossils showing switching between mid-latitude and tundra flora provides a clear record of changing climate. Chemical, physical, and physico-chemical/isotopic indicators are commonly used as well. The relationship of an indicator to climate is often direct, but may be complex. The width of a tree ring, for example, is especially sensitive to water availability in dry regions, but may also react to shading by neighboring trees or fertilization. In these instances multiply-duplicated records from many sites are used to help clarify relations, and robust results are based on agreement among these multiple indicators.

In favorable cases age determinations can be obtained on layered sediments by counting of annual layers checked by identification of known time horizons. For example, in ice cores, the chemically fingerprinted ash of historically dated volcanic eruptions provides highly accurate testing of annually dated chronologies. In most cases, radiometric or other techniques are used, often with redundancy obtained by the application of multiple techniques (e.g., Jull *et al*., 2004).

1.2. Why the Arctic?

Over the past century the planet has shown an overall warming of 0.74 [0.56 to 0.92]°C (IPCC, 2007). Over land areas in the Arctic, a warming trend in air temperatures of as much as 3°C (exceeding 4°C in winter; Serreze and Francis, 2006) has been experienced over the same period of time. Instrumental records indicate that, over the past 30 years, average temperatures in the Arctic have increased at almost twice the rate of the planet as a whole. Attendant changes include reduced sea ice, reduced glacier extent, increased coastal erosion, changes in vegetation and wildlife habitats, and permafrost degradation. Global climate models incorporating the current trend of increasing greenhouse gases project continued warming in the near future and a continued amplification of global signals in the Arctic. The sensitivity of the Arctic to changed forcing is due to powerful positive feedbacks in the Arctic climate system. These feedbacks produce large impacts on Arctic climate while also having significant impacts on the global climate system. This high degree of sensitivity makes the paleoclimate history of the Arctic especially informative when considering the issue of modern climate change.

Summaries of recent Arctic environmental change (e.g., Correll, 2004; Richter-Menge *et al*., 2006) are primarily based on observations and instrumental records. This CCSP product will utilize paleoclimate records to provide a longer term context for recent Arctic warming in order to better understand the potential for future climate changes. Paleoclimate records provide a mechanism to define the range of past natural variability in the Arctic and the magnitude of polar amplification, to evaluate the past rates of Arctic climate change (and thereby provide a long-term context for current rates of change), and to identify past Arctic warm states that are potential analogs of future conditions. The paleoclimate record also permits quantification of the impacts of abrupt perturbations (e.g., large injections of volcanic ash into the atmosphere) and threshold behaviors, and offers insights into how the Arctic has behaved during past warm times by identifying critical feedbacks and their mechanisms. Understanding threshold behavior in the highly non-linear Arctic system is one of the key areas of uncertainty in predicting future impacts. In addressing the above issues, we will seek to characterize the levels of uncertainty associated with paleoclimate data and to define research priorities for ways to reduce these uncertainties.

Large interagency programs such as SEARCH (Study of Environmental Arctic Change; <psc.apl.washington.edu/search>) have now been launched to monitor ongoing change and to develop models for predicting its magnitude and direction. Although the main temporal focus of SEARCH is on the last several decades, it also aims to investigate climatic conditions over the past 2,000 years, which is crucial to evaluating current warming trends in both the Arctic and throughout the world. The longer time scale of paleoclimatic data, coupled with this 2,000 year focus, is needed to fully characterize the periods when the Arctic was as warm or warmer than it is today. Paleoenvironmental data provide specific examples of naturally driven circumarctic warming and the impacts of that warming on natural systems in and beyond the Arctic.

This CCSP synthesis and assessment product will summarize the state of knowledge of the history of Arctic and subarctic climate as it relates to ongoing and future climate from published studies that have utilized climate records from a variety of indicators including, but not limited to, tree rings, ice cores, lake sediments, pollen records, distributions of marine and terrestrial organisms as well as isotopic indicators measured on them, and the temporal evolution of terrestrial depositional and erosional environments. The geographic scope of this report will not be limited strictly to the north circumpolar region above the Arctic Circle, but will draw upon the published scientific literature focused on the high northern latitudes wherever the investigation yields information and insight into the climate processes that operate or have operated in this region. Similarly the report will focus on a time scale for which meaningfully resolved records exist, for which the role of orbital forcing would come into play, and for which good analogs for present conditions exist—at least the past 125,000 years. Both the geographic and temporal scope of the report will be flexible enough to yield meaningful insights and not be artificially constrained by setting limits which might exclude consideration of relevant analogs lying outside such a limit.

