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# Arctic Climate Systems Analysis

Mark D. Ivey, David G. Robinson, Mark B. Boslough, George A. Backus, Kara J. Peterson, Bart G. Van Bloemen Waanders, Laura P. Swiler, Darin M. Desilets, and Rhonda K. Reinert

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**Abstract**

This study began with a challenge from program area managers at Sandia National Laboratories to technical staff in the energy, climate, and infrastructure security areas: apply a systems-level perspective to existing science and technology program areas in order to determine technology gaps, identify new technical capabilities at Sandia that could be applied to these areas, and identify opportunities for innovation. The Arctic was selected as one of these areas for systems level analyses, and this report documents the results. In this study, an emphasis was placed on the arctic atmosphere since Sandia has been active in atmospheric research in the Arctic since 1997.

This study begins with a discussion of the challenges and benefits of analyzing the Arctic as a system. It goes on to discuss current and future needs of the defense, scientific, energy, and intelligence communities for more comprehensive data products related to the Arctic; assess the current state of atmospheric measurement resources available for the Arctic; and explain how the capabilities at Sandia National Laboratories can be used to address the identified technological, data, and modeling needs of the defense, scientific, energy, and intelligence communities for Arctic support.

# Acknowledgments

This study was supported by the Energy & Climate (EC) Program Management Unit (PMU) at Sandia National Laboratories. The authors gratefully appreciate the funding provided by the EC PMU (ECIS SMU at the time) as part of a systems studies initiative. We thank John Roskovensky, a former Sandian, for the extensive satellite assessment he conducted and described in Section 4 and Appendix A as well as the significant expertise he brought to our team.

In addition, we acknowledge the significant contributions of Professor Johannes Verlinde (Penn State University) and Wayne Einfeld (Sandia National Laboratories, retired) in the writing and editing of Section 5. Rhonda Reinert, one of the authors, provided outstanding technical writing and editing support, combining the contributions from many authors across a variety of scientific disciplines and with diverse writing styles into this final report.

The DOE Atmospheric Radiation Measurement facilities on the North Slope of Alaska are mentioned several times in this report. We acknowledge the efforts of Bernie Zak, retired Sandian, who led the team that established facilities in Barrow and Atqasuk, Alaska, and put teams on the Canadian icebreaker *Des Grosseilliers* for the SHEBA campaign in 1997. We anticipate that Sandia National Laboratories will be engaged in frontline science and engineering activities in the Arctic for many decades to come. We hope this report will inform and motivate other Sandians as well as the broader research community as we seek a better understanding of the Earth's climate system and an improved ability to predict the future of the Arctic.

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# Executive Summary

The warming of the Earth's surface has important implications for national security. A recent report by the Center for a New American Security summarizes the case well:

> Climate change will affect national security in the broadest sense, potentially affecting everything from economic growth to social stability. More narrowly, global climate change may spur sudden onset (i.e., hurricanes and floods) and slow onset (i.e., droughts and famines) disasters around the world, provoking humanitarian crises that will require military and other governmental responses. Climate change will alter the military operating environment, as well, requiring advanced planning and ongoing reevaluation.[1]

As a leading national security laboratory, Sandia is engaged in conducting assessments of future climate impacts. The primary technical themes of Sandia's Energy & Climate (EC) Program Management Unit (PMU) are interdependent and intersect at the impact of climate change on energy and national security. Sandia's established concentration in Arctic climate measurements, models, and studies distinguishes our climate program from those at other national laboratories.

The Arctic is receiving increased attention from the international scientific community, a variety of U.S. federal agencies, and foreign nations with geopolitical or economic interests in that region. Geophysical information from the Arctic is sparse, intermittent, or of uncertain quality.

There are many reasons to be concerned with the changing Arctic:

1. Because of polar amplification, the Arctic is more sensitive to changes in atmospheric forcing, on average, than other regions of the globe.

2. Rapid changes in the Arctic have a disproportionate effect on the surrounding northern continents, home to a majority of Organization of Economic Co-Operation and Development (OECD) countries and the developed world.

3. The Arctic is one of the most data-sparse regions on Earth.

4. The Arctic has mineral wealth, water, fisheries, trade routes, and a militarily-strategic location.

5. Nations with Arctic borders depend on a natural defensive barrier against potential aggressors.

6. The Arctic contains domestic and human resources that are vulnerable to change.

[1] Quote available at http://chicagoclimateonline.org/webresources/center-new-american-security-climate-change.

7. The Arctic atmosphere is a major component of the complex Arctic system. The Arctic is one of the least understood but most important climate subsystems in the Earth climate system.

This study started with a single systems-level question: How should the United States prioritize atmospheric measurement resources in the Arctic to better support anticipated mission-related needs of the U.S. Department of Defense (DOD) in the Arctic as well as the current, high-priority needs of the Arctic scientific community? Despite this focused beginning, this study soon branched into other technical areas, and it proved difficult to limit the investigation to atmospheric science and technology alone. In this report, we attempted to capture the critical needs and opportunities for research in areas not only related to the arctic atmosphere, but to the broader challenges related to engineering and science challenges related to the Arctic. This Arctic Systems study was initially funded by the Energy, Climate, and Infrastructure Strategic Management Unit (ECIS SMU) at Sandia as one of several systems-levels studies of technical areas of interest within that SMU.

## DOD and U.S. Coast Guard

Sandia has engaged in discussions with the U.S. Northern Command (USNORTHCOM) and is attempting to establish a working relationship with the U.S. Coast Guard (USCG) related to the Arctic. The DOD and the USCG each recognize several areas where there are gaps in their ability to carry out their perceived missions in the Arctic. For example, the DOD has identified 9 areas in the Arctic that have research and development, strategic, and operational gaps (DOD 2011), and the USCG has identified 11 areas.[2] The USCG and NORTHCOM prioritized these sets of items into four gap focus-areas for the Arctic (GAO 2012):

1. Communications
2. Maritime domain awareness
3. Search and rescue
4. Environmental observation and forecasting

## Toward an Arctic Predictive Capability

An integrated measurement, modeling, and analysis capability for the Arctic with demonstrated predictive power would be of great benefit to energy and national security interests in that region. This study looked at capability gaps that must be addressed to fulfill this need.

### Data Fusion

Collecting and integrating a wide array of data from multiple sources in the Arctic is challenging. The DOD is funding a major initiative focused on collection and access tools for Arctic data. As recounted by Spehn (2012):

[2] See http://www.uscg.mil/top/missions/.

> The ACE JCTD will provide a web-based, open-access, Arctic-focused, environmental research and decision-support system that integrates data from existing remote-sensing assets and in situ observations to provide monitoring, analysis, and visualization based on earth observation data and modeling. The ACE JCTD will enable local, regional, and international cooperation and coordination on long-term environmental planning and near-term actions in response to climatic and environmental changes occurring in the Arctic region.

Sandia's capabilities in managing massive data sets and emerging capabilities in data fusion techniques will be essential for rendering and assimilating data in useable forms. Spatio-temporal data fusion is described as a promising technique for fusing remote-sensing data sets.

### Satellites

Satellites are essential assets in the Arctic for several reasons. They are an important source of environmental information in a region with limited access. They also provide communications capabilities, although the need for improved communications capacity in the Arctic is high on the list of DOD and scientific needs. This study includes a survey of satellites and sensors that provide data on the Arctic environment.

### Unmanned Aircraft Systems

Unmanned aircraft systems (UASs) will benefit national security and scientific interests in the Arctic. The Department of Energy's (DOE's) focus on developing a better understanding of processes important to predicting climate variations requires routine and limited-duration observations. There are several important Arctic climate processes for which there are little data and poor modeling capability but that have global implications. There are specific opportunities to study these important processes that are currently only possible from a new DOE Atmospheric Radiation Measurement (ARM) site in Oliktok Point, Alaska. We believe that a combination of short-term observations with manned aircraft and regular operations of UASs and tethered balloons offers the best vehicles to gather the necessary data for addressing the uncertainties associated with several of these critical questions.

Many of the model uncertainties are associated with the deep Arctic, but most experiments with manned aircraft have been conducted near the coast. Given the scientific importance of processes over the ocean in the Arctic, the ARM program is planning to use UASs at Oliktok to provide measurements in regions distant from the coast that are otherwise unavailable to scientists. The scientific questions will direct the observational strategy. Additionally, UAS measurements will provide in situ data for calibrating the scanning measurements associated with the AMF3, the third ARM mobile facility, and the flight pattern over the ocean will greatly extend the footprint of the ground instruments. Thus, these measurements both augment and enhance the value of the ground-based measurements.

### Uncertainty Quantification Methods

Sandia's work in nuclear weapons simulations and analysis resulted in a concentration of expertise in uncertainty quantification (UQ). The UQ expertise as applied to Arctic models is important for assessing the predictive power and error of the model results. This study contends there is a need for a strong coupling of numerical analysis and acquisition strategies, as current data acquisition strategies have not particularly produced quality climate forecasts. The Weather Research and Forecasting (WRF) model, including a version designated as Polar-WRF, provides a means to address UQ questions at a regional level. Recent work at Sandia to use WRF for UQ and source attribution provides insight into the utility of this approach and possible alternate methods.

### Uncertainty Analysis for Climate Models

Sandia's experience with climate models in general informs this study on the topic of uncertainty analysis, which is also applicable to Arctic models. A detailed discussion is provided about the significant needs and challenges faced by climate models and the tools and methods that Sandia has available and has used to address these concerns. This section of the study also highlights Sandia's participation in a multi-laboratory climate-science initiative called Climate Science for a Sustainable Energy Future (CSSEF). Sandia's CCSEF work includes support for land UQ and atmosphere UQ modeling activities.

### Atmospheric, Land, Ocean, and Sea Ice Models

Interactions among land, ice, ocean, and atmosphere are not well represented in current models. Nonlinear Arctic feedback mechanisms can drive dramatic, abrupt, and possibly irreversible changes in global climate; these feedbacks are not well represented in current models. Fundamental work is needed to understand Arctic clouds and aerosols. This section of the study reviews models at Sandia that could be applied to the Arctic region and data needs for those models.

### MEDEA

MEDEA is a program designed to share intelligence community data with the climate and environmental science community. MEDEA is managed by the Global Climate Change Research Program (GCCRP) in the Central intelligence Agency. For this study, Sandia reviewed and summarized the basic contents of a number of classified and unclassified reports on MEDEA and gained a deeper understanding of GCCRP's responsibilities for documenting the state and trends of global climate, providing metrics needed to monitor and verify global climate treaties, and assessing the national security implications of climate and global change.

Sandia is well positioned to make major contributions to MEDEA because of its unique subject domain experts, its existing projects involving Arctic systems and climate change, its strong relationships with the intelligence, global-monitoring, and climate science communities, and its staff who have security clearances and access to Sensitive Compartmented Information Facilities.

## References


DOD (U.S. Department of Defense). (2011). *Report to Congress on Arctic Operations and the Northwest Passage*. Washington DC: Department of Defense. www.defense.gov/pubs/pdfs/Tab_A_Arctic_Report_Public.pdf (accessed on March 28, 2014).

GAO (U.S. Government Accountability Office). (2012). *DOD Addressed Many Specified Reporting Elements in Its 2011 Arctic Report but Should Take Steps to Meet Near- and Long-term Needs*. GAO-12-180. Washington, DC: GAO. http://www.gao.gov/assets/590/587676.pdf (accessed on March 29, 2014).

Spehn, S. (2012). "Arctic Collaborative Environment." http://www.dtic.mil/dtic/tr/fulltext/u2/a567865.pdf (accessed on July 28, 2014).

# Nomenclature

| | |
|---|---|
| 2D | two-dimensional |
| 3D | three-dimensional |
| ACE | Arctic Collaborative Environment |
| ACRF | ARM Climate Research Facility |
| AFRICOM | Africa Command |
| AIS | Automatic Identification System |
| ALTOS | Arctic Lower Troposphere Observed Structure |
| AMSU-B | Advanced Microwave Sounding Unit-B |
| ANOVA | analysis of variance |
| AR4 | IPCC Fourth Assessment Report |
| ARM | Atmospheric Radiation Measurement |
| ASC | Advanced Simulation and Computing |
| ASI | Agenzia Spaziale Italiana |
| ASR | Arctic System Reanalysis |
| BER | Biological and Environmental Research |
| CAST | China Academy of Space Technology |
| CBERS | China–Brazil Earth Resources Satellite program |
| CCN | cloud condensation nuclei |
| CCSM4 | Community Climate System Model |
| CD | convection-diffusion |
| CDTI | Center for Technology and Industrial Development (Spain) |
| CEOS | Committee on Earth Observation Satellites |
| CESM | Community Earth System Model |
| $CH_4$ | methane |
| CIA | Central Intelligence Agency |
| CISM | Community Ice Sheet Model |
| CNES | Centre National d'Etudes Spatiales (French) |
| CO` | carbon monoxide |
| $CO_2$ | carbon dioxide |
| CONAE | Comission Nacional de Actividades Espaciales (Argentina) |
| CRESDA | Center for Resource Satellite Data and Applications (China) |
| CSA | Canadian Space Agency |
| CSFR | NCEP Climate Forecast System Reanalysis |
| CSSEF | Climate Science for a Sustainable Energy Future |
| CTD-SRDL | Conductivity-Temperature-Depth Satellite-Relay Data Loggers |
| DAKOTA | Design Analysis Kit for Optimization and Terascale Applications |
| DLR | Deutsches Zentrum fur Luft und Raumfahrt (German Aerospace Center) |
| DMSP | Defense Meteorology Satellite Program |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DSCOVR | Deep Space Climate Observatory |
| EC | Energy & Climate (used with PMU) |
| EC | European Community |

| | |
|---|---|
| ECMWF | European Center for Medium Range Weather Forecasting or European Centre for Medium-Range Weather Forecasts |
| EO | Earth Observing |
| EOL | End-of-Life |
| ESA | European Space Agency |
| EUCOM | European Command |
| EUMETSAT | European Organization for the Exploitation of Meteorology Satellites |
| FAA | Federal Aviation Administration |
| FMI | Finnish Meteorological Institute |
| GAO | Government Accountability Office |
| GCCRP | Global Climate Change Research Program |
| GEO | Geostationary Orbit |
| GFS | Global Forecast System |
| GHGIS | GreenHouse Gas Information System |
| GISTDA | Geo-Informatics and Space Technology Development Agency (Thailand) |
| GOME | Global Ozone Monitoring Experiment |
| GOS | Global Observing System |
| GOSAT | Greenhouse gases Observing SATellite |
| GP | Gaussian process |
| GPS | global-positioning system |
| HEO | Highly Elliptical Orbit |
| HIGPS | High-Integrity Global Positioning System |
| HOMME | High-order Method Modeling Environment |
| HRLDAS | High Resolution Land Data Assimilation System |
| IAI | Israel Aircraft Industries |
| IARPC | Interagency Arctic Research Policy Committee |
| INPE | National Institute for Space Research (Brazil) |
| IPCC | Intergovernmental Panel on Climate Change |
| IR | infrared |
| ISA | Israel Space Agency |
| ISRO | Indian Space Research Organization |
| JAXA | Japan Aerospace Exploration Agency |
| JPSS | Joint Polar Satellite System |
| K | Kelvin |
| KARI | Korea Aerospace Research Institute |
| kg | kilogram |
| km | kilometer |
| LEO | Low Earth Orbit |
| LIDAR | light detection and ranging |
| LOS | line of sight |
| m | meter |
| MARS | Multivariate Adaptive Regression Splines |
| MDA | MacDonald Dettwiter and Associates |
| MEDEA | Measurements of Earth Data for Environmental Analysis |

| | |
|---|---|
| MEO | Medium Earth Orbit |
| MEOP | Marine Mammals Exploring the Oceans Pole to Pole |
| MERRA | Modern-Era Retrospective Analysis for Research and Applications |
| METI | Ministry of Economy, Trade, and Industry (Japan) |
| MOAT | Morris One-At-A-Time Sampling |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MOE | Ministry of Education (Japan) |
| MOGA | multiobjective genetic algorithm |
| MPACE | Mixed-Phase Arctic Cloud Experiment |
| MTI | Multi-Thermal Imager |
| NAM | North American Mesoscale |
| NASA | National Aeronautics and Space Administration |
| NASRDA | National Space Research and Development Agency (Nigeria) |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Center for Environmental Protection |
| NDSI | Normalized Difference Snow Index |
| NEXRAD | Next-Generation Radar |
| NIES | National Institute for Environmental Studies (Japan) |
| NIVR | Netherlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart |
| NMSU | New Mexico State University |
| $NO_2$ | nitrogen oxide |
| NOAA | National Oceanic and Atmospheric Administration |
| NPOESS | National Polar-orbiting Operational Environmental Satellite System |
| NPP | NPOESS Preparatory Project |
| NRD | Normalized Reflectance Difference |
| NRL | Naval Research Laboratory |
| NRO | National Reconnaissance Office |
| NRSCC | National Remote Sensing Center of China |
| NSAU | National Space Institute of Ukraine |
| NSC | Norwegian Space Centre |
| NSIDC | National Snow and Ice Data Center |
| NSMC-CMA | National Satellite Meteorology Center – China Meteorology Administration |
| NSO | Netherlands Space Office |
| NSOAS | National Satellite Ocean Application Service (China) |
| NSPO | National Space Organization (Taiwan) |
| NSTC | National Science and Technology Council |
| OCO | Orbiting Carbon Observatory |
| ORS | Operational Responsive Space |
| OSCAR | Observing Systems Capability Analysis and Review |
| PCE | polynomial chaos expansion |
| PCW | Polar Communications and Weather |
| PDE | partial differential equation |
| PISCEES | Predicting Ice Sheet and Climate Evolution at Extreme Scales |

| | |
|---|---|
| PMU | Program Management Unit |
| POES | Polar-orbiting Operational Environmental Satellite |
| ppm | parts per million |
| PWRF | Polar Weather Forecast Model |
| R&D | research and development |
| RASM | Regional Arctic System Model |
| RMS | root-mean-square |
| ROSHYDROMET | Russian Federal Service for Hydrometeorology and Environmental Monitoring |
| ROSKOSMOS | Russian Federal Space Agency |
| Sandia | Sandia National Laboratories |
| SAR | Synthetic Aperture Radar |
| SCIAMACHY | Scanning Imaging Absorption Spectrometer for Atmospheric Chartography/Chemistry |
| SciDAC | Scientific Discovery through Advanced Computing |
| SCIF | Sensitive Compartmented Information Facility |
| SEACISM | Scalable, Efficient, and Accurate Community Ice Sheet Model |
| sec | second |
| SMMR | Scanning Multichannel Microwave Radiometer |
| SNR | signal-to-noise ratio |
| SNSB | Swedish National Space Board |
| SPOT | Système Pour l'Observation de la Terre |
| SSM/I | Special Sensor Microwave Imager |
| STDF | spatio-temporal data fusion |
| SWIR | short-wave infrared |
| TAS-i | Technical Advisory Service for Images (UK) |
| TEKES | Finnish funding agency for technology and innovation |
| TOA | top of the atmosphere |
| TRIMM | Tropical Rainfall Measuring Mission |
| TUBITAK | Turkish space technology research institute |
| UAS | unmanned aircraft system |
| UAV | unmanned aerial vehicle |
| UCAR | University Corporation for Atmospheric Research |
| UKSA | United Kingdom Space Agency |
| UQ | uncertainty quantification |
| UQTk | UQ Toolkit |
| USCG | United States Coast Guard |
| USGS | United States Geological Survey |
| USNORTHCOM | United States Northern Command |
| UV | ultraviolet |
| VIIRS | Visible Infrared Imager Radiometer Suite |
| VNIR | visible, near-infrared |
| WMO | World Meteorological Organization |
| $W\ m^{-2}$ | watts per square meter |
| WRF | Weather Research and Forecasting (Model) |

# 1 Introduction

The United States is an Arctic nation. Its 49th state, Alaska, has roughly 6,600 miles of coastline, more than 1,000 miles of which border the Arctic Ocean and lie above the Arctic Circle, starting at the native village of Kotzebue and stretching east to the Canadian Border near Kaktovik.[3] Much of this Arctic coastline borders the North Slope Borough, the equivalent to a "county" in the lower 48. For perspective, the North Slope Borough is larger than 39 of the 50 states but has a population of about 20,000 people.[4]

The United States is one of the eight voting members of the Arctic Council. Founded in 1996, the Arctic Council includes Finland, Sweden, Norway, Denmark, Iceland, Russia, Canada, and the United States. In 1991, the same eight states signed the Declaration and Strategy for Protection of the Arctic Environment. In 2015, the leadership of the Arctic Council will rotate from Canada to the United States (Kraska 2011).

