The "New Normal" for the Arctic Requires Updated Research Priorities for Arctic Climate Observations, Modeling and Prediction

A discussion paper to identify priorities for FY2015 and beyond for the NOAA Climate Goal

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Introduction

For the past few decades, there has been a debate regarding the state of the Arctic environment – was the Arctic experiencing a period of exaggerated natural variability, or was the Arctic responding to a persistent global warming trend. The debate is over. *The Arctic has moved to a "new normal" that lies outside the bounds of recent natural variability and that may be only the first step in a long march to the unknown.*

There is compelling evidence that the Arctic is experiencing significant warming, loss of sea ice, and other interrelated changes due to the impacts of greenhouse gas emissions (Arctic Report Card [http://www.arctic.noaa.gov/reportcard], Overland et al. 2011; Wang and Overland, 2012). Stroeve et al.(2012) show that these changes are occurring considerably faster than projected by climate models. Among these changes is a reduction in Arctic sea ice (Kwok and Untersteiner, 2011), which in turn provides new opportunities for offshore energy-related and other activities having economic value and sometimes environmental risks (AMAP, 2007 and 2011). Loss of sea ice and changing weather conditions affect communities in northern Alaska (ref) and provide incentives and obstacles to business and commerce (ref). Living marine resources in the U.S. Arctic contribute to both national and local economies and food security and their future in a changing Arctic is uncertain (Moore et al., 2010). The transformation of the physical state of the Arctic has implications for regional, hemispheric and global weather and climate variability (Francis and Vavrus, 2012, Liu et al., 2011). The Arctic region has emerged as a high priority area in response to issues surrounding climate change, resource exploitation, indigenous societies, and national security.

The National Oceanic and Atmospheric Administration (NOAA) has four strategic goals (http://www.ppi.noaa.gov/wp-content/uploads/NOAA_NGSP.pdf), each of which has elements related to the Arctic region. NOAA's climate goal focuses on climate adaptation and mitigation, and robust observing, modeling, and prediction capabilities. This paper describes four necessary Arctic research priorities to meet NOAA's new climate goal responsibilities.

State of Strategic Planning at the NOAA and National Levels

The President of the United States released an Executive Order in July 2010 titled *STEWARDSHIP OF THE OCEAN, OUR COASTS, AND THE GREAT LAKES* (http://www.whitehouse.gov/the-press-office/executive-order-stewardship-ocean-our-coasts-and-great-lakes). Under this order, the National Ocean Council has identified

nine priority areas, including one focused on changing conditions in the Arctic. A strategic action plan is nearing completion for this priority area. NOAA is engaged in creation of the Arctic strategic action plan and some of the priorities identified in this paper can be traced to it.

In 2011 NOAA released its Arctic Vision and Strategy (AVS) that provides a high level view of NOAA's interests and priorities in the Arctic over the coming decade (http://www.arctic.noaa.gov/docs/NOAAArctic_V_S_2011.pdf). There are six high level goals[1] that guided the priorities defined in this paper.

The Interagency Arctic Research and Policy Committee (IARPC) was created by Congress under the Arctic Research and Policy Act of 1984. In 2010, the IARPC was identified by the Administration as a component of the Office of Science and Technology Policy (http://www.whitehouse.gov/the-press-office/presidential-memorandum-arctic-research-and-policy-act) and took on the task of preparing a Federal interagency plan for Arctic research for the five year period beginning in 2013. NOAA is participating in the preparation of this plan, and its draft version includes many priorities that intersect with NOAA's missions.

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Process for Preparing this Discussion Paper

A team of experts from the NOAA Office of Oceanic and Atmospheric Research (OAR) was established to guide development of this discussion paper. The priorities given below represent the consensus of the team and will be submitted to the leadership of NOAA's climate goal for use in planning for FY15. The Climate Goal Champion and Team will be responsible for coordinating these priorities among other Line Offices and external partners.