This prospectus provides an implementation plan for developing and producing this report. In keeping with the guidelines for structuring these syntheses, a set of highly relevant questions have been chosen that serve as the overarching framework for the report. These four questions were chosen because they unify the main relevant scientific work that has been ongoing in the Arctic and subarctic, and lead to results that will be of importance to policymakers and stakeholders in the Arctic and worldwide. In the discussion of these key questions that follows authors attempt to provide information not only on the types of records that will be considered and the general approach, but also to address the issue of why these questions are important within the policy arena.

1.3. List of Key Questions and their Relevance

The report will be organized around ways that paleoclimate data can help answer key questions about the present and future changes of relevance to policymakers and stakeholders. Key areas of relevance are discussed for each question.

What does the paleoclimate record tell us about past changes in Arctic sea ice cover, and what implications does this have for the scope of current and future potential changes?

This report will document past periods when Arctic sea ice extent was reduced, and will also evaluate the scope, causes, and effects of these reductions as evidenced in sea floor and coastal sedimentary records indicative of ice drift and related oceanographic processes (e.g., CAPE, 2006). Records of past sea ice extent are recorded in sediments preserved on the sea floor dating back over several glacial cycles. Sea ice extent can also be reconstructed from fossil assemblages preserved in ancient beach deposits along many arctic coasts (Brigham-Grette and Hopkins, 1995; Dyke *et al*., 1996). This type of information will provide a context within which the impacts of the current and future ice-reduced state of Arctic sea ice can be evaluated. Recent advances in tapping the Arctic paleoceanographic archives, notably the first deep-sea drilling in the central Arctic Ocean (Shipboard Scientific Party, 2005) and the 2005 Trans-Arctic Expedition (Darby *et al*., 2005), have provided new, high-quality material with which to identify and characterize warm, low-ice events of the past during the Late Cenozoic (last few million years).

Recent observations document significant retreat and thinning of the Arctic sea ice cover over the past several decades, a trend that is expected to continue (e.g., Holland *et al*., 2006). A reduction in sea ice will continue to accelerate Arctic warming through the ice-albedo feedback mechanism. Through impacts on the surface-energy budget and heating contrasts, changes in sea ice will influence weather systems in the Arctic and perhaps in middle latitudes. Changes in ice cover and freshwater flux out of the Arctic Ocean will also affect oceanic circulation of the North Atlantic, which has notable influence on European and North American climate (Seager *et al*., 2002).

Continued reduction of sea ice can also accelerate coastal erosion. This is due to the longer fetch of winds over open water areas that results in increased wave action. Reduction in sea ice would also change the Arctic Ocean food web, at levels from phytoplankton production to top predators. Wildlife, such as polar bears and seals that depend on the ice cover, would also be impacted. This, in turn, would affect indigenous human populations that harvest such species. The loss of sea ice would also provide the opportunity for greater commercial exploitation of the Arctic Ocean. Increased navigability of the northern sea routes would provide opportunities for increased commercial shipping and increased natural resource exploitation. This increased level of activity would result in impacts to the environment (e.g., from contamination, noise, and infringement on natural habitats).

A persistent loss of sea ice cover also raises issues of national security for the Arctic countries as well. Greater ship-based access to unprotected and unpopulated coasts would provide increased opportunity for illegal entry. Naval forces may need surface ships and aircraft better able to operate safely in cold environments if an ice-reduced Arctic requires naval action to protect or interdict shipping, or contend with a hostile force. Both navies and coast guards may need to prepare for increased search-and-rescue activities as shipping and tourism increase in response to diminished Arctic sea ice (NRC, 2007).

What does the paleoclimate record tell us about the past extent and status of the Greenland ice sheet and its implications for sea level changes?

Paleoclimate data allow reconstruction of changes in the size of the Greenland ice sheet at various times in the past, and provide insight into the climatic conditions that produced those changes. This report will summarize paleo-data available on the size and condition of the Greenland ice sheet and its relationship to past sea levels and climatic conditions, and the implications for mechanisms capable of producing significant change. Rates of change are of interest; models project centuries to millennia for major changes in the ice sheet but lack key “fast” processes as documented in IPCC (2007); any insights will be summarized in this report.