It is important to understand and predict future states of the Arctic for many reasons. Accurate predictions based on numerical models for the future states of Earth systems are important for our energy future, for geopolitical reasons, and for national security. Although the Arctic contains a tiny fraction of the world's total population, its influence on the rest of the world, both in a geophysical and a geopolitical sense, is large.

It is useful to consider the Arctic as a system. That framework allows models to be developed that enable a focused analysis of specific parts of the Arctic or specific interdependencies, as in, for example, the response of sea-ice extent to increasing temperatures or downwelling long-wave radiation. An important caveat to this approach is recognition that the Arctic is a highly complex geophysical system and that models of the Arctic system are by necessity approximations to reality. The skill and accuracy of these approximations are improving, and results of these efforts can be useful for decision making and policy determination.

## 1.1 The Arctic System

The following quotes emphasize the systemic nature of the Arctic:

> The Arctic is a highly coupled system in which the individual components are strongly interdependent. Theoretically, a change in one variable in a part of the Arctic System might initiate a cascade of events throughout the system. These connections need to be understood and quantified in order to achieve a level of predictability. It is a complex adaptive subsystem of the Earth undergoing rapid change. Therefore, it offers a striking opportunity to serve as the basis for new environmental management tools that may be adapted and applied to other regions of the globe. (Roberts et al. 2010, 9)

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[3] Coastline data available at http://www.infoplease.com/ipa/A0001801.html (accessed on July 17, 2014).

[4] Personal communications between Alaska Representative Benjamin Nageak and Mark Ivey, July 10, 2014.

> Climate change will affect national security in the broadest sense, potentially affecting everything from economic growth to social stability. More narrowly, global climate change may spur sudden onset (i.e., hurricanes and floods) and slow onset (i.e., droughts and famines) disasters around the world, provoking humanitarian crises that will require military and other governmental responses. Climate change will alter the military operating environment, as well, requiring advanced planning and ongoing reevaluation.[5]

> The Arctic exerts a special influence over global climate… (Hassol 2014, 34)

Although the Arctic contains a tiny portion of the world's population, its importance to the rest of the world is large. The Arctic contains a significant fraction of the world's energy and mineral resources. Changes in the Arctic, both observed and projected, will have major impact on the security of nations that border the region.

The Arctic is an important element in the Earth's climate system, and understanding the Arctic begins with observations. The first Arctic observations are attributed to the ancient Greeks. Reports of a "curdled" ocean, found north of the British Isles, originate with the explorer and sailor Pytheas, a contemporary of Aristotle. The Vikings, noted for their sailing and navigational skills, explored and, for a time, settled regions above the Arctic Circle. They established settlements in Greenland that survived until the long cold period associated with the Little Ice Age (circa 1500 AD) forced them out. Native Arctic explorers, the Inupiat and Inuit people, used dog teams and sealskin boats to transit their traditional lands and explore northward, their observations of the Arctic environment becoming part of the collected, oral traditional knowledge that is essential to subsistence hunting and survival.

In an age of satellite remote sensing and regularly scheduled trans-polar air traffic, Arctic observations are still essential for forecasting next week's weather in the lower 48 states as well as for predicting future states of Arctic geophysical systems, such as permafrost beneath Prudhoe Bay and sea ice off Barrow. In addition, Earth system models and the data used to initialize and bound those models are important to decision makers around the globe.

Understanding changes in the Earth's climate is an important goal for organizations within Sandia and for core customers of Sandia. The Energy & Climate (EC) Program Management Unit (PMU) at Sandia National Laboratories (Sandia) has recognized the importance of improving our abilities to predict future states of the Arctic system. A fundamental research challenge recognized by EC PMU management is to develop an integrated measurement, modeling, and analysis capability of sufficient predictive power to address long-term energy and national-security issues for areas such as the Arctic. Current physical models have major weaknesses, e.g., inaccurate cloud physics, and inadequate understanding of atmospheric structure and land/sea/ice interface dynamics.

[5] Quote available at http://chicagoclimateonline.org/webresources/center-new-american-security-climate-change.

Furthermore, nonlinear Arctic feedback mechanisms that can drive dramatic, abrupt, and possibly irreversible changes in global climate are not well represented. Much more detailed and comprehensive data characterizing the Arctic atmosphere is needed to address these issues and could be obtained by combining existing and proposed land, airborne, and space-based measurement capabilities (ECIS SMU 2013).

With the Department of Energy's (DOE's) Office of Science, improvements in the current generation of Earth System Models are viewed as a high priority. A specific goal of the Climate and Environmental Sciences Division in the DOE's Office of Science, Office of Biological and Environmental Research (BER) is "to advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges" (Geernaert 2012).

## 1.2 Why the Arctic Is Important Now

The Arctic is receiving increased attention from the international scientific community, a variety of U.S. federal agencies, and foreign nations with geopolitical or economic interests in that region. Geophysical information from the Arctic, however, is sparse, intermittent, or of uncertain quality.

There are many reasons to be concerned with the changing Arctic:

1. Because of polar amplification, the Arctic is more sensitive to changes in atmospheric forcing, on average, than other regions of the globe.

2. Rapid changes in the Arctic have a disproportionate effect on the surrounding northern continents, home to a majority of Organization of Economic Co-Operation and Development (OECD) countries and the developed world.

3. The Arctic is one of the most data-sparse regions on Earth.

4. The Arctic has mineral wealth, water, fisheries, trade routes, and a strategic location.

5. Nations with Arctic borders depend on a natural defensive barrier against potential aggressors.

6. The Arctic contains human and natural resources that are vulnerable to change.

The Arctic atmosphere is a major component of the extraordinarily complex Arctic system, which is part of the larger Earth system. The Arctic thus cannot be analyzed in isolation. The Arctic is one of the least understood but most important climate subsystems in the Earth climate system.

## 1.3 Definitions of “the Arctic”

The defined boundaries of “the Arctic” can vary depending on application and purpose. Scientists commonly define the Arctic as the region north of the Arctic Circle, an imaginary line that circles the globe at 66°32" N (NSIDC 2014). Other boundaries that are used to define the Arctic region include permafrost zones, tree lines, sea-ice boundaries, temperature boundaries, geo-political boundaries, and military operating unit boundaries. Three definitions of the Arctic are shown in the map in Figure 1-1.


**Figure 1-1.** Three definitions of the Arctic: the tree line, the 10°C isotherm, and the Arctic Circle at 66°32" N [Source: NSIDC 2014].

As explained by the National Snow and Ice Data Center (NSIDC) (2014) on their website, the tree line is colored green; the isotherm line is colored red; and the dashed line around the Arctic Circle is colored blue. The temperature of 10°C for the isotherm boundary is equivalent to 50°F. As can be seen in the above map, the Arctic is very large. The Smithsonian (2014) reports on its Arctic Studies Center website that the Arctic is almost equal in size to the entire North American continent.

On the Arctic theme page of its website, the National Oceanic and Atmospheric Administration (NOAA) (2014) offers some interesting perspectives on daylight, darkness, and seasons at the North Pole. At the Spring Equinox on approximately March 21, the sun rises at the North Pole and rises higher in the sky each subsequent day until it reaches a maximum height at the Summer Solstice, approximately June 21. Throughout the entire summer, the North Pole is in full sunlight all day long. On approximately September 21, the Autumn Equinox, the sun sinks below the horizon, leaving the North Pole in twilight until early October. Afterwards, the North Pole is in full darkness for the winter. The darkest time of the year at the North Pole is the Winter Solstice, approximately December 21. This darkness will last until the beginning of dawn in early March.

## 1.4 Purpose and Scope of This Study

The initial purpose of this study was to address how the United States should prioritize atmospheric measurement resources in the Arctic to better support anticipated mission-related needs of the U.S. Department of Defense (DOD) in the Arctic as well as the current, high-priority needs of the Arctic scientific community. Once we started into our efforts to characterize the Arctic, particularly the Arctic atmosphere, as a system, we found the problem to be complex, with extensive work by other organizations in this area and new technical work that had bearing on the problem. To limit the scope to something practical, we concentrated on identifying capabilities at Sandia that can be used to address the initial question, on high-level analyses that will identify areas where future deeper investigations are likely to yield significant results, and on identification of potentially high-payoff sources of information and methods that could be applied to the problem.

## 1.5 Technical Approach

Creation of the data and analysis products needed by the scientific, defense, and intelligence communities requires that a wide variety of Arctic atmospheric data sources be merged. Future investments in atmospheric measurement, data analysis, and modeling capabilities by the DOE, the Department of Defense, NOAA, Sandia, other institutions, or U.S. federal agencies with Arctic interests can be guided by a systems analysis study of current gaps and needs for information.

To conduct the systems analysis study, Sandia assembled a multidisciplinary team with broad expertise in climate and Arctic studies and analysis. Members of the project team took responsibility for particular task areas, and the team met regularly over a three-month period to present and share information and results. For most of the topical areas addressed in this report, team members performed a review of the literature as well as any relevant data sets, data sources, and models in their topical area; communicated with other subject matter experts as necessary within and outside Sandia; developed recommendations and/or solutions, including architectures, metrics, and specific data products where appropriate, that Sandia could provide to address the needs and gaps in Arctic data identified during the initial research activity; and documented the results of their individual analyses in this report.

## 1.6 Concepts and Terms

In the table below, we have included definitions for several concepts and terms that are used in this report to make the work more accessible to a general audience. These definitions are for the most part taken verbatim from the sources cited.

| Concept or Term | Definition |
|---|---|
| **albedo** | The percentage of incoming radiation reflected off a surface. An albedo of 1 means that 100% of incoming radiation is reflected (no radiation is absorbed); an albedo of 0 means that 0% of incoming radiation is reflected (all radiation is absorbed).[6] |
| **Arctic amplification** | The degree of warming observed in the Arctic is greater than that observed in the rest of the Northern Hemisphere.[7] |
| **Arctic oscillation** | Atmospheric pressure fluctuations (positive and negative phases) between the polar and middle latitudes (above 45° North) that strengthen and weaken the winds circulating counterclockwise from the surface to the lower stratosphere around the Arctic and, as a result, modulate the severity of the winter weather over most Northern Hemisphere middle and high latitudes. Also known as the Northern Hemisphere annular mode.[8] |
| **permafrost** | A thick subsurface layer of soil that remains frozen throughout the year, occurring chiefly in polar regions.[9] |
| **radiative forcing** | As defined by the Intergovernmental Panel on Climate Change (IPCC), radiative forcing is a measure of the influence a given climatic factor has on the amount of |

[6] ECOCEM, s.v. "albedo," accessed May 29, 2014, http://www.ecocem.ie/environmental,albedo.htm.
[7] Climate Hot Map, s.v. "Arctic amplification," accessed May 29, 2014, http://www.climatehotmap.org/global-warming-locations/arctic-amplification-chukchi-sea.html.
[8] The Free Dictionary, s.v. "Arctic Oscillation," accessed May 29, 2014, http://encyclopedia2.thefreedictionary.com/Arctic+Oscillation.
[9] Oxford Dictionaries, s.v. "permafrost," accessed May 29, 2014, http://www.oxforddictionaries.com/us/definition/american_english/permafrost.

| Concept or Term | Definition |
|---|---|
| | downward-directed radiant energy impinging upon Earth's surface. Climatic factors are divided between those caused primarily by human activity (such as greenhouse gas emissions and aerosol emissions) and those caused by natural forces (such as solar irradiance); then, for each factor, so-called forcing values are calculated for the time period between 1750 and the present day. "Positive forcing" is exerted by climatic factors that contribute to the warming of Earth's surface, whereas "negative forcing" is exerted by factors that cool Earth's surface.[10] |
| **sea ice** | Any form of ice found at sea that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice less than one year old is called *first-year ice*. *Multi-year ice* is sea ice that has survived at least one summer melt season.[11] |
| **sea ice extent** | The latitudinal ocean area that is covered by ice at any given time. Maximum extent occurs in late winter/early spring while minimum extent occurs in late summer/early fall.[12] |
| **sea level rise** | An increase in the mean level of the ocean.[13] |
| **uncertainty** | A probabilistic measure for the lack of knowledge about the value of a variable, such as cost or precipitation (Backus et al. 2010). |

## 1.7 Document Overview

In addition to the executive summary, this report consists of 10 sections and 4 appendices. Each of the 10 sections has its own list of references. Highlights of these sections follow:

- Section 1 has introduced characteristics of the Arctic, explained why and how the report was prepared, and defined relevant terms.

- In Section 2, we examine the needs and interests of defense and scientific communities for Arctic data.

[10] Encyclopaedia Britannica, s.v. "radiative forcing," accessed May 29, 2014, http://www.britannica.com/EBchecked/topic/235402/global-warming/274821/Radiative-forcing.
[11] Climate Hot Map, s.v. "sea ice," accessed May 29, 2014, http://www.climatehotmap.org/global-warming-glossary/s.html.
[12] Sila, s.v. "sea ice extent," accessed May 29, 2014, http://nature.ca/sila/glssry_e.cfm#S.
[13] Climate Hot Map, s.v. "sea level rise," accessed May 29, 2014, http://www.climatehotmap.org/global-warming-glossary/s.html.

- Concerns and approaches to collecting and integrating Arctic data are discussed in Section 3.

- Section 4 describes an assessment we conducted of satellite data and their derived products. For this assessment, four mission areas were defined to evaluate the value of satellite sensor data.

- Section 5 argues that unmanned aircraft systems (UASs) are the best option for safely taking measurements in the Arctic.

- Section 6 discusses why measurements taken in the Arctic exhibit considerable uncertainty and proposes, by demonstration, the coupling of data acquisition and numerical analysis to reduce measurement uncertainty.

- In Section 7, we explore Sandia's capabilities to meet the needs and challenges encountered when performing uncertainty analysis for climate models, a process that is also applicable to Arctic models.

- Section 8 surveys data needs for sea-ice simulations and assesses problems with existing reanalysis products.

- Through Section 9, we learn about the history of MEDEA, a program in the intelligence community that is concerned with global environmental change. The contents of a variety of MEDEA documents provided to Sandia are summarized and/or outlined.

- A synthesis of Sandia's capabilities to meet the needs and gaps discovered through this systems analysis study is provided in Section 10.

The contents of the four appendices in general supplement several of the individual sections. Appendix A contains a summary of current and future satellite data compiled as part of the assessment described in Section 4. Appendix B has illustrations of several UASs, serving as a companion to Section 5. A list of previous UAS operations in the Arctic is available in Appendix C. Appendix D features part of a systems study shared with the study team by the operational manager of the Arctic Collaborative Environment (ACE), which is sponsored by the U.S. European Command (EUCOM) and mentioned in several of the document sections.

## 1.8 References

Backus, G., T. Lowry, D. Warren, M. Ehlen, G. Klise, V. Loose, L. Malczynski, R. Reinert, K. Stamber, V. Tidwell, V. Vargas, and A. Zagonel. (2010). *Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies among U.S. States*. SAND 2010-2052. Albuquerque, NM: Sandia National Laboratories. http://prod.sandia.gov/techlib/access-control.cgi/2010/102052.pdf (accessed on May 31, 2014).

ECIS SMU (Energy, Climate, and Infrastructure Security Strategic Management Unit). (January 2013). A Climate Mission Challenge. [The name of the ECIS SMU was subsequently changed to Energy & Climate Program Management Unit (EC PMU), which is used throughout this document.]

Geernaert, G. (2012). "The Energy-Climate Nexus." A presentation by the director of the Climate and Environmental Sciences Division, DOE/SC/BER in August 2012 at Sandia National Laboratories, Albuquerque, NM. [See also http://science.energy.gov/~/media/ber/berac/pdf/20120216Meeting/Geernaert_CESD_Feb2012.pdf, which represents a PowerPoint presentation given earlier in the same year that includes the quoted material on page 5 (accessed on May 28, 2014)].