Summary of Four Arctic Priorities for FY15 and Beyond to Support NOAA's Climate Goal

Using NOAA's Arctic Vision and Strategy, the National Ocean Council's Ocean Plan and the IARPC Five Year Plan as guides, these priority tasks are proposed:

1. Develop new capabilities for NOAA sea ice forecasting on weekly, seasonal and decadal scales through innovative and sustained observations, modeling, and product implementation, with focus on newly opening sea-ice-free areas;

2. Detect and predict changes in physical, chemical, and biological structure and dynamics in the US Arctic marine environment through new and sustained observations, modeling, process studies, and analysis;

[1] 1) Forecast sea ice; 2) Strengthen foundational science to understand and detect Arctic climate and ecosystem changes; 3) Improve weather and water forecasts and warnings; 4) Enhance international and national partnerships; 5) Improve stewardship and management of ocean and coastal resources in the Arctic; and 6) Advance resilient and healthy Arctic communities and economies.

3. Evaluate the potential for strengthened linkages between Arctic climate change (e.g., loss of sea ice and snow cover extent, ocean heat storage) and mid-latitude climate and extreme weather events. Upgrade NOAA predictive capabilities to capture this new understanding through integration of observations and model results; and

4. Determine cause and estimate future impacts of changes in atmospheric composition and radiative fluxes over the Arctic region.

NOAA anticipates increasing responsibilities in response to a changing Arctic. These four priority tasks are necessary to advance NOAA's service capabilities to meet these new challenges.

Follow Up to this Discussion Paper

The intended use of this discussion paper is to inform the leadership of both the NOAA Climate Goal and the NOAA Office of Oceanic and Atmospheric Research (OAR) of the views of a cross-section of OAR experts. It is intended that these views be considered by OAR and the Climate Goal in developing the FY2015 budget request. Based on feedback from OAR and the Climate Goal, the authors of this paper are ready to deliver more specific information that could feed directly into the FY2015 budget submission.

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Expanded description of Priority Tasks

Priority Task 1: Develop new capabilities for NOAA sea ice forecasting on weekly, seasonal and decadal scales through innovative and sustained observations, modeling, and product improvements, with focus on newly opening sea-ice-free areas

The new activity and its payoff to NOAA:

Using new technologies and the latest understanding, new sustained observations will be initiated, designed specifically to improve the accuracy of sea ice forecasting models within NOAA and in other organizations. Improved forecasts will enable NOAA and its partners to meet unmet demands for sea ice services on multiple time scales and increase NOAA's relevance in the new Arctic era.

Background:

Sea ice summer extent has retreated 37 % and coverage of old thick sea ice has diminished 45 % in the last decade (Kwok and Untersteiner, 2011, Comiso, 2012). Much of the loss has been centered on the American Arctic, opening shipping and oil exploration, but also shifting ecosystems, creating a warmer, fresher, and more-acidic upper ocean, and suggesting non-local climate impacts. The Arctic Program of the NOAA Climate Program Office and the Alaska Region of the National Weather Service hosted a NOAA Sea Ice Forecasting Workshop during 19-21 Sept 2011 in Anchorage, AK (http://www.arctic.noaa.gov/docs/NOAA_Sea_Ice_Forecasting_Workshop_Summary.pdf). The Workshop developed recommendations and priorities for improving NOAA sea ice forecasting at the weather, seasonal, and decadal-scales that form the basis of this section.

Benefits:

Improved operational forecasts support safe operations and ecosystem stewardship on a weekly to seasonal basis, and reduce uncertainty in predictions at longer time scales for better informed policy and decision making at local, state, national, and international levels.