The ice sheet leaves “tracks” showing how far it extended, and when it exhibited that extent, on land and in the ocean (e.g., Denton *et al*., 2005). On land, moraines (primarily rock material) deposited around but in contact with the ice are especially important. Beaches now raised out of the ocean following retreat of ice that previously pushed the land down and other geomorphic indicators also preserve important information. Moraines and other ice-contact deposits in the ocean record evidence of extended ice; isotopic ratios of foraminifera may reveal input of meltwater, and iceberg-rafted debris identified in sediment cores can be traced to source regions supplying the icebergs (e.g., Hemming, 2004).

The history of ice thickness can be traced by moraines or other features on rock projecting above the level of the ice sheet, by the history of land rebound following removal of ice weight during deglaciation, and by indications (especially total gas content) in ice cores (Raynaud *et al*., 1997). Models can also be used to assimilate data from coastal sites and help constrain inland conditions. This report will integrate these and other sources of information on past changes in the Greenland ice sheet.

Changes in glaciers and ice sheets, especially the Greenland ice sheet, would have global impacts. Melting of the Greenland ice-sheet would raise global sea level by 7 m if it were to melt completely; even partial melting would create important challenges for coastal populations through subsurface incursion of saline water into hydrological systems in addition to outright inundation. Freshwater from ice-sheet melting delivered to the oceans into key sensitive regions—the North Atlantic Ocean, for example—could contribute to important changes in sea ice extent, ocean circulation, and climate, with strong regional and possibly global impacts. Continued retreat would potentially impact ecotourism as well.

What has been the extent of temperature and precipitation changes in the high latitudes in the past, and what can this tell us about how much warmer/colder, wetter/drier it may become in future?

This report will document what is known of high-latitude environmental conditions during earlier warm periods on a variety of time scales, using sedimentary, biological and geochemical proxies largely from ice cores, lake sediment, and marine sediment records (North Greenland Ice Core Project members, 2004; Anderson *et al*., 2003; Kaufman *et al*., 2004). These depositional records can be supplemented by information documented using the stratigraphy of sediments studied in river and coastal bluffs across many regions of the Arctic. By means of a variety of graphical and synthetic techniques, data can be utilized to summarize past changes in temperature and precipitation based upon the best interpretation of proxies—in other words, indices that have been calibrated in some way to represent past changes in a particular climatic feature (see review by Bradley, 1999). Many proxies are routinely used, including changes in the character of the organic matter, the isotopic geochemistry of minerals or ice, macro and micro fossils content, and biomarkers such as alkenones derived from coccolithophorids. Historical records taken from diaries, notebooks, and logbooks are also commonly used to link modern data and paleoclimate reconstructions. These proxies extracted from the literature permit quantification of changes in air, ground, and sea surface temperature, precipitation, and attendant ecosystem change for comparison with the magnitudes and rates of contemporary change. While recognizing that pre-Holocene warm-time forcings were different from modern anthropogenic forcings (IPCC, 2007), the paleo-record still provides insights into how the Arctic has behaved during past warm times and helps to elucidate critical feedbacks and their mechanisms (Serreze and Francis, 2006).

Both recent and past records show similar fluctuations in Arctic climate, but the recent fluctuations are superimposed on a general warming trend over the past 150 years (Serreze *et al*., 2000). Continued warming would have widespread impacts on all aspects of the Arctic system, some with global consequences (ACIA, 2005). More than 85% of the Arctic landscape is underlain by permanently frozen ground (permafrost) that is vulnerable to warming. Permafrost thaw induces landscape instability, which impacts infrastructure, rivers, and ecosystems and in this report authors will attempt to summarize what is known of past changes in thaw during warmer intervals in the past (Eisner *et al*., 2005). Thawing of permafrost is already increasing the decomposition of widespread high-latitude peatlands (Vörösmarty, 2001). This can potentially increase the rate of carbon dioxide and methane release to the atmosphere from these areas (Smith *et al*., 2004). Injections of methane could also come from breakdown of clathrates (frozen gas hydrates) known to be widespread beneath the Arctic continental shelves (Thomas *et al*., 2002). Such changes would have global consequences, increasing greenhouse gas loadings, in turn amplifying warming processes.

Warming would also allow northward migration of agriculture and natural land and marine ecosystems, in a fashion similar to migrations during earlier warm periods

(CAPE, 2006). Climate models using data from past studies suggest that the northward migration of the treeline would amplify climate changes through feedback mechanisms. Anticipated increases in precipitation, like those documented in the paleorecords, provide insight into how future warming would likely alter the Arctic's freshwater budget with impacts on sea ice, ecosystems, and potentially, thermohaline circulation (Otto-Bliesner *et al*., 2006).