Hassol, S. J. (2004*). Impacts of a Warming Arctic, the Arctic Climate Impact Assessment*. Cambridge, UK: Cambridge University Press.

Kraska, J., ed. (2011). *Arctic Security in an Age of Climate Change*. Cambridge: Cambridge University Press.

NOAA (National Oceanic and Atmospheric Administration). (2014). "Daylight, Darkness and Changing of the Seasons at the North Pole." http://www.arctic.noaa.gov/gallery_np_seasons.html (accessed on May 30, 2014).

NSIDC (National Snow and Ice Data Center). (2014). "All about Arctic Climatology and Meteorology." https://nsidc.org/cryosphere/arctic-meteorology/arctic.html (accessed on May 29, 2014).

Roberts, A., J. Cassano, R. Doscer, L. Hinzman, M. Holland, M. Mitsudera, A. Sumi, and J. E. Walsh. (2010). *A Science Plan for Regional Arctic System Modeling*. IARCTP10-0001. Fairbanks, AL: International Arctic Research Center. [This is a report by the Arctic Research Community for the National Science Foundation Office of Polar Programs.]

Smithsonian (Smithsonian National Museum of Natural History). (2014). "Resources / Frequently Asked Questions." Arctic Sciences Center. http://www.mnh.si.edu/arctic/html/resources_faq.html (accessed on May 31, 2014).

# 2 Defense and Scientific Community Needs and Interests in the Arctic

The Arctic is receiving increased attention nationally and internationally as rapid changes in climate reduce its ice cap and make the region more accessible to human activity. In Section 2, we examine unique as well as common needs and interests of the defense and scientific communities in the Arctic. We highlight Sandia's past efforts to deal with the identified areas of concern as well as our capabilities to collaborate with organizations in the communities to address current and future challenges in the Arctic.

## 2.1 Stated Needs of U.S. Northern Command and U.S. Coast Guard

### 2.1.1 Background

The rapid reduction of ice cover in the summers and the reduced ice thickness in the winter have encouraged the growth of both licit (Emmerson and Lahn 2012; Astill 2012) and illicit (Carafano et al. 2011) economic activity in the Arctic. Because of the natural resources and shipping opportunities the Arctic affords, many nations are vying for access to the region (Sulimina 2012). Some indigenous groups and ecological organizations, however, oppose the rapid development of the Arctic (The Canadian Press 2010; Astill 2012). With the accelerated human activity in the Arctic region, the United States Coast Guard (USCG) envisions playing an enlarged role in the Arctic (Wolf and Klimasinska 2012; Papp 2012), as does the Department of Defense (DOD) (Winnefeld 2011; Jacoby 2012). The United States Northern Command (USNORTHCOM) is the primary organization in the DOD responsible for U.S. security in the Arctic. Several reports provide background on the primary Arctic issues of search and rescue, intervention, and defense (Burke et al. 2008; Carmen Parthemore, and Rogers 2010; Huebert et al. 2012).

Sandia has produced several studies indicating the national security implications for the DOD and the USCG of an opening Arctic (Romig, Backus, and Baker 2011). These studies focus on the physical phenomena that relate to human risk (Boslough et al. 2008; Boslough, Backus, and Carr 2009) and the economic activity that places more people within the Arctic environment (Backus and Strickland 2008; Rumpf, Backus, and Millick 2009). While there is minimal concern that interactions among the actual Arctic nations (Russia, Norway, Canada, Denmark, and the United States) will lead to conflict, there is less assurance that the operations of non-Arctic nations within the Arctic will avoid causing geopolitical tensions (Backus 2012; Huebert 2012; Morosov 2012; Backus, Millick, and Rumpf 2011). Sandia was also a key contributor to the *High Latitude Study Mission Analysis Report* produced for the USCG to evaluate resource needs (ABS Consulting 2010), as summarized by the U.S. Government Accountability Office (GAO) in GAO 2012.

### 2.1.2 Capability Gaps

As described below, both the DOD and the USCG recognize several areas where there are gaps in their ability to carry out their perceived missions in the Arctic.

The DOD has identified nine areas in the Arctic where they believe they have R&D, strategic, and operational gaps (DOD 2011):

- Maritime domain awareness
- Search and rescue
- Regional security cooperation
- Humanitarian assistance/Disaster response/Defense support of civil authorities
- Maritime security
- Power projection
- Sea control
- Strategic deterrence
- Air and missile defense

For the USCG, there are 11 areas noted as missions,[14] with each area limited by the resources the USCG has available:

- Ports, waterways, and coastal security
- Drug interdiction
- Aids to navigation
- Search and rescue
- Living marine resources
- Marine safety
- Defense readiness
- Migrant interdiction
- Marine environmental protection
- Ice operations
- Other law enforcement

The USCG and USNORTHCOM prioritized these items into four gap focus-areas for the Arctic (GAO 2012):

1. Communications
2. Maritime domain awareness
3. Search and rescue
4. Environmental observation and forecasting

The GAO (2012) report additionally notes an underlying foundational gap for the infrastructure available to carry out missions in the Arctic. The GAO (2012) report provides an excellent summary of the key Arctic concerns. Each of these gaps is discussed below.

[14] See http://www.uscg.mil/top/missions/.

**Communications.** The atmospheric conditions make communication difficult in the Arctic. More importantly, the Arctic has a sparse and limited number of installations that allow defense-quality, high-speed communications. Although USNORTHCOM believes it understands the technical issues for solving the communication issues, the cost and lead-time for such a sophisticated system is problematical if operation is required in the near term. Sandia and USNORTHCOM have considered methods that allow the use of (1) existing low-bandwidth commercial communications, (2) satellites, and (3) the modest modification of existing radar installations to fill the communication gap in the interim (Moore 2012). The USCG is less farther along in considering communication issues, with its initial efforts focused on procuring icebreaker capabilities (Neffenger 2012; GAO 2010, 2011). As of 2014, the USCG's polar feet consisted of one 399-foot polar icebreaker named Polar Star, one 420-foot polar icebreaker named Healy, and some ice-capable tugs and tenders (USCG 2014).

**Maritime domain awareness**. This broad, key area of concern for both DOD and the USCG is an area where Sandia can provide much-needed capabilities. First, there is a need to understand present and forecasted atmospheric and ice conditions, both via sensing and computer modeling. Second, there are basic scientific needs to understand physical processes within the Arctic for informing sensor requirements and computer model algorithms/parameterizations. The USCG and DOD want to be able to monitor continuously land and sea conditions for human activity and for guiding field operations, as need dictates. Sandia's expertise in terrestrial and space-based sensing, in Divisions 1000, 5000, and 6000, would be useful to DOD and the USCG. Progressive hedging methods can be used to determine the maximal benefit of additional sensing capabilities for domain awareness, navigation, and weather/ice forecasting, given budgets, timing, and technological constraints.

**Search and rescue.** Although search and rescue is a major component of the USCG's mission in the Arctic, it is not a not a force-sizing or force-shaping mission for the agency. The DOD must assist the USCG in search and rescue activities to the best of its ability, if requested. The maritime domain awareness capabilities of Sandia, as noted above, would be useful to USCG planning. The Sandia work often emphasizes uncertainty considerations that relate, for example, to adequate weather and ice forecasts, adequacy of response assets, and knowledge of human activity within the Arctic. Monitoring stations within the Arctic are very expensive and will be of limited number in the foreseeable future. Sandia's experimentation with small UASs (unmanned aircraft systems) flying out of Oliktok Point, Alaska, could provide information that leads to a dramatic reduction in the number of monitoring stations necessary for making weather and ice forecasts that have adequate spatial and temporal coverage. Sandia's uncertainty methods could be used to determine what minimal additional information would most improve the maritime domain awareness needed to perform USCG and DOD missions successfully. The UASs could then be sent to a peripheral location where the added monitoring capability and information quality best support the intelligence needs of a specific DOD/NORTHCOM operation. The UASs could also drop sondes to maintain locational awareness as a mission executes. See Section 5 of this report for a discussion of UASs.

USNORTHCOM is concerned with search and rescue operations related to Operation Noble Eagle, a DoD-wide enterprise that supports homeland security following the 9/11 terrorist attacks. Sandia can help with uncertainty quantification to determine the most likely geographical locations where USNORTHCOM would need to respond. Although classified information on equipment reliability and the history of Noble Eagle flight paths would be required, Sandia could perform Bayesian statistical analyses to indicate where rescue missions for downed Nobel Eagles would most likely occur in the future (and for the locations with lower probabilities as well). Such knowledge would aid rescue planning and decision making about preparedness.

**Environmental observation and forecasting.** Maritime domain awareness is broadly concerned with operational conditions, but its scientific foundation is based on environmental observation and forecasting. The Sandia efforts in Barrow and Oliktok for the Atmospheric Radiation Measurement (ARM) program could provide many valuable avenues for enhanced observations supporting improved forecast modeling. The funding and timing of additional monitoring capabilities present a major challenge to the DOD and the USCG. Sandia can help determine the minimum number of land-based or ice-based monitoring stations needed for providing useful weather forecasts for USNORTHCOM and USCG operations. There are two aspects to this minimization. First, there is evidence that, for example, adding a single station at a specific location can greatly improve the forecasting ability. A key question is whether it is possible to determine the optimal locational placement of a new station to enhance information quality and quantity, and to quantify the benefit of doing so. Second, it is possible that a sparse set of stations that feed information to complementary computer models can provide reliable coverage with high resolution throughout the Arctic. Such a system of monitoring stations and computer models could potentially supply weather specifics for small local sites and along the path from the current position of response assets to the location of the monitoring station or to the theater of operation. The critical question is, "What is the minimal modification to the existing monitoring stations that would allow the required spatial and temporal forecast accuracy?" By modifying the placement criteria for atmospheric monitoring to include information relevant to ice modeling, Sandia could improve the forecasting of ice flow/conditions in the hourly-to-weekly/monthly timeframe for missions dependent on ice-obstruction information.

**Infrastructure:** There is little infrastructure available within the Arctic Circle to maintain military and USCG operations. Usable ports and bases are hundreds of miles away from the theater of operations. New ports, bases, and supply stations are limited by logistics, costs, and changing environmental conditions such as storminess, icing, permafrost melting, and water availability. Sandia can assist in the assessment of infrastructure vulnerability, resilience, and environmental constraints with its expertise in Division 6000.

## 2.2 2009 Arctic Roadmap

When we began this systems study in 2012, only the U.S. Navy appeared to have produced a roadmap that delineates its specific needs in the Arctic. One section in *U.S.*

*Navy Arctic Roadmap* (Navy 2009) that particularly resonates with Sandia's capabilities is "Environmental Assessment and Prediction." Its stated overall objective is as follows:

> Roadmap Objective 5: To provide Navy leadership and decision makers a comprehensive understanding of the current and predicted Arctic physical environment on tactical, operational, and strategic scales in time and space. The science-based timeline developed through this focus area will inform accomplishment of the action items and objectives within the other focus areas of this roadmap.

The headings for the action items in Navy 2009 that relate to Sandia are noted below:

- Action Item 5.2: Initiate a *Capabilities Based Assessment* (CBA) of the Navy's Arctic observing, mapping, and environmental prediction capabilities in the Arctic.
- Action Item 5.3: Continue SCICEX accommodation missions (SAMs).
- Action Item 5.4: Identify *Science and Technology Needs for Arctic Assessment and Prediction.*
- Action Item 5.5: Develop cooperative partnerships for environmental observation and mapping with interagency and international Arctic stakeholders.
- Action Item 5.6: Establish an interagency partnership to develop and implement a Next Generation Numerical Environmental Prediction (NEP) capability for coupled air-ocean-ice modeling.
- Action Item 5.11: Increase operations of unmanned systems for Arctic data collection, monitoring, and research.

Navy (2009) explains the technical considerations associated with each item.

Note that the roadmap published in 2009 was updated in 2014. See Section 2.7 of this report for further details on the newer document.

## 2.3 Other Scientific Initiatives

The weather forecasting and navigation needs of the Arctic have also led to Executive Order 13580, [15] which defines several areas where the National Oceanic and Atmospheric Administration (NOAA) and the Department of Interior (DOI 2012) are to pursue science relevant to the Arctic.[16]. The ARM program, along with all the Sandia sensing and modeling expertise noted above, could contribute to these scientific efforts.

[15] http://www.whitehouse.gov/the-press-office/2011/07/12/executive-order-13580-interagency-working-group-coordination-domestic-en

[16] http://summitcountyvoice.com/2012/08/02/feds-plan-arctic-energy-science-push/

## 2.4 Funding Considerations

This section focuses mostly on USNORTHCOM and USCG interactions. Although USNORTHCOM has the primary responsibility for Arctic operations, the U.S. European Command (EUCOM) is responsible for the periphery of the Arctic region that encompasses European and Asian interests. Although scientific endeavors can be directly funded by the USCG, EUCOM and USNORTHCOM must act through the service branches, such as the U.S. Navy, by recommending the funding of projects. Sandia needs to work with USNORTHCOM and EUCOM to engage the service branches in promoting the funding of scientific and engineering research for the Arctic.

## 2.5 EUCOM and AFRICOM Science and Technology Needs for Arctic Data

EUCOM and U. S. Africa Command (AFRICOM) are engaged in specialized topical areas related to climate change. In their 2012 conference in Stuttgart Germany, which several Sandians attended, EUCCOM's sponsorship (with USNORTHCOM) of the Arctic Collaborative Environment (ACE) was discussed (DOD 2012; The Patuxnet Partnership 2012). ACE is a web-based tool that is used by Alaskan Command/Joint Task Force-Alaska (ALCOM/JTF-AK) for environmental understanding and coordinating responses to regional events.[17]

One way to advance Sandia's ability to support Air Force missions is to make the atmospheric measurements taken at the DOE ARM facilities available to ACE users. Discussions are under way for importing these atmospheric measurement data from the North Slope into ACE.

## 2.6 Arctic Research Programs and Organization Reference

The list below is from the NOAA Arctic theme page titled "Research programs and organizations." The entities in the list are programs and projects that are focused on the Arctic.[18]

- International Arctic Science Committee (IASC)
- International Arctic Systems for Observing the Atmosphere (IASOA)
- Sustaining Arctic Observing Networks (SAON)
- Arctic Council Home Page - high-level intergovernmental forum
- NOAA's Arctic Vision and Strategy & NOAA News article

[17] Email correspondence between Stephen Spehn, operational manager for the ACE Joint Capability Technology Demonstration (JCTD) and deputy science advisor at EUCOM, and Mark Ivey, manager of the DOE Atmospheric Radiation Measurement facilities in Alaska, May 30, 2014.

[18] See http://www.arctic.noaa.gov/research.html, where the entities in the list are linked. The list was accessed on June 24, 2014.

- New! NOAA Sea Ice Forecasting Workshop Summary, 19-21 Sept 2011, Anchorage, AK
- NOAA Arctic Research Program
- Arctic Research Institutes at the University of Alaska Fairbanks, including the International Arctic Research Institute and Geophysical Institute
- Tiksi Arctic Observatory
- Bering Strait and Pacific Arctic Dynamics (UW)
- Arctic Weather Support
- PAG - Pacific Arctic Group
- U.S. Navy Submarine Arctic Science Program (SCICEX) - from the US Navy
- The Freshwater Switchyard of the Arctic Ocean - from the University of Washington Polar Science Center
- Study of Environmental Arctic Change (SEARCH)
- NSF Arctic Sciences Section of the NSF Office of Polar Programs
- RUSALCA - Russian-American Long-term Census of the Arctic
- International Arctic Buoy Program from U of Washington
- Program in Arctic Regional climate Assessment (PARCA) from U of Colorado
- Arctic Research Consortium of the United States (ARCUS)
- Arctic Monitoring and Assessment Program (AMAP)
- Center for Disease Control's Arctic Investigations Program
- CRDF - U.S - Russian cooperation to promote scientific and technical collaboration between the U.S. and the former Soviet Union
- Arctic Regional Ocean Observing System - European institutions working actively with ocean observation and modelling systems for the Arctic Ocean and adjacent seas - from Arctic ROOS
- Arctic TRANSFORM - an international project supporting adaptation in the marine Arctic environment
- United Nations Climate Change Conference (COP-15) in Copenhagen, December 7-18, 2009.
- U.S. Center website | US Dept of Commerce website
- International Polar Year in 2007-2008 | NOAA IPY Activities | First IPY in 1881-1884

On its Arctic theme page, NOAA also has a list of Arctic data sets.[19]

[19] See http://www.arctic.noaa.gov/data_center.html for a list of Arctic data sets.

## 2.7 Recent Arctic Strategy and Planning Documents

A number of important strategy and planning documents about the Arctic were published in 2013 and 2014 by the federal government, indicating how concerns about the Arctic have been elevated to national prominence since we began this Arctic systems study in 2012 and how coordination is being fostered among agencies. Following are brief synopses of several key strategy and planning documents.

**IARPC research plan.** In February 2013, the Interagency Arctic Research Policy Committee (IARPC) produced its required five-year plan, *Arctic Research Plan FY2013–2017,* which was released by the National Science and Technology Council (NSTC) of the Executive Office of the President. In the plan, the IARPC identifies seven overlapping research areas that compose the national policy for Arctic research:

1. Sea ice and marine ecosystems
2. Terrestrial ice and ecosystems
3. Atmospheric studies of surface heat, energy, and mass balances
4. Observing systems
5. Regional climate models
6. Adaptation tools for sustaining communities
7. Human health

Implementation of research activities in these areas depends on effective federal coordination, as called out in the plan (NSTC 2013). The first five areas listed also relate to Sandia's research interests and capabilities as discussed throughout this report.

**National strategy.** In May 2013, *National Strategy for the Arctic Region* (The White House 2013) was published. The document describes the U.S. government's strategic priorities for the Arctic region as three lines of effort: (1) advance U.S. security interests, (2) pursue responsible Arctic region stewardship, and (3) strengthen international cooperation. The second line of effort explicitly calls out several key components of the Arctic requiring urgent attention:

> land ice and its role in changing sea level; sea-ice and its role in global climate, fostering biodiversity, and supporting Arctic peoples, and the warming permafrost and its effects on infrastructure and climate. (The White House, 2013, 8)

**USCG strategy.** Also in May 2013, the USCG (2013) published *United States Coast Guard Arctic Strategy*, acknowledging guidance by the president of the United States as well as from several important documents, including *National Strategy for the Arctic Region*. In the report, the USCG outlined the "ends, ways, and means for achieving strategic objectives in the next 10 years." The strategic objectives for the USCG are (1) improving awareness, (2) modernizing governance, and (3) broadening partnerships.