The five year research plan recently released by the Interagency Arctic Research Policy Committee, (IARPC) stresses that "continued loss of sea ice will affect marine and terrestrial ecosystems, coastal communities, maritime transportation, natural resource development, regional and global weather and climate, and homeland and national security". The IARPC plan further states that "the sea-ice edge during the Arctic spring through fall seasons is dynamic with rapid and large location changes in response to amount of snow cover; clouds, solar radiation and albedo; winds and ocean waves; and air and water temperatures. Interactions and feedbacks among those variables, from local to regional scales, are believed to amplify Arctic-wide climate change and sea-ice retreat (Perovich and Richter-Menge 2009). Better knowledge of such feedbacks is vital for …improving daily to seasonal weather and sea-ice forecast models and increasing the accuracy of longer-term sea-ice and climate projections".

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Proposed new activities and linkages:

Successful OAR response to challenges of a newly developing sea ice free Alaskan Arctic summer requires additional offshore observations of sea ice and weather, model development and evaluation, and coordination with NWS and Ice Center Operations. Improvement in sea ice and weather forecasts are tightly coupled and are to be pursued together.

Current data are insufficient for NOAA's present Arctic service requirements. Increases in *in situ* atmospheric and ocean observations, and better use of remotely sensed data are needed for documenting Arctic changes, model initialization, and understanding a new set of Arctic feedbacks. Desired data types include: snow depth, ice thickness distribution, motion, and melt rates; surface air temperature, radiation, and sea level pressure; atmospheric temperature profiles; and ocean mixed layer temperature and chemistry data. Such data is obtained from moorings, combinations of ocean and sea ice capable drifters, wave gliders, ships, and aircraft. Better use of existing remote sensing is needed to provide large-scale characteristics of sea ice, such as ice concentration, ice type (first-year vs. perennial), ice motion, leads/polynyas, melt pond fraction. Recovery of temperature profiles from satellites is still not tuned for Arctic conditions. Sea ice concentration estimates from different satellite sensors are inconsistent. An aircraft reconnaissance of snow and sea ice thickness at the beginning and end of the summer melt season are necessary for spatial initialization and validation of sea ice models.

Partnerships with national inter-agency, international and private industry are needed so that platforms can be equipped with instrumentation for many of the needed observations on a mutually beneficial basis. International collaboration is necessary, not only because Canada and Russia share the target region with the U.S., but also because international collaboration is needed for data sharing (e.g. ESA CryoSat-2 for ice thickness).

At the NOAA Sea Ice Forecasting Workshop, there was a sense of urgency among those interested in forecasting at the weather-scale given that there is no operational 3-5 day NOAA sea ice forecasting model to support decision makers, and user demands are growing faster than the capability of the forecasters and modelers. This led the workshop participants to agree on one overarching weather-scale goal –develop a coupled ice-ocean-atmosphere forecast model capability. Already, the Alaska Region of the NOAA Weather Service is partnered with the Naval Research Laboratory (NRL) at Stennis Space Center to access output from the NRL Arctic CAP forecast model for 5-day sea ice forecasts. Forecast skill is limited due to lack of in situ weather and sea ice data and a lack of methods of assimilating real time data into NOAA and NRL models. The group agreed that a coupled modeling effort of the scope needed should be developed across NOAA (NWS, ESRL, NESDIS, GLERL), with external partners (NASA, Navy, BOEM, Environment Canada, Army Corps of Engineers, industry, WMO), and other stakeholders involved from the outset.

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A summer seasonal forecast product is also an important need. On a seasonal scale, sea ice impacts shipping, resource exploration, marine mammal habitat, coastal erosion, and regional weather, and provides evidence of longer-term climate change. Workshop participants agreed that the present Sea Ice Outlook (SIO) activity at PMEL should convert the SIO from an informal international 'group of the willing' to a formal NOAA product. Additional activities support model development and evaluation at ESRL, GLERL, NCEP, and PMEL, particularly focusing on producing meteorological and sea ice forecast ensembles. Seasonal forecasts necessarily are dependent on the improved observational base. Metrics are needed to guide and evaluate the development of seasonal outlooks.