Historical records such as recovered instrumental observations, seasonal phenologies, and descriptive records can be used to link instrumental and paleoclimatic records (e.g., Smol *et al*., 2005). These historical records show that the Arctic climate has fluctuated from region to region in the past. Changes were noticed and recorded, and were large enough to affect agriculture, marine resources, and transportation.

What have been the past rates of change and what does this tell us about current and future rates of change?

The climate record of the Earth shows changes that operate on a wide range of time scales. These changes reflect mechanisms that operate on time scales as long as it takes continents to disassemble and reassemble through the mechanisms of plate tectonics and as short as it takes a major volcanic eruption to load the atmosphere with dust and aerosols. This report will summarize paleoclimate data on past rates of change in the Arctic and subarctic on all relevant time scales with special attention to characterizing the records of past abrupt changes that have had widespread impacts. This section of the report will be coordinated with CCSP Synthesis and Assessment Product 3.4, the complete focus of which is on global aspects of abrupt climate change. This coordination will be carried out by cross-attendance at meetings and exchange of draft materials at critical junctures in the development of the two respective products.

Current climate models project that annual temperatures in the Arctic will increase between 4 and 6°C by the end of the 21st century for mid-range emission scenarios (IPCC, 2007). Significant variations from year to year and between decades are also superimposed upon this general rising trend. This rising trend, as well as annual and decadal variations, will (if continued) have socioeconomic and environmental impacts of importance to policymakers and stakeholders. The paleoclimatic and early instrumental records document climate variability comparable to that modeled (Overpeck *et al*., 1997; Johannessen *et al*., 2004) but paleoclimatic records also indicate that changes of even larger magnitude have occurred more rapidly, although rarely, than those currently being experienced in and projected for the Arctic (Alley *et al*., 2003). Climate models do not capture these rare events well. Faster or less expected changes have larger impacts on natural and human systems then slower, better anticipated changes. Socioeconomic and infrastructure viability thus depend on rates of change. Conditions more extreme than any experienced in the memory of a system can be especially stressful. Even if such events should prove to be highly unlikely, any non-zero probability motivates interest.

1.4. Stakeholders

This CCSP synthesis and assessment product is intended to provide state-of-the-art information based on paleoclimate science to support U.S. government policy and adaptive-management decisionmaking. The information contained within this report is intended for use in national resource assessments and socioeconomic decision-support activities. Primary stakeholders include but are not limited to U.S. government agencies; U.S. Congress; the Executive Branch; energy and transportation sectors; federal, regional, and local resource and land managers; the human health sector; circum-Arctic populations; commercial and environmental sectors; and scientific researchers and the general public.

1.5. Intended Use

This report is intended to set a pre-instrumental context for current and projected changes in Arctic and subarctic climate. The report will provide a synthesis and assessment of the most reliable paleoclimate information available today, and utilize this record to provide a perspective on contemporary climate change. The report is intended to inform Federal, regional, and local policy decisions and land-use and resource management decisions, and to provide the basis for informed adaptive-management decisionmaking by providing a long-term perspective on current conditions of climate change in the Arctic. The report will also assist funding agencies to identify areas of future research.

1.6. Data Resources

This report will be based on the publicly available scientific literature. Refereed scientific papers that are published or in press will be the primary data source, supplemented by limited use of books and of abstracts from national and international conferences, which will be noted. Copies of all cited materials will be maintained by the Designated Federal Officer at the lead agency.

1.7. Treatment of Uncertainty

This report will adopt the guidance of the Intergovernmental Panel on Climate Change for Lead Authors of the Fourth Assessment Report regarding procedures for assessing and expressing uncertainties.

2. Contact Information: E-mail and Telephone for Responsible Individuals at the Lead and Supporting Agencies

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3. Lead Authors: Required Expertise of Lead Authors and Biographical Information for Proposed Lead Authors

Lead author nominees below have been identified based on their interest in this product and record of accomplishments in the relevant fields of expertise:

- Richard Alley, Pennsylvania State University
- Julie Brigham-Grette, University of Massachusetts, Amherst
- Gifford Miller, Institute for Arctic and Alpine Research, University of Colorado
- Leonid Polyak, Ohio State University.

Brief biographies of the lead authors are provided in Appendix A. It is anticipated that additional contributing authors will be finalized by the lead agency in consultation with the lead authors.