For the improving awareness objective, the USCG emphasizes that it is necessary to collect and share more maritime data and also to cooperate in the analysis and sharing of that information. Proper infrastructure, the USCG notes, is needed to sense, collect, fuse, analyze, and disseminate information. Regarding the broadening partnerships objective, collaboration with academia and nongovernmental partners is necessary, the USCG says, to "incentivize Arctic research and expand the base of Arctic-related literature" (p. 22).

A concise listing of the USCG's 2014 Arctic priorities can be found in Haun 2014.

**DOD strategy.** In November 2013, the DOD (2013) published its *Arctic Strategy*. The DOD's strategy describes how the department will support the three lines of effort presented in *National Strategy for the Arctic Region*. The DOD identifies the following ways in which it will accomplish its objectives:

- Exercise sovereignty and protect the homeland
- Engage public and private sector partners to improve domain awareness in the Arctic
- Preserve freedom of the seas in the Arctic
- Evolve Arctic infrastructure and capabilities consistent with changing conditions
- Support existing agreements with allies and partners while pursuing new ones to build confidence with key regional partners
- Provide support to civil authorities, as directed
- Partner with other departments and agencies and nations to support human and environmental safety
- Support the development of the Arctic Council and other international institutions that promote regional cooperation and the rule of law

As can be seen in the strategies of other defense-related agencies, some of these DOD approaches are held in common.

**Updated Navy roadmap.** In February 2014, the U.S. Navy released its updated Arctic roadmap for 2014 to 2030. The roadmap supports both national and DOD aims, as set forth in *National Strategy for the Arctic Region* and the DOD's *Arctic Strategy*. The roadmap provides direction for U.S. naval operations in the near term (present to 2020), near term (2020 to 2030), and far term (beyond 2030), in anticipation of the impacts of climate change (Navy 2014).

A significant part of the roadmap is Appendix 3, which is a highly detailed implementation plan. Khalifa (2014) describes Appendix 3 in this way: "A painstaking grid of detailed action items, Appendix 3 serves as a checklist for, among other things, bolstering the predictive capabilities of meteorological and oceanic conditions and how they will impact naval operations in the near, mid and long term." (p. 66)

**NOAA action plan.** In April 2014, NOAA (2014) released *NOAA's Arctic Action Plan*. The six strategic goals in the plan are aligned with the three levels of effort in *National Strategy for the Arctic Region*, as indicated below.

| NOAA's Strategic Goals | National Strategy for the Arctic Region |
|---|---|
| 1. Forecast sea ice | Advance U.S. security interests |
| 2. Improve weather and water forecasts and warnings | |
| 3. Strengthen foundational science to understand and detect Arctic climate and ecosystem changes | Pursue responsible Arctic region stewardship |
| 4. Improve stewardship and management of ocean and coastal resources in the Arctic | |
| 5. Advance resilient and healthy Arctic communities and economies | Strengthen international cooperation |
| 6. Enhance international and national partnerships | |

A list of NOAA's milestones for 2014 and 2015 associated with these goals is provided in the appendix of *NOAA's Arctic Action Plan*.

## 2.8 References


ABS Consulting. (2010). *High Latitude Region Mission Analysis.* Houston, TX. [This report was prepared for the United States Coast Guard with Sandia National Laboratories.]

Astill, J. (2012). "The Melting North." *The Economist*, June 16. Special Report: The Arctic. http://www.economist.com/node/21556798 (accessed on March 28, 2014).

Backus, G. (2012). "Arctic 2030: What Are the Consequences of Climate Change? The US Response." *Bulletin of the Atomic Scientists* 68, no. 4: 9–16.

Backus, G., J. Millick, and R. Rumpf. (2011). "The National Security Importance of the Arctic Will Change Even If the Climate Doesn't." *Common Defense Quarterly*, Fall: 5–7.

Backus, G. A., and J. H. Strickland. (2008). *Climate-Derived Tensions in Arctic Security*. SAND2008-6342. Albuquerque, NM: Sandia National Laboratories. https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/Tensions_in_Arctic_SecurityFinal.pdf (accessed on July 2, 2014).

Boslough, M., G. Backus, and M. Carr. (2009). *Global Situational Awareness and Early Warning of High-Consequence Climate Change*. SAND2009-4702. Albuquerque, NM: Sandia National Laboratories. https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/SAND2009_4702_gsa.pdf (accessed on July 2, 2014).

Boslough, M. B. E., M. Ivey, M. A. Taylor, B. D. Zak, and G. A. Backus. (2008). *The Arctic as a Test Case for an Assessment of Climate Impacts on National Security*.

SAND2008-7006. Albuquerque, NM: Sandia National Laboratories. https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/SAND2009_4702_gsa.pdf (accessed on July 2, 2014).

Burke, S. E., J. Gulledge, M. Horowitz, C. Parthemore, and N. Patel. (2008). *Uncharted Waters: The U.S. Navy and Navigating Climate Change*. Washington, DC: Center for a New American Security.

Carafano, J., A. Cohen, S. McNamara, and R. Weitz. (2011). "EUCOM Should Lead U.S. Combatant Commands in Defense of National Interests in the Arctic." *Backgrounder*, no. 2536. The Heritage Foundation. http://thf_media.s3.amazonaws.com/2011/pdf/bg2536.pdf (accessed on March 28, 2014).

Carmen, H. E., C. Parthemore, and W. Rogers. (2010). *Broadening Horizons: Climate Change and US Armed Forces*. Washington, DC: Center for a New American Security.

DOD (U.S. Department of Defense). (2011). *Report to Congress on Arctic Operations and the Northwest Passage*. Washington DC: Department of Defense. www.defense.gov/pubs/pdfs/Tab_A_Arctic_Report_Public.pdf (accessed on March 28, 2014).

DOD. (2012). "Joint Capability Technology Demonstration (JCD) Program Conference Preserving Strategic Partnerships and Preparing for Transnational Threats." June 25–29, Stuttgart, Germany.

DOD. (2013). *Arctic Strategy*. Washington DC: Department of Defense.

DOI (U.S. Department of the Interior). (2012). "Addressing Science and Planning Needs for Energy and Other/Development Activities in Alaska." Memorandum, Department of Interior, June 30. Washington, DC: Department of the Interior. http://www.doi.gov/news/pressreleases/loader.cfm?csModule=security/getfile&pageid=311370 (accessed on March 28, 2014).

Emmerson C., and G. Lahn. (2012). *Arctic Opening: Opportunity and Risk in the High North*. London, UK: Lloyd's and Chatham House. http://www.chathamhouse.org/sites/default/files/public/Research/Energy,%20Environment%20and%20Development/0412arctic.pdf (accessed on March 28, 2014).

GAO (U.S. Government Accountability Office). (2010). *Coast Guard Efforts to Identify Arctic Requirements Are Ongoing, but More Communication about Agency Planning Efforts Would Be Beneficial*. GAO-10-870. Washington, DC: United States Government Accountability Office.

GAO. (2011). *Observations on Arctic Requirements, Icebreakers, and Coordination with Stakeholders*. GAO-12-254T. Washington, DC: United States Government Accountability Office.

GAO. (2012). *DOD Addressed Many Specified Reporting Elements in Its 2011 Arctic Report but Should Take Steps to Meet Near- and Long-term Needs*. GAO-12-180. Washington, DC: United States Government Accountability Office. http://www.gao.gov/assets/590/587676.pdf (accessed on March 29, 2014).

Haun, E. (2014). "US Coast Guard Outlines Arctic Priorities." *Maritime Reporter and Marine News Magazines Online*. http://www.marinelink.com/news/priorities-outlines371451.aspx (accessed on June 23, 2014).

Huebert, R. (2012). "Arctic 2030: What Are the Consequences of Climate Change? The Canadian Response." *Bulletin of the Atomic Scientists* 68, no. 4: 17–21.

Huebert, R., H. Exner-Pirot, A. Lajeunesse, and J. Gulledge. (2012). "Climate Change & International Security: The Arctic as a Bellwether." Arlington, VA: Center for Climate and Energy Solutions. http://www.c2es.org/docUploads/arctic-security-report.pdf (accessed on March 29, 2014).

Jacoby C. (2012). "Statement Of General Charles H. Jacoby, Jr., United States Army Commander United States Northern Command And North American Aerospace Defense Command Before The Senate Armed Services Committee, 13 March 2012." Washington, DC: Senate Armed Services Committee, U.S. Senate, http://www.airforcemag.com/SiteCollectionDocuments/Reports/2012/March2012/Day16/031312jacoby.pdf (accessed on July 15, 2014).

Khalifa, D. R. (2014). "Arctic Plan." *Seapower* 57, no. 4: 66–70. http://www.seapower-digital.com/seapower/april_2014/?pg=68#pg68 (accessed on July 2, 2014).

Moore, H. (2012). Communications between Dr. Hal Moore, Division Chief, NORAD-USNORTHCOM Maritime Science and Technology Directorate and George Backus of Sandia National Laboratories, August 2011 through August 2012.

Morozov, Y. (2012) "Arctic 2030: What Are the Consequences of Climate Change? The Russian Response." *Bulletin of the Atomic Scientists* 68, no. 4: 22–27.

Navy (U.S. Department of the Navy). (2009). *U.S. Navy Arctic Roadmap*. Washington DC: U.S. Department of Defense, Department of the Navy, Vice Chief of Naval Operations. www.navy.mil/navydata/documents/USN_artic_roadmap.pdf (accessed on March 29. 2014).

Navy. (2014). *The United States Navy Arctic Roadmap for 2014 to 2030*. Washington DC: U.S. Department of Defense, Department of the Navy, Chief of Naval Operations. http://greenfleet.dodlive.mil/files/2014/02/USN-Arctic-Roadmap-2014.pdf (accessed on June 24, 2014).

Neffenger, P. (2012). Communications between Vice Admiral Peter Neffenger, U. S. Coast Guard Deputy Commandant for Operations, and George Backus of Sandia National Laboratories, April 2011 through January 2012.

NOAA (National Oceanic and Atmospheric Administration). (2014). *NOAA's Arctic Action Plan – Supporting the National Strategy for the Arctic Region*. Silver Spring, MD: U.S. Department of Commerce, NOAA. http://www.arctic.noaa.gov/NOAAarcticactionplan2014.pdf (accessed on July 2, 2014).

NSTC (National Science and Technology Council). (2013). *Arctic Research Plan FY2013–2017*. Washington DC: NSTC. http://www.whitehouse.gov/sites/default/files/microsites/ostp/2013_arctic_research_plan.pdf (accessed on July 2, 2014).

Papp, R. J., Jr. (2012). "The Emerging Arctic Frontier." *Proceedings Magazine* 138/2/1,308. http://www.usni.org/magazines/proceedings/2012-02/emerging-arctic-frontier (accessed on March 29, 2014).

Romig, A., G. A. Backus, and A. B. Baker. (2011). *A Deeper Look at Climate Change and National Security*. SAND2011-0039. Albuquerque, NM: Sandia National Laboratories. https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/Climate_Change_and_National_Security.pdf (accessed on March 29, 2014).

Rumpf, R., G. Backus, and J. Millick. (2009). "Melting Borders: Economic and National Security Concerns Associated with Arctic Icemelt." *Common Defense Quarterly*, Summer. http://www.commondefensequarterly.com/archives/CDQ2/arctic.htm (accessed on March 29, 2014). [Invited cover-article].

Sulimina, A. (2012). "Arctic Cold War Heats Up." *The Moscow News*, April 3. http://indrus.in/articles/2012/04/03/arctic_cold_war_heats_up_15340.html (accessed on March 29, 2014).

The Canadian Press. (2010). "Arctic Terror Threats Real: Security Agencies." *CBC News Canada*, November 10. http://www.cbc.ca/news/canada/north/arctic-terror-threats-real-security-agencies-1.868895 (accessed on March 29, 2014).

The Patuxnet Partnership. (2012). 2012 USEUCOM AND USAFRICOM Science and Technology Conference. http://paxpartnership.org/index.cfm?content=60 (accessed on June 16, 2014).

The White House. (2013). *National Strategy for the Arctic Region*. Washington DC: The White House.

USCG (United States Coast Guard). (2013). *The United States Coast Guard Arctic Strategy.* Washington, DC: USCG. http://www.uscg.mil/seniorleadership/DOCS/CG_Arctic_Strategy.pdf (accessed on July 2, 2014).

USCG. (2014). "Icebreaker." Acquisition Directorate. http://www.uscg.mil/hq/cg9/icebreaker/ (accessed on June 16, 2014).

Winnefeld, J. A., Jr. (2011). "Statement Of Admiral James A. Winnefeld, Jr., U.S. Navy Commander United States Northern Command and North American Aerospace Defense Command before the House Armed Services Committee, 30 March 2011." Washington, DC: House Armed Services Committee, U.S. Congress. http://armedservices.house.gov/index.cfm/files/serve?File_id=2e953277-823d-4aa3-9f70-32ec8a18713b (accessed on March 29, 2014).

Wolf, C., and K. Klimasinska. (2012). "As the Arctic Opens for Oil, the Coast Guard Scrambles." *Bloomberg BusinessWeek*, July 26.

# 3 Data Fusion Methods

Hall (2004) defined data fusion as the process of combining information from heterogeneous sources into a single composite picture of the relevant process such that the composite picture is generally more accurate and complete than that derived from any single source alone. This section begins with an examination of the needs and concerns that arise when collecting and attempting to integrate data from multiple sources in the Arctic region. Next, we look at the costs associated with the data collection and then review some data fusion methods that can be used to make these data more informative to users of the data. Subsequently, the topic of choosing an optimal mode of data sampling is addressed to minimize the amount of data that needs to be collected. The section continues with a brief overview of a current collaborative effort at data integration and then provides examples of how Sandia has managed massive data sets and employed data fusion techniques. A list of references concludes the section.

## 3.1 Data Collection Needs and Concerns

A wide array of data is necessary to characterize the current and future state of the climate in the Arctic region. Data are needed to characterize, for example, sea ice location and thickness, salinity, temperature, winds, clouds, sea life, wildlife, and resources. Questions naturally arise regarding where and when to sample, how the data can assist in answering questions related to climate, and how each sample contributes to answering these questions.

The collection of data, such as temperature, wind speed, and trace gas measurements, across wide, diverse regions of space and time is accomplished with great expenditure of resources. Sources and modalities of these data vary widely in resolution, sensor type, and collection method.

A tremendous amount of climate data are generated every day: weather station reports, observations from remote sensing platforms, trace gas measurements from ice cores, raw radiance data provided by geostationary and polar orbiting satellites, etc. Information collection must be managed effectively, and data must contribute efficiently to satisfy the needs of a broad spectrum of scientific objectives and the intended modeling communities. Each piece of data has value relative to these objectives, providing the opportunity for discovery and reducing the uncertainty in estimates and predictions.

The rapid and efficient integration and uncertainty quantification of data are exacerbated by the complex mix of data-collection modalities and support. For example, surface temperature may be collected at points that are separated from each other by widely spaced, generally irregular, points on Earth’s surface with temporal regularity. Simultaneously, temperatures may be indirectly collected from high-resolution infrared sensors over a much broader area for a relatively short period of time.

Consider the situation depicted in Figure 3-1. Multiple passes from different unmanned aircraft systems (UASs) result in large quantities of information. While data are collected on the identical atmospheric variables, alternative sensor-package options result in variations in resolution and sampling frequency. Questions such as the following arise regarding the most efficient integration of the two data sources in the figure, i.e., Sensor 1 and Sensor 2: Given that data from Sensor 1 is available from a discrete array of ground sensors, what is the value of collecting additional data from a second pass using a different collection modality (Sensor 2)?

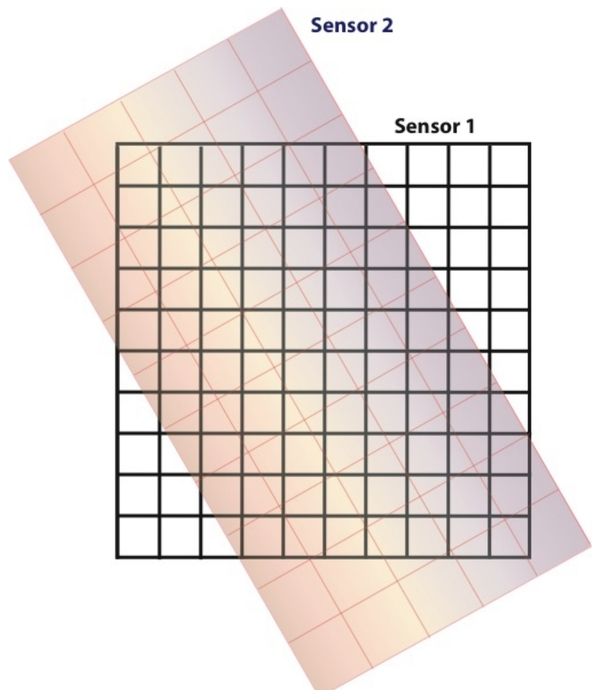



**Figure 3-1.** Multiresolution, anisotropic data acquisition.

A particularly difficult data-integration problem is depicted in Figure 3-2. The Marine Mammals Exploring the Oceans Pole to Pole (MEOP) program, as described in Boehme et al. 2009, utilizes marine mammals as observation platforms. Sophisticated sensor tags are attached with fast-setting glue to seals. As the seals recover from a dive, the sensors record temperature, salinity, and pressure at various ocean depths. The sensors then transmit the stored profile to a satellite when the animals surface. After approximately 11 months, when the seals molt, the sensors fall off naturally. The three-dimensional, multimodal nature of the data, coupled with the generally random nature of the spatial locations of data collection, lead to very complex data fusion.