Sea ice is a major decadal climate change indicator as there may be a nearly sea-ice free summer sometime before mid-century; changes are occurring now and are faster than projected by climate models. Sea ice is transitioning from old, thick ice to mostly mobile first-year ice. Comprehensive Atmosphere-Ocean General Circulation Models (AOGCMs) comprise the major objective tool to account for the complex interaction of processes that determine future climate change, yet there appears to be little progress on modeling Arctic climate in the present versions of models used for IPCC, based on low spatial resolution and the uncertainties in coupling of radiation with sea ice processes. Support is necessary for continued improvements in sea ice parameterizations of Arctic climate in AOGCMs at GFDL and other centers, and continued observation and model evaluation at PMEL, GLERL and ESRL.

Incremental resources required:

The necessary observational and developmental modeling activities can be undertaken for an annual cost of $3.5 M if reliance on opportunistic logistic arrangements is assumed. If dedicated logistic support is desired to guarantee observations are conducted according to NOAA's requirements, then an additional $2M per year will be required. Effective links will be required with both NESDIS, for delivery of remote sensing observations, and NWS for production and dissemination of forecast products. These organizations will need resources not included here.

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Priority Task 2: Detect and predict changes in physical, chemical, and biological structure and dynamics in the U.S. Arctic marine environment through new and sustained observations, modeling, process studies, and analysis

The new activity and its payoff to NOAA:

NOAA will produce a four dimensional electronic interactive environmental "atlas[2]" for the U.S. Arctic marine environment through integration of new observing technologies, improved regional understanding, and the latest coupled models from OAR Laboratories and external sources. This will provide to NOAA and the nation the ability to make better informed resource management decisions and plan for continued environmental changes in the U.S. Arctic.

Background:

The NOAA Arctic Report Card confirms "that there are now a sufficient number of years of data to indicate a shift in the Arctic Ocean system… As a result of increased open water area, biological productivity at the base of the marine food chain has increased and sea ice-dependent marine mammals continue to lose habitat". As carbon dioxide-driven global warming is a fact of life for many more years, there is little doubt that major changes in the U.S. Arctic will continue, and perhaps accelerate, with increasing oceanic physical and biological impacts, and social consequences (Duarte et al., 2012; Notz and Marotzke, 2012).

Changes to Arctic ecosystems have been documented over the past few years. Phytoplankton species diversity is becoming skewed to smaller size classes and total primary production may have increased (Wassman et al., 2011). Due to sea ice loss, walrus, seals, and polar bears are changing their behavior (Stirling and Derocher, 2012), and salmon are more common along Alaska's north coast (ref). Furthermore, the continued increase of anthropogenic CO_2 coupled with enhanced continental respiration and ice melt will result in under-saturated surface waters of the Arctic Ocean over the coming decades with respect to aragonite, an important shell forming mineral; ocean acidification serves as a particular additional stress to Arctic marine ecosystems. (Anderson et al., 2010), and is the subject of an in-depth assessment underway by the Arctic Council.

Increasing human use of the Alaskan Arctic marine environment provides another driver of environmental change. The potential for discovery of significant amounts of offshore oil and gas resources will bring people, massive infrastructure and risk of spills and operational disturbances to a comparatively pristine environment. Ship-based tourism and transportation also will leave a footprint.

[2] A data visualization capability consisting of computer generated three-dimensional snapshot views of water column characteristics (e.g., temperature, salinity, flows, nutrients, chlorophyll, zooplankton, etc) at a given time, with an animation of different time snapshots. The computer images are supported by and linked to traditional two dimensional views, complete data tables and model outputs.

Benefits:

NOAA's role in the U.S. Arctic is at a new intersection of increased industrial demands and environmental stewardship. Management and decision-making for resource exploitation and protection requires knowledge of the current state of the environment and reliable outlooks for the future state under alternate legal, social, and economic regimes. The Arctic "atlas", based on necessary long-term observations of key variables, coupled with appropriate models and analysis tools, will support the needs of managers and decision-makers, who must often balance near-term economic and social interests against long-term environmental protection and ecosystem sustainability.