4. Stakeholder Interactions

The process for drafting, receiving comments, and finalizing the document will be open to the public and will comply with the Federal Advisory Committee Act (FACA). The drafting committee will be designated as a FACA committee; thus, all committee meetings will be open to the public. Timely notice of each meeting will be published in the *Federal Register*, and other types of public notice will be used to ensure that all interested persons are notified of the meeting. Interested persons will be encouraged to attend, appear before, or file statements with the committee, subject to such reasonable rules or regulations that may be prescribed. All records of the committee will be available for public inspection and reproduction at a designated location. Requests for public comment will be posted in the *Federal Register*.

5. Drafting Process (Including Materials to be Used in Preparing the Product)

Under the leadership of a convening lead author for each of the chapters, the group of lead authors and contributors is charged with the preparation of the scientific/technical analysis section of the synthesis report. They will draw upon published, peer-reviewed scientific literature in the drafting process.

The synthesis and assessment product will include an Executive Summary, which will present key findings from the report. This Executive Summary will be written by a team consisting of lead authors assisted by representatives from the supporting and lead agencies.

The synthesis and assessment product will identify disparate views that have significant scientific or technical support, and will provide confidence levels for key findings, as appropriate. The synthesis and assessment product will pay special attention to addressing uncertainties and confidence levels.

6. Review

The lead authors identified on page 7 will compile a draft of the synthesis for review, to be conducted by a panel of experts in the field of paleoclimate research with some individuals knowledgeable about Arctic paleoclimates. During expert review, the lead authors will revise the draft product by incorporating comments and suggestions from the reviewers, as the lead authors deem appropriate. Following this revision, the draft product will be released for public comment. The public comment period will be 45 days and will take place in the winter of 2008. The lead authors will prepare a third draft of the product, taking into consideration the comments submitted during the public comment period. The scientific judgment of the lead authors will determine responses to the comments.

Once the revisions are complete, the lead agency will submit the synthesis and assessment product to the CCSP Interagency Committee for approval. If the CCSP Interagency Committee determines that further revision is necessary, their comments will be sent to the lead agency for consideration and resolution by lead authors. If needed, the National Research Council will be asked to provide additional scientific analysis to bound scientific uncertainty associated with specific issues.

If the CCSP Interagency Committee review determines that no further revisions are needed and that the product has been prepared in conformance with the Guidelines for Producing CCSP Synthesis and Assessment Products and the Data Quality Act (including ensuring objectivity, utility, and integrity as defined in 67 FR 8452), they will submit the product to the National Science and Technology Council (NSTC) for clearance. Clearance will require the concurrence of all members of the Committee on Environment and Natural Resources. Comments generated during the NSTC review will be addressed by the CCSP Interagency Committee in consultation with the lead and supporting agencies and the lead authors.

7. Related Activities, Including Other National and International Assessment Processes

The international science community began the International Polar Year in March 2007. There will be opportunities for further analysis of past instrumental data and paleo-data through this activity, although many of these analyses may conclude after publication of this assessment report. For example, NOAA and Roshydromet are engaged in a new analysis of radiosonde data from the Russian Arctic that will improve understanding of Arctic climate variability and change from the early 20th century. The National Science Foundation will provide new support for the Study of Environmental Arctic Change (SEARCH) that may include support for Arctic paleo-studies. The International Study of Arctic Change (ISAC)—the international parent of SEARCH—may also conduct similar studies. The Arctic Council is considering what it should do as a follow-up to the *Arctic Climate Impact Assessment*; additional studies of past climate change are a possibility.

8. Communications: Proposed Method of Publication and Dissemination of the Product

USGS, as the lead agency, will produce and release the completed product using a standard format for all CCSP synthesis and assessment products. The final product and the comments received during the expert review and the public comment period will be posted, without attribution (unless specific reviewers agree to attribution), on the CCSP web site.

The lead authors will also be encouraged to publish their findings in the scientific literature.

9. Proposed Timeline

Task	Completion
Draft prospectus delivered to CCSP	Aug 2006
Review of draft prospectus by CCSP	Sep/Oct 2006
Prospectus comment period (30 days)	Nov 2006
Revision of draft prospectus	May 2007
Prospectus published	June 2007
First Lead Authors Meeting	July 2007
Zero order draft complete	Oct 2007
Second Lead Authors Meeting	Oct 2007
Expert Review (first) draft complete	Nov 2007
Expert Review	Dec 2007
Third Lead Authors Meeting	Jan 2008
Public Comment (second) draft complete	Feb 2008
Public Comment Period	Apr 2008
Final draft complete	May2008
Submission to CCSP	June 2008

References

ACIA, 2005, *Arctic Climate Impact Assessment*: Cambridge University Press, 1042 p.