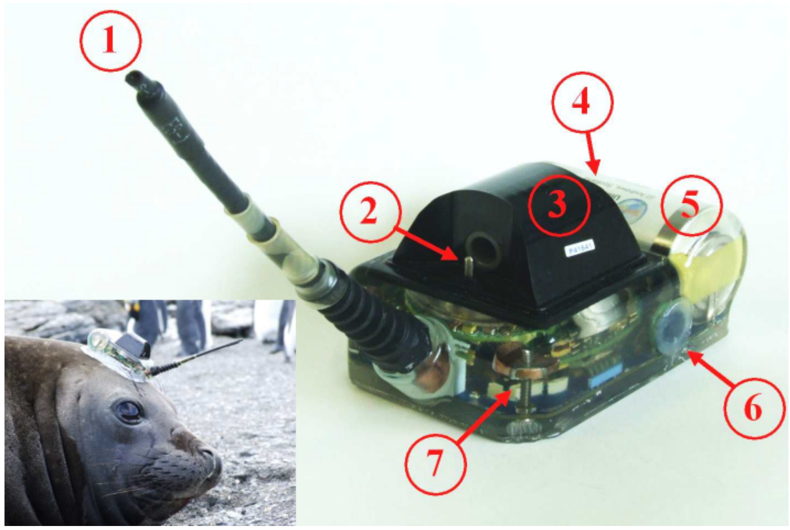



**Figure 3-2.** Conductivity-Temperature-Depth Satellite-Relay Data Loggers (CTD-SRDL) data collection [Source: Boehme et al. 2009]

In Figure 3-2 above, the numbered components are as follows: (1) antenna, (2) temperature probe, (3) inductive cell, (4) pressure sensor (not visible), (5) battery, (6) communications port, and (7) wet-dry sensor.

Figure 3-3 is a map showing the location of temperature and salinity profiles collected by seals instrumented as part of the MEOP program. *Interestingly, more oceanographic profiles have been collected in the sea ice zone using seals than using traditional oceanographic tools like ships and floats* (Biuw et al. 2007).

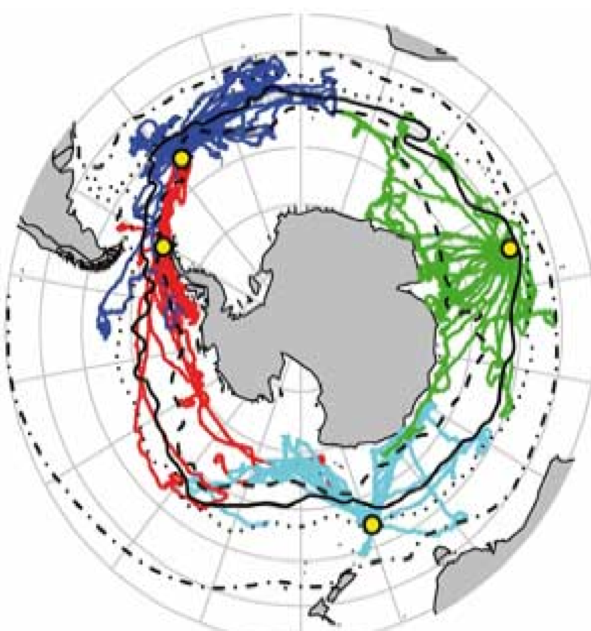


**Figure 3-3.** CTD-SRDL temperature and salinity profiles [Source: Biuw et al. 2007].

## 3.2 Data Value

The Arctic region is characterized by incredible challenges related to its harsh and sensitive environment. This affects both the reliability and cost of data acquisition. There are substantial costs to be considered when identifying optimal data-collection schema. These are costs incurred not only through the expenditure of resources, such as fuel or lost equipment, but also as the result of safety risks to aircraft flight crew. Even if the major data costs can be expressed in dollars, the value of the data cannot always be so easily expressed in scientific investigations.

For a typical stationary system, data collection after enough data have been collected to characterize the system tends to increase cost without increasing knowledge, as can be seen in the plot of Figure 3-4. The question remains, however, what is “enough” data?

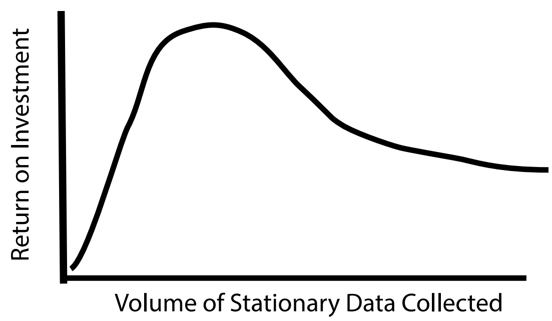



**Figure 3-4.** Return on investment (ROI) of stationary data collection.

The variability in the prediction of climate trends is much greater in the Arctic than anywhere else on Earth (ACIA 2001). Traditionally, data collection is focused on those areas where the uncertainty or variability in the estimates is greatest. Focusing on the **r**eduction of this estimation variance is a relatively simple approach to a goal: know the spatial variation of a property to within a certain level of confidence. This approach, however, discounts the possibility that fusion of multisensor data provides an advantage over single-source data. In addition to the statistical benefit over combining same-source data (e.g., obtaining an improved estimate of a physical phenomena via redundant observations), the use of multiple types of sensors may increase the accuracy with which a quantity can be observed and characterized.

In summary, data are available from a wide range of commercial and military sources, from a multitude of sensor types, and across a broad spectrum. The resolution varies considerably from sonobouy to aircraft to satellite. Further, the modality of data sources ranges from thermal to optical, from analog to digital.

Can we develop techniques and tools to decide what data to collect and where to collect it? Where should we deploy a UAS and with what sensor package? Are expendable sonobuoys a more cost-effective alternative? Where should they be deployed?

## 3.3 Data Fusion

The fusion of data collected at different points in space and at different resolutions, i.e., with variable support, is an established technique in geostatistics and provides a quick, first-order approach for combining data from multiple sources. However, this approach is limited in accuracy, and recently new statistical methods have been developed that lead to more efficient use of the data, a significant reduction in the prediction errors, and a full appreciation of the relationship between input and output uncertainty.

As emphasized by Nguyen, Katzfuss, et al. (2012), we need to take advantage of the complementary strengths of the individual data and exploit correlations in space and time to reduce the uncertainty in our estimates.

As mentioned previously, difficulties are encountered when fusing remote-sensing data sets. These difficulties are related to massive size of the data, change of data support, anisotropy and nonstationarity, and accounting for the biases of the instruments taking the measurements (see Figure 3-5). Nguyen et al. (2012) demonstrate an approach for data fusion that uses a technique referred to as spatio-temporal data fusion (STDF).

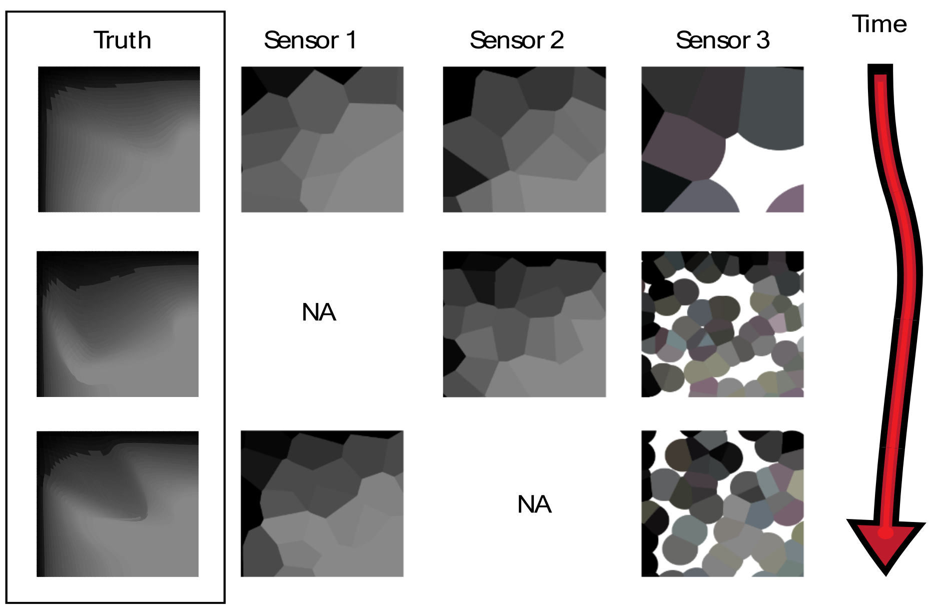



**Figure 3-5.** Data analysis challenge: temporal, multisensor, multiresolution.

Kriging is a common statistical method that provides the best linear unbiased prediction of spatial data. The STDF is an extension of fixed-rank kriging that has the following properties: the ability to derive joint estimates of two or more processes, and the ability to exploit both spatial and temporal dependence in the data. The main idea behind the STDF is to account for temporal dependence using a first-order auto-regressive model. Optimal predictions are made using a variant of the Kalman smoother.

The STDF is particularly appealing for Arctic remote-sensing data sets. It is fast and scalable to large data inputs and exploits the interprocess correlation for improved accuracy. The STDF takes advantage of both temporal and spatial dependence in the data. The methodology also provides quantitative measures of uncertainty that propagate input-data uncertainty appropriately.

## 3.4 Optimal Data Sampling

Sensor technologies available for observational platforms such as UASs or satellite systems have continued to expand as research and development continues at an accelerated pace. Multisensored, net-centric platforms are becoming the norm.

Adding to the challenge is the complex nature of the observational platforms (e.g., satellite, UAS). These platforms are progressively multisensored with overlapping or complementary collection modes.

Our goal is to characterize the state of the Arctic climate region with minimum cost and therefore with a minimum of observational data, i.e., to identify the data mode (e.g., UAS, sonobouy) and flight path or deployment location in such a way as to minimize the expected number of future observations needed to characterize the climate state. Fundamentally, we wish to maximize the rate at which information is collected relative to a particular climate variable.

Equivalently, it is desired to identify the optimal sensor-package configurations and locations to minimize the uncertainty in the posterior distribution of the predicted variables. This differentiates the current problem from the classic problem associated with optimal control. A new approach would involve the use of Shannon entropy to maximize the mutual information collected by the suite of observers relative to the information contained in the state of the target. The entropy metric will provide a measure of the uncertainty in the random variable characterizing our knowledge of the desired climate variables (temperature, salinization, etc.).

Preliminary explorations in this area have begun, but much remains to be formalized.

## 3.5 DOD Initiative

The DOD is funding a major initiative focused on collection and access tools for Arctic data. ACE (2014), the website for this effort, describes the initiative in this way:

> Arctic Collaborative Environment (ACE) Joint Capability Technology Demonstration (JCTD) is an internet-based, open-access, Arctic-focused, environmental research and decision support system that integrates data from existing remote sensing assets with products from existing and new environmental models to provide monitoring, analysis, and visualization based on earth observation data and modeling. With an initial focus on the Arctic region, researchers, students, search-and-rescue operators, native hunters, etc can draw from the open-access data.

A partnership of agencies developed the website and are acknowledged as such, including the National Aeronautics and Space Administration, U.S. European Command, Von Braun Center for Science & Innovation, North American Aerospace Defense Command / U.S. Northern Command, University of Alaska Fairbanks, and University of Alabama in Huntsville. A number of other agencies are supporting the collaborative's efforts as well (ACE 2014).

## 3.6 Sandia Capabilities

Sandia has successfully employed spatial-temporal data fusion on a number of projects. A successful spatial-temporal autoregressive model was developed to predict the time and location of improvised explosive devices in Afghanistan. Dynamic spatial information that was merged included Blue and Red Force activity, terrorist social-network activity, convoy movement, geographical and topographical characteristics (terrain, building/structure features, etc.). In addition, data from much larger spatial-scale sources, such as tribal and ethnic affiliation of various regions and agricultural land use, were included in the prediction model (Robinson 2014).

Another area that is the focus of a current research effort is the dynamic assessment of shale-gas-reservoir characteristics, such as reservoir size, estimation of gas reserves, and geological structure. Wellhead flow rate data as well as gas chemistry samples are coupled with microseismic test data over the data collection area.

## 3.7 References

ACE (Arctic Collaborative Environment). (2014). https://ace.arsc.edu/ (accessed on April 2, 2014).

ACIA. (2001). *Report from the Arctic Climate Impact Assessment Modeling and Scenarios Workshop*. Fairbanks, AK: ACIA Secretariat. http://www.acia.uaf.edu/PDFs/Stockholm_final.pdf (accessed on April 7, 2014).

Biuw, M., L. Boehme, C. Guinet, M. Hindell, D. Costa, J.-B. Charrassin, F. Roquet, et al. (2007). "Variations in Behavior and Condition of a Southern Ocean Top Predator in Relation to In Situ Oceanographic Conditions." *Proceedings of the National Academy of Sciences* 104, no. 34: 13705–13710.

Boehme, L., P. Lovell, M. Biuw, F. Roquet, J. Nicholson, S. E. Thorpe, M. P. Meredith, and M. Fedak. (2009). "Technical Note: Animal-borne CTD-Satellite Relay Data Loggers for Real-Time Oceanographic Data Collection. (2009). *Ocean Science* 5, no. 4: 685–695. http://www.ocean-sci.net/5/685/2009/os-5-685-2009.pdf (accessed on August 28, 2014)

Hall, D. L. (2004). *Mathematical Techniques in Multisensor Data Fusion*. Norwood, MA: Artech House, Inc.

Nguyen, H., N. Cressie, and A. Braverman. (2012) “Spatial-statistical Data Fusion for Remote Sensing Applications,” *Journal of the American Statistical Association* 107, no. 499: 1004–1018.

Nguyen, H., M. Katzfuss, N. Cressie, and A. Braverman. (2012). “Spatial-Temporal Data Fusion for Remote Sensing Applications.” http://www.samsi.info/sites/default/files/Nguyen_january2012.pdf (accessed on April 2, 2014).

Robinson, D. (2014). *Successful Prediction of Improvised Explosive Device Events in Afghanistan*. Albuquerque, NM: Sandia National Laboratories. [The report is currently in review.]

# 4 Current and Future Satellite Resources in the Arctic

Section 4 describes an assessment we conducted of satellite data and their derived products. The assessment provides useful information on the Arctic region for forecasting, climate, surveillance, and communications, which we refer to as *mission areas*. Both current and future satellites are included in the assessment so that gaps in data can be determined from the present to the near-term. The assessment was driven by the data requirements we developed for each of the four mission areas.

The analysis process followed these sequential steps:

- Identification of mission requirements
- Production of a comprehensive list of satellites, sensors, and their key characteristics
- Acquisition of key data traits such as spatial resolution, spatial coverage, and frequency of observations
- Determination of missions that could potentially benefit from particular satellite data
- Assessment of the current and future satellite data contribution to mission support
- Identification of unexploited data as well as limitations and apparent data gaps

Our assessment of the satellite systems is a top-level overview and does not include investigation and evaluation of specific derived products from these systems. Knowledge of the general satellite sensor type made it possible initially to assess its importance to each mission area without fully understanding the characteristics of individual sensors and data. It should be noted that the existence of data does not necessarily provide useful information for the mission areas. Data processing and retrieval algorithms are equally important for ensuring accurate and precise information that is actually useful.

Section 4.1 gives a general introduction to terminology common to the satellite community. Section 4.2 provides data definitions of the mission requirements that were used to evaluate the value of the satellite sensor data. In Section 4.3, we identify important satellite assets. Simple statistical analysis is provided to summarize the long list of current and future satellites that have potential contribution in the Arctic. Section 4.3 provides a more in-depth analysis of how satellite data support the individual mission areas. Also included in this section are discussions about the difficulties of satellite remote sensing in the Arctic and recommendations for enhancing the satellite contributions in these areas of focus. Section 4.5 summarizes the key points of the assessment and identifies some areas of future work. References are listed in Section 4.6.

## 4.1 Satellite Orbits

Figure 4-1 depicts the four orbits in which satellites from all nations can be found.

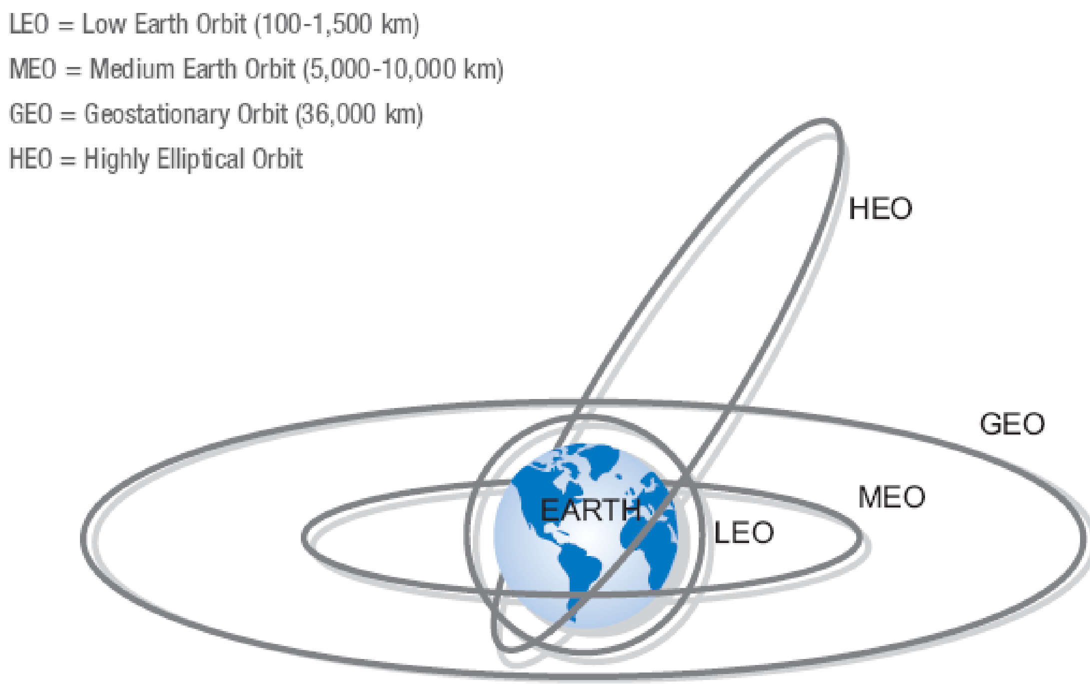



**Figure 4-1.** Types of satellite orbits [Source: quarkology.com 2014].

The legend in Figure 4-1 defines each of the four acronyms and provides the altitude of three of the four orbits. The HEO is above 36,000 kilometers (km).