Proposed new activities and linkages:

Evaluating both the global climate and local human use drivers of change requires a multi-decadal perspective. Past work by both OAR (through the long-term involvement of PMEL in Bering Sea observations and analysis, the Russian-American Long-term Census of the Arctic [RUSALCA]) and NMFS (through Arctic marine living resource surveys) have demonstrated the sensitivity of the U.S. Arctic to ecosystem change and have established a record upon which to evaluate future changes.

The new requirement for OAR is an integrated and sustained monitoring, research, and modeling activity including physical, chemical, and biological variables that describe ecological status and support forecasts of change. These requirements include both *in situ* and remotely sensed observations to track changes in sea ice, primary production, zooplankton and fish communities, distribution of higher trophic level species, ocean acidification, underwater acoustic environment, and other relevant variables. A mixture of observing platforms (moorings, gliders, ships, processed data from satellites, various autonomous vehicles and even instrumented animals) will be needed to capture all of the relevant variables at appropriate time and space scales. This is most efficiently achieved through frequent sampling at 'sentinel' locations nested within lower frequency hydrographic and ecological spatial surveys. In addition, process-level activities at the sentinel sites, undertaken internally or with external partners, will provide an interpretive understanding of the broad survey data. These monitoring and process efforts will set limits for diagnostic or forecast modeling tools. The planned enhancement in the observing system will be engineered to inform directly a new emphasis on development of physical -biogeochemical-ecological models used to predict changes in the physiochemical state of the Arctic and population- and ecosystem-level effects, including key species and potential socioeconomic impacts (e.g., Jin et al., 2011). New visualization techniques will be needed to implement fully the "atlas".

The sentinel sites concept for the Arctic has been developed by the Pacific Arctic Group (PAG) and the Arctic Council (AC). NOAA played a lead role in the PAG and its development of the north-south oriented Distributed Biological Observatory (DBO), focused on a small set of sites from the Northern Bering Sea, through Bering Strait and

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into the Chukchi Sea. The DBO is an international organizing framework (Grebmeier et al., 2010) that calls for a collaborative network of scientific and logistical support from the PAG member countries (Canada, China, Japan, Korea, Russia and the USA). and a decadal perspective. The DBO also requires partnerships among NOAA LOsos and relevant U.S. agencies (especially NASA, NSF and BOEM), coordinated through the Interagency Arctic Research Policy Committee (IARPC). Similarly, the Arctic Council developed with NOAA leadership the marine component of the Circum-polar Biodiversity Monitoring Program (CBMP). The CBMP consists of an east-west network of sampling sites, for detecting environmental status and change. In the U.S. Arctic, the DBO sentinel sites are included within the CBMP sites.

NOAA has the capability to undertake the necessary in situ observations. PMEL initiated an Arctic program in the late 1980s and has deployed moorings in the Bering Sea for decades, and more recently has applied more advanced sensors and piloted the use of wave gliders. The Arctic Research Program began in 1999 and has organized Arctic research by NOAA and its academic partners focused on marine productivity, physical and chemical state, and climate variability and change. The Alaska Fisheries Science Center conducts fishery stock assessment cruises and marine mammal surveys in the Bering and Chukchi Seas with a growing capability for multi-disciplinary observations. NOAA's academic partners bring a full range of interests and capabilities for technology, observations, and modeling.

The U.S. Arctic marine environment is projected to experience increased commercial use with the continued loss of sea ice. Scenarios for future subsistence and commercial use will be constructed (taking advantage of existing projects such as the Alaska Center for Climate Assessment and Policy) to serve as guides to project future ecosystem status and human and climate driven ecosystem stresses, and allow proactive adaptation to changing conditions.