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke, R.A., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D., Wallace, J.M., 2003, Abrupt climate change, *Science* 299 (5615): p. 2005-2010.

Anderson, P.M., Edwards, M.E., and Brubaker, L.B., 2003, Results and paleoclimate implications of 35 years of paleoecological research in Alaska: In: *The Quaternary Period in the United States* (A.R. Gillespie, S.P. Porter, and B.F. Atwater, eds.). Elsevier, New York, p. 427 - 440.

Bradley, R.S., 1999, *Paleoclimatology: Reconstructing Climates of the Quaternary*: San Diego, CA, Academic Press, 610 p.

Brigham-Grette, J., and Hopkins, D.M.,1995, Emergent-Marine record and Paleoclimate of the Last Interglaciation along the northwest Alaskan coast, *Quaternary Research*, v. 43, p. 154-173.

CAPE-Last Interglacial Project Members, 2006, Last Interglacial Arctic warmth confirms polar amplification of climate change. Quaternary *Science* Rev. 25, p. 1383-1400.

Correll, R. et al., 2004, *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*: Cambridge University Press, 139 p.

Crowley, T.J. and G.R. North, 1991, *Paleoclimatology*: Oxford University Press, 339 p.

Cuffey, Kurt M. and G. D. Clow, 1997, Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research*, Vol. 102, No. C12: p. 383-26 – 396.

Darby, D., Jakobsson, M., Polyak, L., 2005, Icebreaker expedition collects key Arctic seafloor and ice data. *EOS*, 86, No. 52, p. 549-556.

Denton, G.H., Alley, R.B., Comer G.C., and Broecker W.S., 2005, The role of seasonality in abrupt climate change. *Quaternary Science Reviews* 24(10-11), p. 1159-1182.

Dyke, A. S., Hooper, J., and Savelle, J. M., 1996b, History of sea ice in the Canadian Arctic archipelago based on postglacial remains of the bowhead whale: *Arctic*, v. 49, no. 3, p. 235-255.

Eisner, W.R., Bockheim, J.G., Hinkel, K.M., Brown, T.A., Nelson, F.E., Peterson, K.M., and Jones, B.M., 2005, Paleoenvironmental analyses of an organic deposit from an erosional landscape remnant, Arctic Coastal Plain of Alaska, *Palaeogeography, Palaeoclimatology, Palaeoecology* 217, p. 187 – 204.

Hemming, S.R., 2004, Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Reviews of Geophysics* 42(2), Art. No. RG1005.

Holland, M.M., Bitz, C.M., Tremblay, B., 2006, Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters*, 33, L23503.

IPCC, 2007, Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller, eds.]: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Johannessen, O.M., Bengtsson, L., Miles, M.W., Kuzmina, S.I., Semenov, V.A., Alekseev, G.V., Nagurnyi, A.P., Zakharov, V.F., Bobylev, L.P., Pettersson, L.H., Hasselmann, K., Cattle, A.P., 2004, Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus Series A-Dynamic Meteorology and Oceanography* 56 (4): p. 328-341.

Jull, A.J.T., G.S. Burr, L.R. McHargue, T.E. Lange, N.A. Lifton, J.W. Beck, D.J. Donahue and D. Lal, 2004, New frontiers in dating of geological, paleoclimatic and anthropological applications using accelerator mass spectrometric measurements of C-14 and Be-10 in diverse samples. *Global and Planetary Change* 41(3-4), p. 309-323.

Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartelein, P.J., Burbaker, L.B., Coats, L.L., Cwynar, L.C., Duval, M.L., Dyke, A.S., Edwards, M.E., Eiser, W.R., Gajewski, K., Geisodottir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kewin, M.W., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Blisner, B.L., Porinchu, D.F., Rühland, K., Smol, J.P., Steig, E.J., Wolfe, B.B., 2004, Holocene thermal maximum in the western Arctic (0-180°W): *Quaternary Science Reviews* 23, p. 529-560.

North Greenland Ice Core Project, 2004, High resolution record of Northern Hemisphere climate extending into the last interglacial period: *Nature* 431, p. 147-152.

NRC Committee on the Assessment of U.S. Coast Guard Polar Icebreaker Roles and Future Needs, 2007, *Polar Icebreakers in a Changing World: An Assessment of U.S. Needs*: National Academy of Sciences Press, 122 p.