CPI (2014) identifies the preferred orbits of the different types of satellites. LEO is used by weather and reconnaissance satellites. Cellular telephone communication and navigation satellites are in MEO. Global positioning systems (GPSs) and communications occupy GEO. Satellites in HEO are for communications services and other uses at northern latitudes.

## 4.2 Requirements for Mission Areas

This section provides a brief description of the four mission areas that dictated the assessment characteristics used for evaluating individual satellite value for Arctic activities.

### 4.2.1 Forecasting

This mission area focuses on weather prediction, which is crucial for planning and executing near-term activities in the Arctic. These activities include, but are not limited to, travel, exploration, transport, and research. Weather issues have an immediate impact in many ways and can strongly affect the following national sectors: economic, security, and disaster prevention. Good weather forecasting requires accurate knowledge of the atmospheric state used as initial conditions in sophisticated dynamical atmospheric models. The main atmospheric properties needed at incrementally increasing altitudes are the following:

- Three-dimensional wind
- Temperature
- Pressure
- Moisture
- Cloud parameters

These atmospheric properties are also required at specific temporal intervals not longer than 12 hours in duration and in as complete a set as possible across the model three-dimensional (3D) spatial domain. Many sources of errors, however, affect the quality of weather forecasts, including the following:

- Initial condition errors
- Observational spatial density and temporal frequency data coverage
- Errors in the data
- Errors in data assimilation
- Missing variables
- Errors in quality control

Producing quality initial conditions from sparsely resolved data (in space and time) and from incomplete observations is not an easy task. Therefore, it is critically important to have consistent coverage in time and wide coverage in space of atmospheric state data.

### 4.2.2 Climate

The study of climate, which encompasses both seasonal and multiannual prediction, is important for understanding potential longer-term environmental changes than are available in weather prediction and for activities and decision making for future logistical and strategic preparation. Further, the needs for climate data are greater and more specific than are necessary for weather prediction. Climate data needs focus more on both the atmosphere and the surface, including very explicit cloud, aerosol, trace gas, moisture, land, sea, snow, and ice properties. In some regards, all collected data are pertinent. Generally, this mission area is less constrained by specific spatial and temporal coverage but does require long-term commitment to sensors that produce comparable data and environmental products.

### 4.2.3 Surveillance

Surveillance over the Arctic is becoming increasingly important because of the likelihood of more favorable environmental conditions for human activity as a result of climate change (GAO 2012). Remote monitoring of the Arctic is needed to provide situational awareness to both military and civilian commanders who have responsibilities for national security, disaster relief, and search and rescue. Requirements in this mission area include the ability to detect structures, vehicles, and vessels of varying size and type under often difficult, changing environmental conditions. Another key characteristic of useful surveillance data is persistence in terms of both spatial extent and continuity in time.

### 4.2.4 Communications

Communications in the polar regions are difficult and often seen as a vulnerability (DOD 2011). Communication satellites have largely been located in geostationary orbit for consistency and coverage. Geostationary satellites do not provide coverage in the Arctic. In addition, due to magnetic and solar phenomena above 70° N, high-frequency communications are significantly degraded. Availability and bandwidth are also issues.

## 4.3 Important Assets for Monitoring the Arctic

In the fall of 2012, we produced a summary of the current and future satellites that possess sensors with Arctic mission implications. This summary is provided in two tables in Appendix A. The tables were constructed by performing a web-based survey of current orbiting and upcoming satellites. An excellent summary of Earth-orbiting assets that provided the initial framework for these tables can be found on the Committee on Earth Observation Satellites (CEOS) Earth Observing (EO) Handbook website (CEOS ESA 2014). At the time we created the satellite summary in 2012, this database featured details of 260 Earth-observing satellite missions and 784 instruments (396 distinct instruments), which were then operating or planned for launch in the next 15 years (i.e., to 2027). About 30 space agencies worldwide fund and operate these platforms.

Table 4-1 provides an example of several of the satellite entries in Appendix A. A brief explanation of the columns in the satellite summary follows this example.

**Table 4-1. Example Entries from Satellite Summary Table A-1 in Appendix A**

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| AISSat-1<br>Automatic Identification System Satellite-1<br>NSC | L2010<br>E2013 | LEO SSO | Demonstrate and extend access to AIS (Automatic Identification System) signals beyond the land-based AIS system operated by the Norwegian Coastal Administration today. Observe ship traffic in the High North. | SDR | | Surveillance |
| .<br>.<br>. | .<br>.<br>. | .<br>.<br>. | .<br>.<br>. | .<br>.<br>. | .<br>.<br>. | .<br>.<br>. |
| CARTOSAT-1<br>Cartography Satellite - 1 (IRS P5)<br>ISRO | L2005<br>E2012 | LEO SSO<br>618 km<br>97 mins<br>97.87 deg | High precision large-scale cartographic mapping of 1:10000 scale and thematic applications (with merged XS data) at 1:4000 scales. | PAN (Cartosat-1) | S: 30 km<br>R: 2.5 m<br>C: 0.5 %, 8.2% | Surveillance<br>Climate |

The EO Handbook provided the following information on each satellite that filled the first five columns of the two tables in Appendix A: Satellite name, agency, launch and End-of-Life (EOL) dates, orbital information (type, altitude, period, and inclination), general applications, and onboard instrument list. The supplemental information about sensor swath and resolution in the sixth column was determined (not fully completed) by manual web search as well as with an additional table supplied by the EO Handbook. The relevant missions in the seventh column of the satellite tables were determined by the authors of this study through examination of the respective satellite and its onboard sensor characteristics.

The EO Handbook did not provide information on communication satellites. These were found via web searches. Satellites that were determined to have little impact on Arctic mission were excluded and removed from initial versions of the tables. Notably missing are geostationary satellites and other low-inclination (less than 45°) satellites because they cannot view the polar regions in any meaningful way. Satellites with a non-Earth focus, either spaceward looking or with solar missions, were also excluded. Finally, nonproductive satellites, such as QuickSAT, were also not included in the final list.

The four missions, as previously stated, were assigned by the authors of this study to appropriate satellites that possessed sensors whose data could directly support the mission. The mission assignments were generally determined by the following criteria:

Forecasting: Data specifically for input to weather models

Climate: Multipurpose environmental monitoring of all atmospheric, oceanic, and surface properties

Surveillance: High-resolution imagers for mapping and monitoring, scanning radars for detection, electronic signal detection

Communications: Ground-to-space-to-ground communication sensors

To determine the coverage of a satellite, we developed a coverage calculation tool that provides both single-pass and a daily composite coverage as a fraction of polar cap observed by the sensor. The polar cap is defined in this study as the area north of 55° N latitude and encapsulates an area of just over 46 million square km or about 9% of the Earth's surface. These coverage values are given in Table A-1 of Appendix A for all sensors with known swath and altitude. General swath characteristics and coverage statistics are summarized in Table 4-2 for the sensor types and general mission categories. The large swath of the operational meteorology satellites provides daily full-pole coverage as required by the modeling mission. Narrow swaths provide better spatial resolution that more closely meet the requirements of the other missions.

### Table 4-2. Summary of Swath and Coverage Characteristics for Selected Sensors and Missions

| Sensor/Mission | Swath | Single-Pass Coverage | Daily Coverage |
|---|---|---|---|
| Operational Meteorology | >2000 km | 35% | 100% |
| Multipurpose Science | 100–500 km | 2–8% | 20–50% |
| Radar, SAR, LIDAR | 1–150 km | Maximum 2.5% | Maximum 40% |
| High-Resolution Imaging | <20 km | 0.3% | 5% |

Table 4-3 gives a numerical summary of the missions addressed by the 91 current orbiting satellites defined in Table A-1 of Appendix A. The table shows a large number of current satellites in each mission with the exception of communications, albeit the Iridium constellation consists of 70 individual satellites. Note that the two tables in Appendix A upon which the current and future satellite summary data in this section are based were compiled in 2012. Thus "current" in this context means 2012 and future satellites are post-2012.

### Table 4-3. Numerical Summary of Current Orbiting Satellites (2012) by Mission

| Category | Forecasting | Climate | Surveillance | Communication |
|---|---|---|---|---|
| Number of Satellites | 36 | 69 | 54 | 2 (1 constellation of 70 satellites) |
| Number of Sensors | 202 | 294 | 95 | 2 |
| Number of Agencies | 18 | 38 | 27 | 2 |
| Number of Countries | 9 | 18 | 19 | 1 |

At first glance, the numbers in Table 4-3 above appear more than sufficient in terms of overall observations; but after more poignant consideration, important issues are uncovered. *Many of the current satellites are expected to reach EOL (end of life) soon. By 2013, in fact, 70% of the forecasting satellites, 61% of the climate satellites, and 46% of the surveillance satellites were to have reached EOL*. Another issue is coverage. Most of the satellites observing the poles are in LEO (Low Earth Orbit), which limits their spatial coverage resulting from the near-Earth proximity and their temporal coverage due to the high velocity and single overpass approximately every 90 to 100 minutes. Also because of their high rate of travel, which is approximately 7 kilometers per second (km/sec), short integration times must be used, and it can be difficult to collect data of sufficient quality. Lastly, there is a high degree of redundancy and incompatibility in the data as a result of the large number of agencies and sponsored countries responsible for these satellites. The large number of agencies and countries in the table give a false impression of the amount of useful data and missions being addressed, as many satellite programs sponsored by different agencies and countries collect similar data or do not make their data available to each other.

Future satellites (post-2012) are expected to replace current satellites reaching EOL. Table A-2 in Appendix A lists a total of 119 satellites in which 54 have approved status and 65 are being planned or considered. From 2012 through 2014, 7 forecasting, 43 multipurpose climate type, 22 surveillance, and a single communication satellite were expected to be launched. Similar to the current satellites in orbit, these satellites are sponsored by 17 different agencies from 14 countries. The format and definition of entries in Table A-2 is the same as that for Table A-1. However, the mission status (column 2) includes a field that denotes "Considered" or "Approved," as seen in a sample entry presented next in Table 4-4.

**Table 4-4. Example Entry from Satellite Summary Table A-2 in Appendix A**

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| 3D Winds<br>Three Dimensional Tropospheric Winds from Space Based Lidar<br>NASA | Considered<br>L2030<br>E2033 | LEO SSO<br>400 km<br>97.03 deg | Phase-3 DS Mission, launch order unknown, 3-year nominal mission. Tropospheric winds for weather forecasting and pollution transport. | HDWL (3D Winds) | | Forecasting |

In the entry above, the 3D Winds satellite is being considered for launch in 2030, with its EOL projected in 2033.

## 4.4 Assessment of Satellite Data on Individual Missions

A more through assessment of how satellites address each Arctic mission area is discussed next. Section 4.4.1 explains the difficulties of space-borne remote sensing. Specific mission assessments follow in Section 4.4.2. Section 4.4.3 is devoted to recommendations.

### 4.4.1 Remote Sensing at High Latitudes

In preparation for a more detailed assessment of specific mission support, a few comments should be made about the special issues affecting remote sensing of the Arctic from space. The Arctic region possesses unique properties compared with other regions on the globe that make remote sensing of its properties more challenging. These challenges can be broken up into three major areas: *coverage*, *interest*, and *radiometric*. The coverage issue exists since the polar region is extremely distant and difficult to view from the geostationary orbit directly over the equator. GEO, the geostationary satellite orbit that is some 35,780 km in altitude, is the only orbit in which a satellite is fixed about a particular point on Earth due to both its 24-hour period (same as the Earth's rotation) and the fact that the orbit is normal to the Earth's axis. This special orbit provides continuous viewing of the same place on Earth. Data can be provided of a large area (nearly hemispheric) in consistent formats at specified times. Unfortunately, regions on the polar side of 60° N latitude are viewed at large zenith angles that reduce spatial ground resolution and result in large atmospheric paths that make practical remote sensing impossible. Similar viewing conditions can be achieved for polar regions with

HEOs (highly elliptical orbits) with apogee (highest point in altitude) above the poles. These orbits provide several continuous hours of low relative motion when the satellite is around its apogee. Very few of these satellites exist, especially in the open community with data available to civilian agencies. Most polar-viewing satellites are in circular, LEO below 1000 km. These are more often than not sun-synchronous so that measurements are taken at the same time each day. LEO does provide better spatial resolution and signal-to-noise ratio (SNR) due to the short range involved and is best suited for long-term studies (e.g., climate, multipurpose science missions) that do not require continuous observations. This type of coverage is not ideal for the other three important mission areas previously defined. Despite the narrow swaths (data widths) to which the LEO satellites are limited, there is a high degree of swath or data overlap on each orbit because of the orbital convergence at high latitudes. This presents its own issues though with spatial and temporal data registration. To produce large continuous data fields with LEO satellite measurements, data from many sensors are required. As a result, data assimilation issues such as resolution, accuracy, and format are more pronounced.

The second major problem is a general lack of interest in the polar regions. The polar regions have been seen as less important, likely in part because of their low population and minimal human activity. These areas were generally considered, up until recently, to be relatively homogeneous, environmentally displaying small seasonal and climatic variation. Moreover, much of the year they exist in partial or total darkness, which makes it all the more easy to ignore them. This reduced interest results in on-orbit sensors that are not being designed to optimally measure polar regions that do have vastly different properties than the rest of the globe.

Lastly, space-based remote sensing of the Arctic is difficult due to radiometric challenges. Solar illumination varies significantly on an annual basis. Much of the year there is no incident solar energy on the surface. Many surface and atmospheric properties are derived using solar scattering and thus cannot be retrieved during large continuous durations. Even when the Sun is above the horizon, it is at very low elevation angles (high zeniths). At high latitudes, the Sun’s zenith angle is generally larger than 55°, and often larger than the maximum (70°) for which atmospheric correction algorithms have been developed based on plane-parallel radiative transfer calculations. Consequently, the quality of retrieved environmental properties at high latitudes may suffer a great deal throughout the year. For example, atmospheric methane concentrations derived from the GOME and SCIAMACHY sensor measurements in the Arctic were never reliable because of the low-light conditions and persistent cloud and ice cover (Buchwitz 2012).

Other radiometric issues stem from the distinctive environmental conditions in the Arctic, especially the presence of surface ice. Bright surface-ice conditions cause many remote-sensing problems, including saturation, lower property contrast (low SNR), and difficulty in determining clear sky. One particular troublesome issue is sea ice adjacency that contaminates neighboring pixels due to their brightness. Bélanger, Ehn, and Babin (2007) and Wang and Shi (2009) have examined MODIS data and found significant impacts in calibrated radiances and level-2 ocean products over the first several kilometers from the ice-edge and for concentrations of subpixel ice floes. Arctic ice thaws lead to unique ocean-fresh-water conditions that create statistical relationships between surface chlorophyll and chlorophyll concentration developed for lower latitudes that are most probably not valid for the polar seas (Martin et al. 2010). This statistical difference likely leads to significant error in the estimation of the areal primary production (the synthesis of organic compounds from atmospheric or aqueous carbon dioxide) in the Arctic Ocean (Pabi, Van Dijken, and Arrigo 2008; Hill and Zimmerman 2010).

The polar regions also suffer from persistent cloud and fog, which reduces lower-atmospheric-property and surface-property retrieval opportunities. Fog is particularly prevalent over open water as the ice breaks apart due to the cold atmospheric temperature. Perrette et al. (2011) found that in the Arctic Ocean only 50% of the open ocean pixels near sea ice had at least three clear observations during a 20-day observation period. Differentiating between clouds, snow, and ice presents challenges as well. Clouds in the Arctic also possess a larger amount of mixed-phase particles, making their property retrieval more difficult.

The cold polar surface often produces boundary-layer temperature inversions in which temperature increases with height just above the surface. These inversions add to the difficulty in atmospheric property retrieval and the identification of clear sky from clouds. This is especially problematic during the dark, nonsolar periods where thermal remote sensing is relied upon.

## 4.4.2 Satellite Data and Product Support for Specific Missions

Satellite support for the four mission areas is discussed separately for each mission in Sections 4.4.2.1 through 4.4.2.4.

### 4.4.2.1 Support for Forecasting Mission

Weather forecasting is more difficult in the Arctic compared to the rest of the planet due to the lack of atmospheric measurements and the challenging remote-sensing issues discussed previously. In the Arctic there exist only a sparse number of ground stations performing atmospheric measurements, relatively little weather radar, and limited regional weather specialists, making the satellite measurements very important to the forecasting effort. The weather mission requires gridded atmospheric data on large scales at specific times. This requirement is currently problematic over the poles because stationary, hemispheric-viewing sensors do not exist as they do at lower latitudes. Instead, data must be acquired by LEO satellites that provide single measurements every 90 to 100 minutes of about one-third the polar cap area. To form a complete grid, data from many satellites must be put together. Both clouds and air masses move significantly and pose major issues in defining complete and representative fields for models. These highly temporal varying quantities require measurements on tens-of-minutes time scales. To compensate, agencies responsible for weather forecasting utilize operational satellite systems composed of multiple satellites that are similar in design and sensor components. For instance, the Polar-orbiting Environmental Satellite (POES) and the Defense Meteorology Satellite Program (DMSP) systems, both operated by the National Oceanic and Atmospheric Administration (NOAA), currently possess five nearly identical satellites each that can all supply complete polar coverage daily. Routinely derived near-real-time products include rain rate, ice water path, snow cover, sea surface temperature, surface type, sea ice concentration, surface wind speed, and profiles of water vapor and temperature. Direct quality-controlled radiances are also input directly into models using fast radiative-transfer models.

There are several limitations to these data sets. Winds can only be derived at the surface and over the ocean, albeit not through most clouds, by measuring passive polarimetric microwave energy. Turning radiances into quality data products requires the mathematical term called a *Jacobian*. The Advanced Microwave Sounding Unit-B (AMSU-B) onboard the three POES satellites (NOAA-15, 16, and 17) produces data that are sensitive to both water vapor and temperature, especially in drier polar regions. Therefore, the Jacobian used for the AMSU-B data varies significantly from the Equator to the polar regions as does both water vapor and temperature. This dual sensitivity makes the assimilation of AMSU-B data dependent on very accurate prior knowledge of the error statistics of temperature and moisture trial fields (Chouinard and Hallé 2003). Data latency is yet another factor limiting the usefulness of some measurements and derived products from polar-orbiting satellites. Due to only two functioning NOAA ground stations, located in Fairbanks, Alaska, and Wallops Island, Virginia, data downlink time can vary dependent on the orbit. Orbits that cannot directly communicate with these ground stations are referred to as blind orbits. Data from these orbits cannot be acquired, processed, and analyzed in a relatively quick time period and could affect short-term weather prediction accuracy.