OAR will assume responsibility to bring together the capabilities distributed throughout NOAA to meet the new status and forecast requirement. OAR will focus on in situ observations, process research, analysis and modeling, and also create and support linkages to capabilities in other NOAA organizations. A team of experts from throughout NOAA and from NOAA's interagency and international partners will be established to evaluate and forecast the state of the U.S. Arctic ecosystem on a periodic basis over the next decade. OAR will blend the observations, model outputs and expert evaluations to produce the electronic interactive Arctic environmental atlas and make it widely available.

Incremental resources required:

This activity can be undertaken for an annual cost of $5M for science and an additional $2M for ship charter.

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Priority Task 3: Evaluate the potential for strengthened linkages between Arctic climate change (e.g., loss of sea ice and snow cover extent, ocean heat storage) and mid-latitude climate and extreme weather events. Upgrade NOAA predictive capabilities to capture this new understanding through integration of observations and model results

The new activity and its payoff to NOAA:

NOAA is expected to be an authoritative source of information on the current and future state of the Earth's climate. To meet increasing expectations for better climate predictions, NOAA will identify atmospheric patterns that link the increasing changes in the Arctic (e.g., sea ice and snow loss, ocean heat storage, sea level and upper air pressure center shifts) to mid-latitude climate and weather extremes. The effort seeks to tie together Arctic-driven and tropical-driven climate drivers to produce an enhanced system-level understanding of potential mid-latitude climate variability and change (e.g., the US winter of 2009-10). This will lead to improved long-range forecast guidance and more confident predictions of the Earth's future climate state.

Background:

There is strong evidence that "Arctic Amplification", where the Arctic warms faster than lower latitudes under a global warming trend, is related to loss of the Arctic cryosphere (Overland et al., 2011). Earlier and more extensive snow melt on land and faster and more extensive sea ice loss at sea, followed by slower regrowth of ice in the fall, capture more heat for the planet, which in turn is transferred into the Arctic atmosphere. While the interaction of external forcing from the Arctic with chaotic atmospheric flow is complex, evidence suggests a consistent reduction in speed of eastward moving atmospheric patterns around the Arctic (Francis and Vavrus; 2012; Allen and Zender, 2011; Hanna et al., 2012; Liu et al., 2012; Jaiser et al, 2012; Outten and Esau,2012). Slow moving patterns make it more possible for extreme weather conditions to develop (Coumou and Rahmstorf, 2012). It is plausible that changes in the Arctic atmospheric circulation can be implicated in heavy snowfalls along the US northeast coast, western Europe, and eastern Asia, and warmer than normal conditions in west Greenland and western Eurasia. However one should expect considerable intra-season and inter-annual variability in these relationships. As stated by Francis and Vavrus (2012), "Gradual warming of the globe may not be noticed by most, but everyone – either directly or indirectly – will be affected to some degree by changes in the frequency and intensity of extreme weather events as greenhouse gases continue to accumulate in the atmosphere". The U.S. can ill afford more extreme weather surprises.

Benefits:

The principal requirements are to verify, understand, and predict the Arctic connection to mid-latitude weather and climate, by identifying the types of Arctic precursors and the climate and weather extremes that might result. Success would provide significant new guidance for policy action on climate change mitigation and adaptation.

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Proposed new activities and linkages to other activities:

Observational case studies, statistical analyses, and modeling are the principal means of identifying and understanding the atmospheric dynamics of these linkages and their remote impacts. For example, spatial mapping of pressure and temperature anomalies around the hemispheric Arctic over the last five years has identified new persistent blocking patterns that link north-south weather (Francis and Vavrus, 2012; Liu et al. 2012). Jaiser et al. (2012) document their temporal development implicating reduction in vertical static stability and the interaction between baroclinic and planetary waves. Spatial variations of radiative forcing may also help lock in these patterns thus implicating shifts in clouds, aerosols, and albedo.