Otto-Bliesner, B. L., S. J. Marshall, J. T. Overpeck, G. H. Miller, A. Hu, and C. L. I. P. members, 2006, Simulating Arctic Climate Warmth and Icefield Retreat in the Last Interglaciation: *Science*, 311, p. 1751-1753.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G., 1997, Arctic environmental change of the last four centuries: *Science* 278 Nov. 14 (5341): p.1251-1256

Raynaud, D., J. Chappellaz, C. Ritx and P. Martinerie, 1997, Air content along the Greenland Ice Core Project core: A record of surface climatic parameters and elevation in central Greenland: *Journal of Geophysical Research* 102(C12), p. 26607-26613.

Richter-Menge, J., Overland, J., Proshutinsky, A., et al., 2006, *State of the Arctic Report*. NOAA OAR Special Report, NOAA/OAR/PMEL, Seattle, WA, 36 p.

Seager, R., Battisti, D.S., Yin, J., Gordon, N., Naik, N., et al. 2002, Is the Gulf Stream responsible for Europe's mild winters?: *Quat. J. R. Meteor. Soc*. 128B: p. 2563–86.

Serreze, M.C., Walsh J. E., Chapin III, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., OechelW.C., Morison, J., Zhang, T., and BarryR.G., 2000, Observational Evidence of Recent Change in the Northern High-Latitude Environment: *Climatic Change* 26(1-2), p. 159-207.

Serreze, M.C., and Francis, J.A., 2006, The Arctic Amplification Debate: *Climatic Change* 76(3-4), p. 241-264.

Shipboard Scientific Party, 2005, Arctic Coring Expedition (ACEX): paleoceanographic and tectonic evolution of the central Arctic Ocean. IODP Prel. Rept., 302. www.ecord.org/exp/acex/302PR.pdf.

Smith, L.C., MacDonald, G.M., Velichko, A.A., Beilman, D.W., Borisova, O.K., Frey, K.E., Kremenetski, K.V., and Sheng, Y., 2004, Siberian Peatlands a Net Carbon Sink and Global Methane Source Since the Early Holocene: *Science* 303: p. 353-356.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J, Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M-A., Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, É, Siitonen, S., Solovieva, N., and Weckström, J. 2005, Climate-driven regime shifts in the biological communities of arctic lakes: *Proceedings of the National Academy of Sciences* 102: p. 4397-4402.

Thomas, D.J., J.C. Zachos, T. J. Bralower, E. Thomas, & S. Bohaty, 2002, Warming the Fuel for the Fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum: *Geology*, v.30, p.1067-1070.

Vörösmarty, D.J., Hinzman, L.D., Peterson, B.J., Bromwich, D.H., Hamilton, L.C., Morison, J. Romanovshy, V.E., Sturm, M., and Webb, R.S., 2001, *The Hydrologic Cycle and its Role in Arctic and Global Environmental Change: a Rationale and Strategy for Synthesis Study*. Fairbanks, Alaska: Arctic Research Consortium of the US, 84 p.

Appendix A. Biographical Information for Authors

Richard B. Alley

Dr. Richard B. Alley is Evan Pugh Professor of Geosciences and Associate of the EMS Environment Institute at Pennsylvania State University, University Park, PA. There he teaches and conducts research on the paleoclimatic records, dynamics, and sedimentary deposits of large ice sheets as a means of understanding the climate system and its history, and projecting future changes in climate and sea level. Dr. Alley has spent three field seasons in Antarctica and eight in Greenland. He is a Fellow of the American Geophysical Union, and has been awarded the Seligman Crystal of the International Glaciological Society, the Agassiz Medal of the Cryospheric Section of the European Geosciences Union, the Easterbrook Award of the Quaternary Geology and Geomorpology Section of the Geological Society of America, a Packard Fellowship, a Presidential Young Investigator Award, the Horton Award of the American Geophysical Union Hydrology Section, the Wilson Teaching Award and the Mitchell Innovative Teaching Award of the College of Earth and Mineral Sciences and the Faculty Scholar Medal of the Pennsylvania State University. His book on abrupt climate change, The Two-Mile Time Machine, was the national Phi Beta Kappa Science Award winner for 2001. Dr. Alley recently chaired a National Research Council study on Abrupt Climate Change, and serves, or has served, on many other advisory panels and steering committees, such as the Polar Research Board of the National Research Council, the Intergovernmental Panel on Climate Change, the Antarctic External Review Panel (the “Augustine Commission”), and the board of directors of the Arctic Research Consortium of the United States. He has authored or coauthored more than 170 refereed publications, and his publications have been cited more than 7000 times in the refereed literature; he is listed as a “highly cited” researcher by ISI. He received his Ph.D. in Geology, with a minor in Materials Science, from the University of Wisconsin-Madison in 1987, and earned an MSc degree (1983) and BSc degree (1980) in Geology from the Ohio State University in Columbus, Ohio.