The number of satellites used for forecasting is expected to decrease in the near term. This can be seen clearly by examining EOL and launch dates in the tables in Appendix A. To more clearly view this trend, the number of satellites providing data to the forecasting community per year, beginning in 2012, is plotted in Figure 4-2.

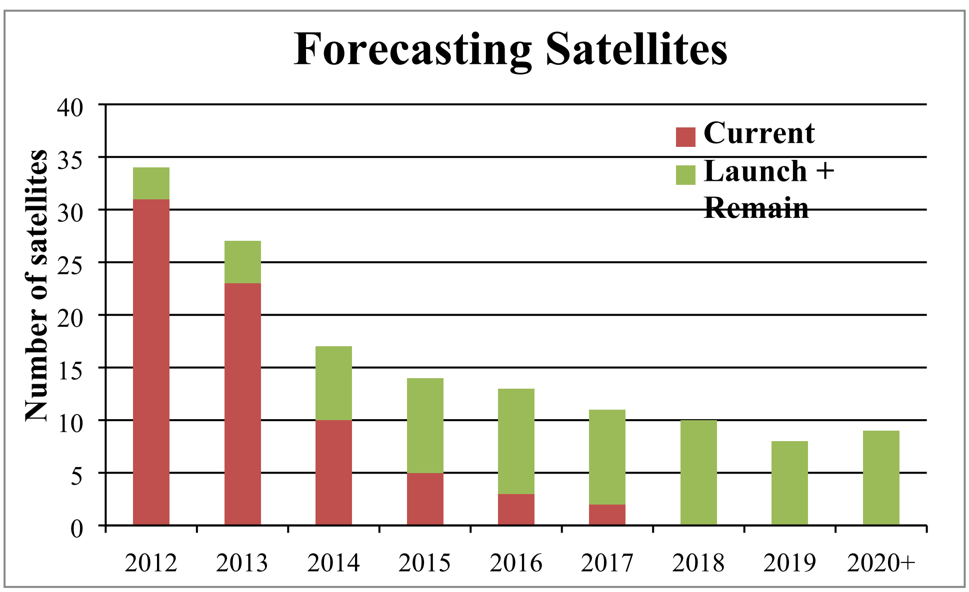



**Figure 4-2**. Number of operating (current and planned) satellites providing data for weather forecasting per year.

Included in the plot in Figure 4-2 above are the remaining satellites available each year based on EOL date as well as the approved and planned satellites based on launch date and a five-year lifetime, which is generally 3–6 years for operational satellites. The satellites included in the plot are mostly those with a primary forecasting mission, but some satellites are also included that are not operational meteorological satellites though they provide important data for the forecasting mission. For instance, the National Aeronautics and Space Administration (NASA) Aqua and Terra satellites provide many useful data sets used in weather models.

From the plot in Figure 4-2 above, it is apparent that there is a general reduction in the number of polar-viewing satellites devoted to forecasting from 2012 through 2020+. Importantly, new satellites *do not* compensate for the number of current satellites that are expected to reach the end of their life. Extending the operational lifetimes of many of the current satellites will help somewhat, yet the impact on polar forecasts remains to be seen. There does seem to be a slight redundancy in the number of current similar satellites that all provide daily coverage. Reducing their number may not produce a corresponding effect on the mission. Still, the downward trend implies a certain vulnerability in the areas of data coverage, latency, and quality.

The total numbers of satellites are only meaningful if all satellite data are shared across agencies. Currently, three agencies provide civilian meteorological-forecasting services: NOAA, the European Organization for the Exploitation of Meteorology Satellites (EUMETSAT), and the National Satellite Meteorology Center – China Meteorology Administration (NSMC-CMA). It is likely that future Russian and Canadian satellites will provide data to meteorology missions. The same plot is made for U.S.-only satellites in Figure 4-3.

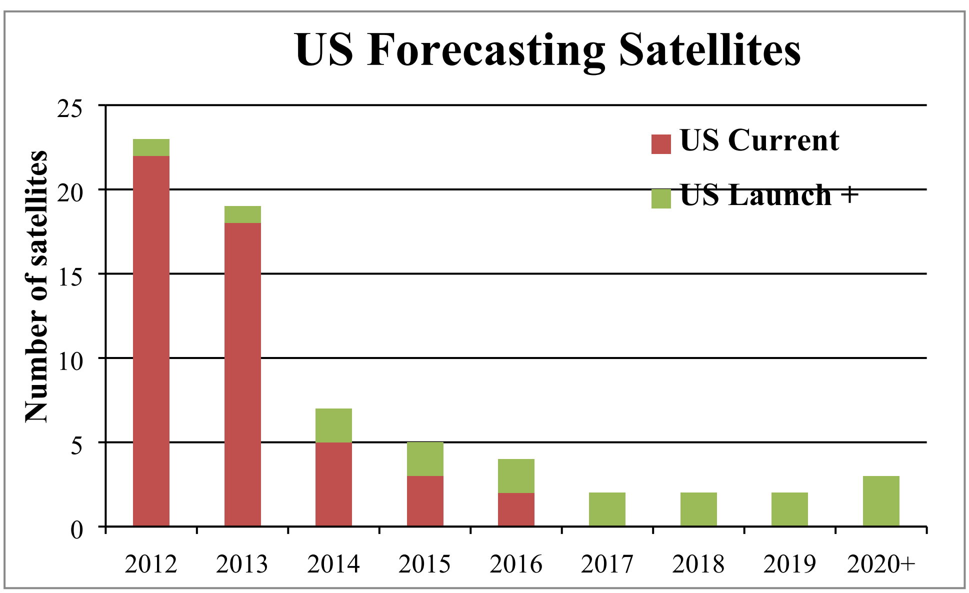



**Figure 4-3.** Number of operating (current and planned) U.S. satellites providing data for weather forecasting per year.

The trend, as shown in Figure 4-3 above, is even worse for the United States. The large current satellite numbers include NASA climate satellites like Terra, Aqua, CloudSat, and Calipso. Only two more DMSP satellites were scheduled to be launched (2012 and 2014), and only two more POES satellites (under the new Joint Polar Satellite System [JPSS] program) are planned to be launched (2017 and 2023). This reduction may be linked in part to the problems that the National Polar-orbiting Operational Environmental Satellite System (NPOESS) experienced before it was dissolved in 2010. NPOESS suffered from overspending, schedule slip, and technical concerns (JPSS 2014). NOAA and NASA now form the new JPSS while the U.S. Air Force, original DMSP sponsor and third partner of NPOESS, is still considering satellite options (Air Force Space Command 2013).

Arctic forecasting is seen to be less accurate compared to the rest of the globe primarily due to the sparseness of atmospheric data. Limited ground measurements in the polar regions make satellite data important in order to fill spatial data gaps. Unfortunately, unlike the tropical and midlatitude oceans, which also suffer from a lack of ground-based measurements, current satellite data from polar regions offer only limited assistance. Data, primarily from LEO satellites, suffer from limited coverage, latency issues, and incomplete data fields resulting from the remote-sensing difficulties that exist in ice-filled, cloudy, and dark environments. Future investment in polar-viewing weather satellites is minimal. Fortunately, there seems to be a path ahead that could positively affect satellite data collection's impact on weather forecasting.

The World Meteorological Organization (WMO) in its vision for the Global Observing System (GOS) in 2025 (WMO 2013) endorsed the concept of HEO satellite systems that hover for long periods over the poles and improve Earth observations in the region. The WMO document further recommends the operational implementation of visible and infrared HEO imagers to monitor high-latitude phenomena related to winds, clouds, volcanic ash plumes, sea ice, snow cover, vegetation properties and wild fires with sufficient temporal resolution (WMO 2013). The Canadian Space Agency (CSA) is in the planning stages of two HEO satellites with weather forecasting and communications missions at their forefront (CSA 2014). The system is called the Polar Communications and Weather (PCW) mission, and both satellites are tentatively slated to be launched in 2018. Figure 4-4, taken from the CSA website, depicts the orbits of the two satellites. Most of the time the satellites are above the Arctic where the orbital velocity is low. Prospects for new commercial satellites with arctic coverage remain limited, although the Iridium communications satellite provides low-bandwidth coverage in polar regions.

**Figure 4-4.** Depiction of planned PCW satellites in HEO [Source: CSA 2014].

The main weather-related instrument onboard the PCW satellites is planned to be an imaging spectroradiometer (CSA 2014). This instrument will be similar in design to the imagers being developed for the next generation of geostationary weather satellites (GOES-R and MTG). A secondary weather instrument (broadband radiometer) is also being considered. Near-real-time environmental products will be generated in a nearly continuous fashion that will be extremely useful for forecast model input, climate study, and safety measures. Table 4-5 provides a preliminary list of near-real-time products from the proposed PCW sensors. This list does not include key atmospheric properties, such as water vapor and temperature profiles, nor does it include calibrated radiances currently utilized in weather models. In addition, there is no indication about how these products will vary in the Arctic light and dark seasons.

**Table 4-5. Preliminary Data Products from PCW Sensors Taken from the CSA**

| Product | Latency | Comment |
|---|---|---|
| Imagery from 1 satellite | 15 minutes | Mapped to grid |
| Imagery from 2 satellites | 30 minutes | Composite image |
| Atmospheric Motion Vectors (AMV) | 1 hour | |
| Cloud mask | 30 minutes | Important for direct radiance assimilation |
| Cloud Height, Temperature, Emissivity, and Amount | 30 minutes | Important for AMV |
| Volcanic Ash Height and Optical Depth | 30 minutes | Aircraft safety |
| Fog and Surface Visibility | 30 minutes | |
| Forest Fires, Hot Spots | 1 hour | |
| Snow & Ice mapping (cover and depth) | 6 hours | Resolution 2 km |
| SST: Sea Surface Temperature | 2 hours | Resolution 4 km |
| LST: Land Surface Temperature | 2 hours | Resolution 4 km |
| Surface Albedo | 6 hours | Resolution 10 km |

| Product | Latency | Comment |
|---|---|---|
| Aerosol Optical Depth (AOD) | 6 hours | Resolution 10 km |
| Atmospheric Stability Index | 1 hour | Resolution 10 km |
| Aircraft Icing | 15 minutes | Resolution 10 km |
| Total Ozone | 1 hour | Resolution 10 km |
| NDVI: Normalized Difference Vegetation Index | 1 day | Resolution 1 km |
| FPAR: Fraction of Photosynthetically Active Radiation | 1 day | Resolution 1 km |
| LAI: Leaf Area Index | 1 day | Resolution 2 km |
| Radiative Fluxes (SW & LW at surface and TOA) | 1 day | Resolution 10 km |
| Land Surface Emissivity | 1 day | Resolution 4 km |

#### 4.4.2.2 Support for Climate Mission

Climate and surveillance types of satellites are greater in current number, have longer expected lifetimes, and have more scheduled launches than forecasting satellites. The number and type of sensors onboard satellites supporting the climate mission area are large and varied. Satellites in this category are sponsored and developed by 38 agencies from 18 different countries. The satellite sensors for the climate mission are generally less concerned about coverage compared to spatial resolution, which is driven by scientific criteria. Most sensor data taken over the course of a day in this area only cover one-fourth to one-half of the polar cap. Some of these sensors are second- or third-generation versions tailored to specific environmental retrievals. For example, the Landsat and the French Système Pour l'Observation de la Terre (SPOT) series of satellites have been in orbit since 1972 and 1986, respectively, with goals of improving the knowledge and management of Earth's resources. A great deal of the satellites deemed as climate missions also have important roles in both forecasting and surveillance due to the multipurpose quality of the data. Some of the sensors are one-of-a-kind and state-of-the-art that have resulted from significant research and development efforts. Climate-type sensors that show utility in weather forecasting do become part of operational satellites. The newer geostationary meteorology satellites have incorporated many new sensor designs from multipurpose polar LEO satellites. Meteosat satellites, for instance, have developed from 3 bands to 16 bands in the future third-generation series and look much more like the nonoperational Moderate Resolution Imaging Spectroradiometer (MODIS) multipurpose climate sensor. The new GOES-R sensor will also possess 16 bands, a jump from the current five channels, and will collect data at one-half the current pixel resolution that is in line with climate sensor technology (GOES-R 2014).

Multipurpose scientific satellites often supply valuable data for product enhancement and new product development. One valuable technique for Arctic remote sensing is the separate identification of clouds from ice. One such technique was developed at Sandia National Laboratories (Sandia) and received a U.S. patent in 2009. The VNIR Opaque Cloud Detection Algorithm (Patent #US7480052)[20] utilizes reflectance data from three distinct bands in the visible, near-infrared (VNIR) spectrum to detect opaque clouds over water, vegetation, desert, snow, and ice surfaces. Data from the Multi-Thermal Imager (MTI) satellite, a multipurpose science satellite developed by the Department of Energy (DOE), was used to test the algorithm. Figure 4-5 shows how a nonopaque, semitransparent cloud in an MTI visible band (left) is identified, using a single test of the algorithm over snow, ice, and water near Barrow, Alaska. The low-light conditions create a difficult scenario in which clear snow and ice regions are bright; thin cloud is gray; and cloud shadows, city streets, and water are dark. The Normalized Reflectance Difference (NRD) test is the ratio of the difference between a near-IR and short-wave visible band divided by their sum. The right image of Figure 4-5 shows the NRD values with the thin cloud appearing light blue with values just under zero. Positive NRD values result from snow and ice surface, whereas dark regions are from shadow and water. This test is able to separate clouds because they are spectrally more flat than any of the types of surfaces.

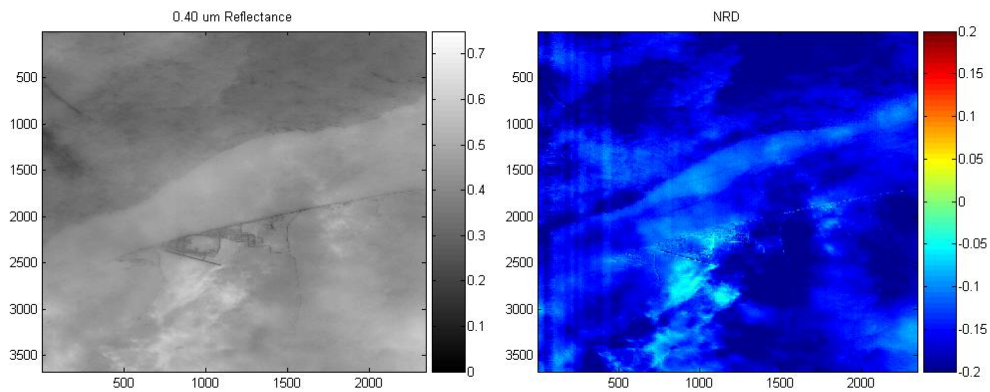



**Figure 4-5.** MTI Band A reflectance (left) and the NRD values (right) over Barrow, Alaska, showing thin stratus above snow, sea ice, and water.

Using more channels from the MODIS sensor, three-color images can clearly color-code clouds above ice as is apparent from the bottom image of Figure 4-6. The true color image (top) shows the similarity of illuminated cloud and ice in traditional visible band imagery. By assigning the correct band combination (visible, short-wave IR, and thermal IR) and scaling to a three-color image, cloud and ice can be somewhat easily identified. This image was likely made from the Normalized Difference Snow Index (NDSI) technique, which is sensitive to the spectral differences in visible and snow absorbing bands.

[20] See http://www.google.com/patents/US7480052 for a description of the patent (accessed on June 20, 2014).

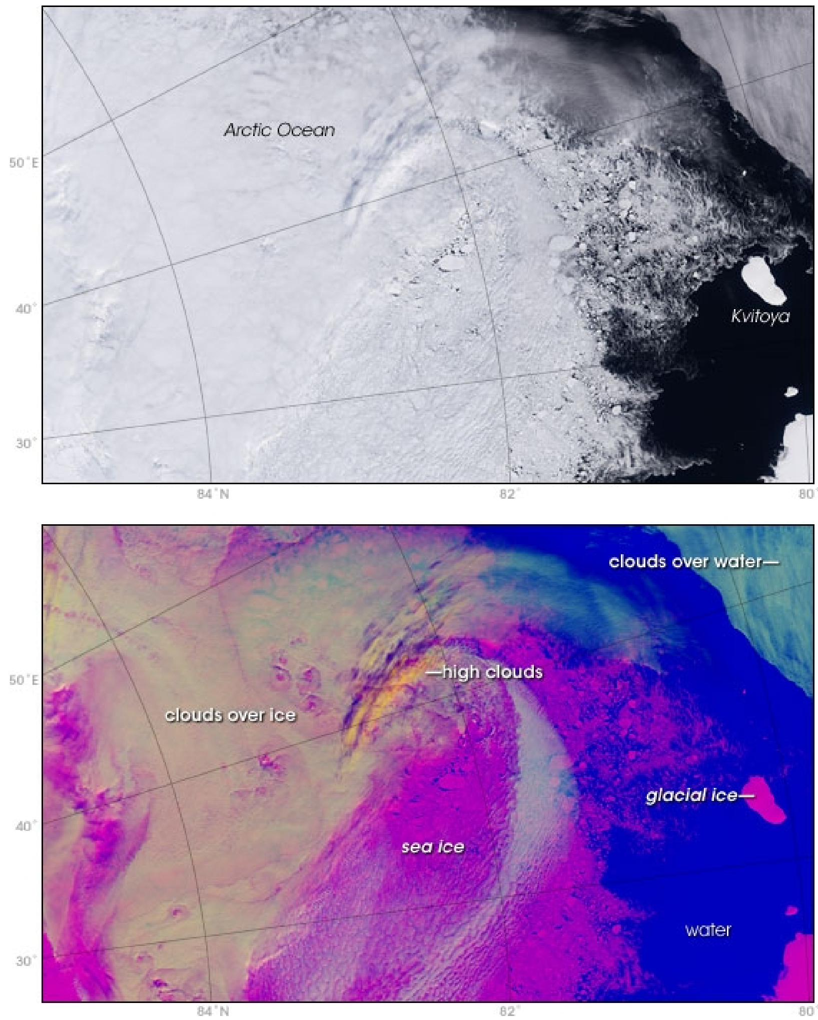



**Figure 4-6.** MODIS true-color image (top) and cloud-ice three-color image (bottom) by Robert Simmon and Jesse Allen (NASA Images 2014).