Observations of large scale climate and weather dynamics must be brought together with shifts in forcing factors such as upper ocean temperature structure and transport; land, sea ice and ocean surface energy balance and albedo shifts; and atmospheric composition. Once patterns that appear to drive north-south linkages are identified through exploratory analysis, they can be dynamically understood through models with multiple ensemble runs, and verified by continuing observations. As new patterns and linkages are identified, their influence provides motivation for weather and climate models to capture such features.

Incremental resources required:

This activity can be undertaken for an annual cost of $1.5M to support NOAA and external experts to conduct the required work.

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Priority Task 4: Determine cause and estimate future impacts of observed changes in seasonal to decadal variability related to changes in atmospheric composition and radiative fluxes over the entire Arctic region.

The new activity and its payoff to NOAA:

NOAA will accelerate development of an informal network of atmospheric observatories in the Arctic and upgrade sensors and samplers to provide an Arctic-wide data set of key climate variables. Analysis will be integrated across data variables and between observatories and synthesized to provide regional perspective that can lead to improved models and drive their outputs. Development of international partnerships to support the network will to NOAA observational capacity that would be logistically and cost prohibitive for NOAA acting alone.

Background:

Arctic amplification of surface air temperatures is well documented in observations but not completely understood or reproduced by climate models. In addition to heat exchange with the ocean, meridional transport, and radiative forcing from atmospheric constituents, the Arctic atmosphere is influence strongly by unique features such as existence of polar night, a high proportion of high albedo surfaces (that recently are showing great seasonal variability), and unusual atmospheric stability. These unique features can change the sign and magnitude of radiative forcing by clouds and aerosols relative to low latitudes, requiring uniquely constructed models to project changes in Arctic atmospheric temperature and other climate variables.

Benefits:

The primary requirement is to improve climate projections for the Arctic, at both pan-Arctic and localized spatial scales. Such projections on decadal and longer time scales are essential to policy- and decision-makers in public and private sectors to guide adaptation and mitigation planning and investments.

Proposed new activities and linkages to other activities:

There are three high priority needs that can be met through enhanced atmospheric observations and modeling. The first is to improve understanding of the source regions and radiative forcing of short-lived climate forcers (SLCF) and their roles in Arctic amplification. The SLCF include black carbon, aerosols, ozone and methane, each having a residence time in the atmosphere of days to years. Black carbon in the atmosphere and deposited on snow and ice surfaces is thought to have an enhanced influence on Arctic radiative forcing relative to mid-latitudes. Methane is a more potent greenhouse gas than carbon dioxide on a per-molecule basis, but its shorter lifetime and lower concentration make it less important than carbon dioxide on a global basis at present rates of methane release to the atmosphere. However the Arctic region contains vast amounts of methane sequestered in permafrost and marine hydrates that

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could influence the global system if release rates were to increase significantly as might happen under a consistent Arctic warming trend.

The second high priority need is to improve understanding of processes that control the formation, longevity and physical properties of Arctic clouds, including their sensitivities to aerosols. Clouds, especially low level ones, occur frequently in the Arctic, and aerosols appear episodically due to long-range transport and variable local sources. Both clouds and aerosols are unevenly distributed in space as well as time, but when they coexist, they participate in highly integrative processes that affect radiative forcing. The existence of low sun angles and highly reflective surfaces complicate these processes. Climate models have large uncertainties because of poor representation of these processes.

The final high priority need is to develop an integrated understanding of Arctic atmospheric processes, their impact on the surface energy budget, and their linkages with oceanic, terrestrial and cryospheric systems. A nationally and internationally coordinated approach is needed to improve observations. Comprehensive and process-level observations are needed at a greater number of atmospheric observatories, especially over the central Arctic basin and other sea-ice environments. In addition to traditional land-based observatories, sustained deployment of ships or ice camps is needed for marine areas and piloted and remotely controlled aircraft should be employed to fill in gaps between surface stations.

Incremental resources required:

This activity can be undertaken for an annual cost of $3M to include both scientific and logistic elements of the work.

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