Julie Brigham-Grette

Dr. Julie Brigham-Grette is a professor in the Department of Geosciences at the University of Massachusetts, Amherst. Dr. Brigham-Grette received her Ph.D. from the University of Colorado's Institute for Arctic and Alpine Research. After post-doctoral research at the University of Bergen, Norway, and the University of Alberta, Canada with the Canadian Geological Survey, she joined the faculty at the University of Massachusetts in the fall of 1987. Dr. Brigham-Grette has been conducting research in the Arctic for nearly 24 years, including eight field seasons in remote parts of northeast Russia since 1991, participating in both the science program as well as dealing with difficult logistics. Her research interests and experience span a broad spectrum dealing with arctic paleoclimate records and the Late Cenozoic evolution of the Arctic climate both on land and off shore, especially in the Bering Strait region. She has published over 65 articles and refereed papers in her area of research expertise. She served as member of the Arctic Logistics Task Force for the NSF OPP 1996-1999 and 2000-2003, chaired the US Scientific Delegation to Svalbard for Shared Norwegian/U.S. Scientific Collaborations and Logistical Platforms in 1999, and was member of the OPP Office Advisory Council 2002-2004. Brigham-Grette is currently Chairman of the International Geosphere/Biosphere Program’s Science Steering Committee on Past Global Change (PAGES) with an international program office in Bern, Switzerland, President of the American Quaternary Association, and is a member of a National Academy of Sciences committee studying the role and future uses the US Icebreaker fleet. She also serves as one of two US representatives to the International Continental Drilling Program.

Leonid Polyak
Dr. Leonid Polyak has been a Research Scientist at the Byrd Polar Research Center (BPRC) at Ohio State University and the Curator of the BPRC Sediment Core Facility since 1993. He received his M.S. degree in Biology from the Leningrad State University and Ph.D. in Geology from the Leningrad Mining Institute in 1980 and 1985, respectively. He is widely published in the fields of Quaternary stratigraphy and paleoceanography of the central Arctic Ocean and marginal Arctic seas, the history of Pleistocene glaciation in the Arctic, and modern Arctic marine environments and the impacts of contaminants and climate change on these environments. He has participated in numerous Arctic field projects and expeditions including the SCICEX geophysical investigation of the Arctic Ocean floor and the Trans-Arctic HOTRAX 2005 seabed coring and profiling mission which involved collaboration with research groups from the United States, Russia, Canada, Norway, and Sweden. Utilizing sonar images of the Arctic Ocean floor during the SCICEX mission he has been able to demonstrate the existence of ancient massive floating ice sheets in the Arctic during the Pleistocene. Dr. Polyak's unique experience and expertise in Arctic sea ice history represent a key component in building a comprehensive evaluation of Arctic paleoclimate for this synthesis and assessment product.

Gifford H. Miller
Dr. Gifford Miller is a professor in the Department of Geological Sciences and the Director of the Center for Geochronological Research at the University of Colorado, Boulder. He received his B.A. in 1970 and Ph.D. in 1975 from the University of Colorado at Boulder and was a Postdoctoral Fellow at the Geophysical Laboratory of the Carnegie Institute from 1974-1976 and a visiting Professor at the University of Bergen, Norway in 1997 – 1980. He is currently a visiting fellow at the Research School of Earth Sciences at Australian National University in Canberra, Australia. He has served on the editorial boards of *Geology* (1992-1994), *Quaternary Science Rev*iew (1988-), *Journal of Quaternary. Science* (1987-), *Quaternary Geochronology* (1993-), and Jøkull (2003-). His research has focused on glaciation, paleoenvironments and paleoclimate of the Eastern Canadian Arctic, Svalbard and the Russian Arctic, and monsoonal variations, faunal extinctions and human-landscape interactions in the Australian Arid Zone. His current research includes the timing and mechanism of ice-sheet growth and decay in Arctic Canada and the European Arctic, and the interactions between ice sheets, oceans, and the atmosphere during the last deglaciation; developing new or improved applications of protein diagenesis in carbonate fossils to date geological and archaeological events; climate-forcing of wet/dry cycles in monsoonal Australia, the earliest immigration of humans to the continent, and their impact on climate, regional vegetation and megafauna extinction; and high-resolution records of environmental change for the Arctic over for the past 20,000 yr based on the record preserved in lake sediments.