One of the important aspects to the climate mission is ensuring long-term continuous data that adequately support climatic trending. There is a less centralized effort that addresses this fundamental issue than in the other three mission areas. Sensor design seems to be driven more by individual organizations with research and development interests than by a central, focused mission concept. Regardless, climate and environmental research has been funded at a sufficient level by many countries over the last decade and has sustained the development and production of important satellite sensors that have provided measurements and assessments in several key climate areas. Three of these areas important to Arctic climate are the surface, clouds and aerosol, and trace gases.

The monitoring of specific surface properties such as sea ice, ocean properties, and land surface characteristics has received a great deal of satellite sensor support. Sea ice cover is one of the most important and indefinable parameters for Arctic climate analysis. Tracking the sea ice cover is the responsibility of the National Snow and Ice Data Center

(NSIDC), a multiagency organization operated by the Navy, NOAA, and the United States Coast Guard. Sea ice products are derived primarily from passive microwave sensors. The mean September 2007 Arctic sea ice concentration derived from Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and DMSP Special Sensor Microwave Imager (SSM/I) passive microwave data is shown in Figure 4-7.

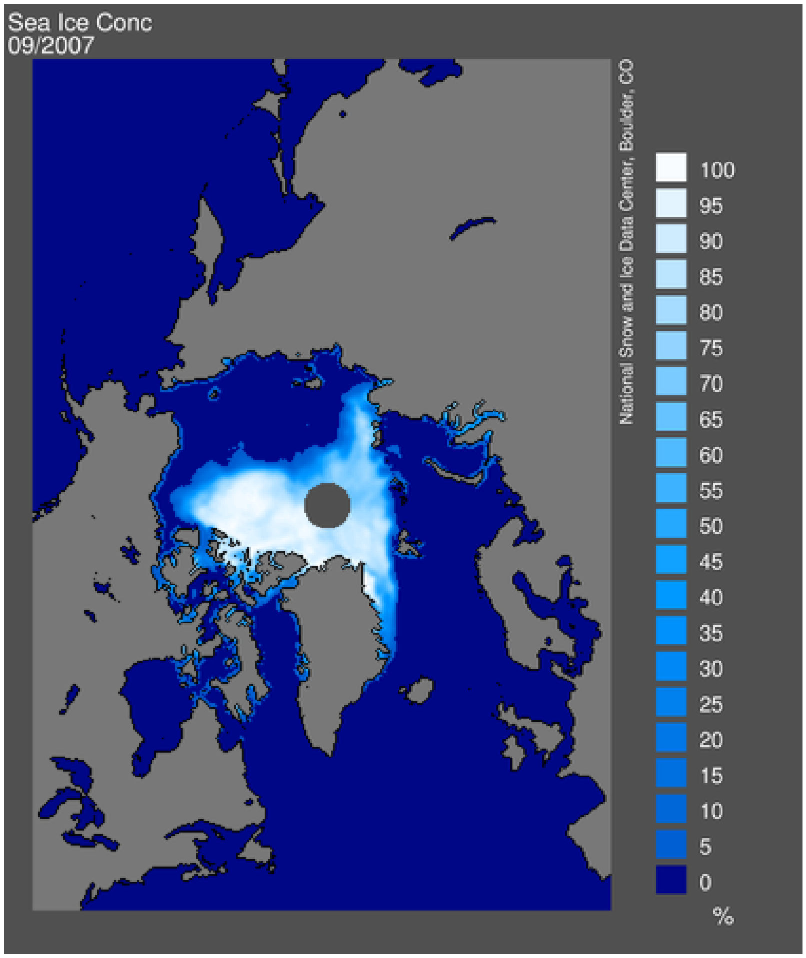



**Figure 4-7.** The mean sea ice extent in September 2007 derived from Nimbus-7 SMMR and DMSP SSM/I passive microwave data. Image courtesy of NSIDC (https://nsidc.org/).

The NSIDC also produces ice products from VNIR sensors such as MODIS. NASA's IceSat-2 sensor planned for launch in 2016 possesses an altimeter light detection and ranging (LIDAR) sensor that accurately measures ice height and can, therefore, infer thickness, at least above the ocean surface. Since the IceSat sensor failed in 2010, NASA has been flying DC-8 aircraft over the ice for a program called IceBridge. This gap in satellite-sensor continuity can cause uncertainty in climate trending. Currently, existing sensors from other countries should be able to fill gaps if collections are co-planned and information is shared. It is unclear that this is currently the case from examining the NSIDC web site. For instance, there is no mention of the ESA (European Space Agency) CryoSata-2 Synthetic Aperture Radar (SAR) sensor that can measure ice height–sea surface difference as well. Several other SAR systems exist from the CSA and the Deutsches Zentrum fur Luft und Raumfahrt (DLR) or German Aerospace Center. Sandia's SAR groups have systems that have been employed in Antarctica for identification of appropriate aircraft landing sites in poor weather and illumination conditions. High-resolution multispectral imagers such as LandSat and MTI can resolve fine structure in ice fields. Figure 4-8 shows an MTI true-color image (left) and a thermal three-band composite image (right) of broken Arctic sea ice. The thermal composite image shows differences in open water (warm and red), thin ice layers (cool, light blue), and subsurface ice cracks (dark blue).

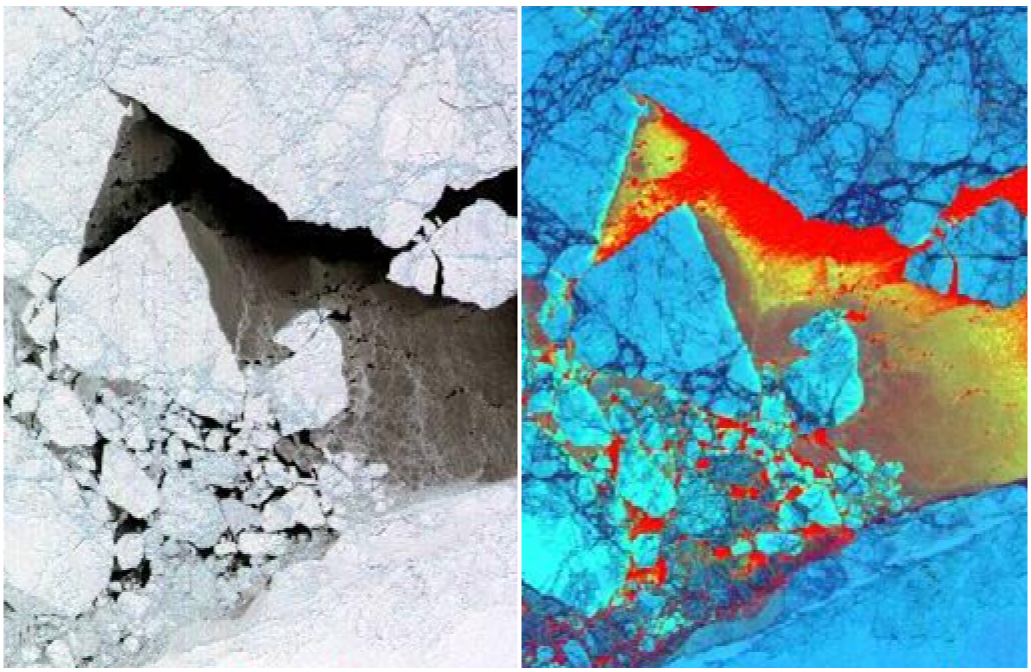


**Figure 4-8.** MTI true color image (left) and thermal three-band composite (right) of Arctic sea ice.

Ocean- and land-surface properties are important to monitor for studying climate. The Arctic Ocean has the lowest salinity of any ocean on Earth due to low evaporation rates and fresh water infusion from melting ice. Monitoring ocean salinity, temperature, and color (biological production) consistently is difficult to do in situ because of the harsh environment. Ocean color is being monitored by many multispectral satellite sensors such as MODIS and the Visible Infrared Imager Radiometer Suite (VIIRS) and will continue to be with a large number of near-future planned sensors. Many current and future active radar sensors are focused on deriving ocean surface properties such as wave height, currents, and wind speed. The least supported ocean area is salinity measurements. The only current long-lasting satellite useful for salinity measurements is the Aquarius sensor onboard the SAC-D satellite that has a mission EOL date around 2015 to 2017. Not until 2019 with the launch of the EPS-SG-a and the Sentinel-5 EUMETSAT satellites will the Arctic Ocean salinity mission once more commence. There is sure to be a major data gap of two to four years. Land properties, such as vegetation indices, temperature, and soil moisture, are being derived from many passive multispectral and microwave sensors as well as from active radar satellites. Questions remain about the accuracy of each sensor-derived product that will require greater investigation.

Cloud and aerosol properties are routinely retrieved around the globe by moderate-resolution multipurpose sensors. The Arctic environment, as previously discussed, is much more demanding on retrieval processes. Properties such as optical depth and effective particle size are more accurately determined using reflected sunlight, but much of the annual period at the poles exists in total darkness or with very low illumination. Liu et al. (2004) found that 44% of the detected cloud by an active LIDAR system during the polar night was not detected by MODIS algorithms that rely on thermal band data. In addition, 8% of true clear sky was retrieved as cloud. These inaccuracies were somewhat mitigated by new algorithm processes, but the results indicate the difficulty involved with Arctic-cloud remote sensing during large portions of the year. Long-term climatic analyses are affected by cloud misrepresentations. In a more recent study, Liu et al. (2010) discovered that decadal cloud totals in the Arctic may be in error by 2.7%, which could result in an 8.5% error in surface net radiative forcing in the region. Even with abundant sunlight, cloud properties over ice are much more difficult to retrieve. The major issues in deciphering clouds from ice from space are as follows:

- Snow, ice, and clouds are all very reflective and bright.
- Clouds are often made of ice or mixed water/ice phase.
- Thin clouds do not obscure the surface; radiometric signals emanate from both the surface and clouds.
- Clouds can be warmer or colder than a snow surface or an ice surface.
- Discriminating clouds from ice often requires tricky algorithms that do not work in all situations.

Continued research and development of sensors that collect data with appropriate resolution so that the sensors are sensitive to cloud over ice will be important for future improvements in the retrieval of cloud properties.

Aerosols and black carbon in the Arctic are also very difficult to measure due to the very bright surface, the high amount of clouds, and the low reflectivity of the aerosols themselves. Aerosols, due to their small size, impart a very small influence in the IR spectral region, making their measurement nearly impossible during the long dark Arctic periods. Unfortunately, their influence on Arctic climate may be somewhat important. Aerosols can influence the radiative budget in opposite ways. Particles that primarily scatter increase the Earth’s albedo and produce a cooling effect while those that absorb sufficiently can warm. Small particles also affect climate indirectly by becoming cloud condensation nuclei (CCN). The CCN may cause a higher occurrence of clouds and increase cloud reflectivity. In a comprehensive modeling study, Shindell and Faluvegi (2009) showed that aerosols may have contributed to 45% of the Arctic warming during the last 30 years, on par with that from increased greenhouse gases. There are two important aerosol contributions: a reduction in sulfate aerosols (which are reflective and are thought to lead to cooling) due to antipollution legislation and an increase in black carbon due to the intensification of fossil fuel combustion in Asia. Black carbon and its relation to warming in the Arctic are of growing scientific interest. The larger warming seen in the Arctic compared to that in the Antarctic supports aerosol impact since these anthropogenic aerosols are produced at a higher rate in the Northern Hemisphere.

A new focus on understanding the role in which trace gases play in climate change has emerged. The systematic measurement of stratospheric ozone from satellites is well established (National Research Council 2000). As of 2012, 16 satellites had sensors that collect data in which ozone can be determined. Post-2012 another 17 satellites containing ozone sensors were approved for near-future launch, with 11 more in the planning stages. The measurement of stratospheric ozone has become nearly operational, as the monitoring of the two polar ozone holes is a high priority. The measurement of ozone is also fairly straightforward with both ultraviolet (UV) and IR techniques available for year-round derivations. Deriving greenhouse gas concentrations are more difficult from space. IR methods are only sensitive to midtropospheric levels, so more attention has turned to visible and short-wave IR (SWIR) data, which utilize reflected sunlight. Many important greenhouse gases produced in man-made processes exist in low concentrations that are impossible to derive remotely, especially from space. As a result, the focus has been on designing instruments that are sensitive to the gases with larger atmospheric concentrations, such as carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), and nitrogen dioxide ($NO_2$). Retrieving gas concentrations in the polar regions is additionally difficult due to low solar irradiance, excessive cloud cover, and difficulty identifying clear sky over ice. Figure 4-9, obtained from the SCIAMACHY website, shows the global annual mean $CO_2$ mole fraction derived from the SCIAMACHY sensor in 2005. It is apparent that $CO_2$ can only be derived above non-ice land surfaces.

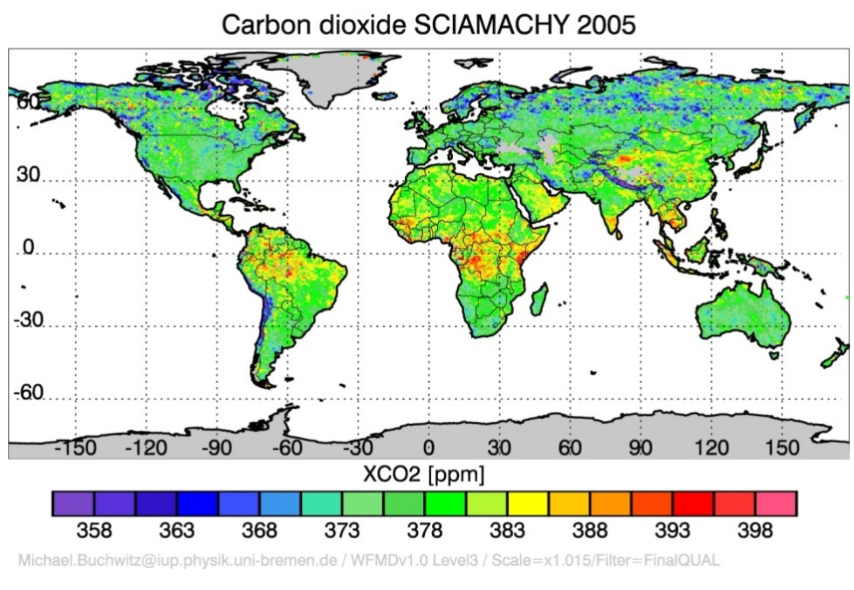


**Figure 4-9.** Mean global 2005 $CO_2$ mole fraction derived from the SCIAMACHY sensor [Source: http://www.sciamachy.org/products/index.php?species=CO2].

Due to low gas SNR from measurements taken by fast-moving LEO satellites, data have traditionally been collected at large resolutions of tens of kilometers. Mean atmospheric concentrations can be derived in time using many temporal measurements, but precise instantaneous gas concentrations required for source attribution derivations require more sensitive sensors. The orbiting Greenhouse gases Observing SATellite (GOSAT) satellite has reduced the derived $CO_2$ and $CH_4$ spatial resolutions to about 10 km (GOSAT Project 2013). The future Orbiting Carbon Observatory (OCO) satellite will reduce these resolutions even further to a few kilometers and retrieve $CO_2$ (only) with 1–2 parts per million (ppm) precision, half that of GOSAT, that will raise the possibility of better distinguishing between natural and anthropogenic $CO_2$ (NASA 2014). The interest in deriving greenhouse gas concentrations suitable for climate- and treaty-monitoring purposes prompted the establishment of the GreenHouse Gas Information System (GHGIS) study for which Sandia took the lead organizing role as well as the data integration design role. This study discussed the difficulty in regional and global measurement of trace gases but showed the utility of central planning in a dedicated multiagency effort (Dimotakis et al. 2011). The current lack of collaborative initiative in this scientific area has resulted in undefined requirements and crucial data gaps in the precise measurements required to fulfill future climate and treaty-monitoring missions.

#### 4.4.2.3 Support for Surveillance Mission

There appears to be ample support for satellites in this mission area as 47 high-resolution satellites were approved or planned for launch from 2012 to 2020. There is a good mix of sensors between the optical requiring clear sky and daylight and SAR that are not limited by clouds or solar illumination. The major limitation of these sensors is their small coverage area, making their capability dependent on their ability to know where to point. The daily maximum coverage of the Arctic region for each sensor is roughly 5%. Large-scale monitoring would require the consolidation of data from many sensors, an effort that is naturally challenging because of the 17 agencies from 14 different countries that own surveillance-type satellites currently. In addition, because these sensors produce imagery and data products that are often strategically sensitive to the individual country, cooperation and data sharing become more difficult. Lastly, many systems are built by private, for-profit companies that require high-prices or predefined contracts in place before data are given.

Development of surveillance satellite sensors often results because of a particular country's necessity. For example, Norway possesses a great deal of coastline adjacent to open ocean important for transportation and travel. The security need to monitor this large susceptible area has resulted in their development of a new satellite with the Automatic Identification System (AIS), which is an automatic electronic tracking system used by ships for ascertaining position, course, speed, and vessel-identification information. Many countries build high-resolution optical satellite systems to monitor their borders and the environment as well as for disaster prevention and assistance. For many satellites, the owning country may not have any active interest in the Arctic, yet the sensor data could be useful for Arctic-monitoring activities. Monitoring the Arctic Ocean in regions of ship transit is an important function. A visible true-color high-resolution (5 meter [m]) image in Figure 4-10 shows the sea ice state and free-ice locations in the Arctic Ocean just off the coast of Barrow, Alaska. This type of imagery is valuable for vessels in transit through the area, especially if it could be produced in near–real time. MTI data and imagery are not real-time products primarily due to the New Mexico location of the single ground station.

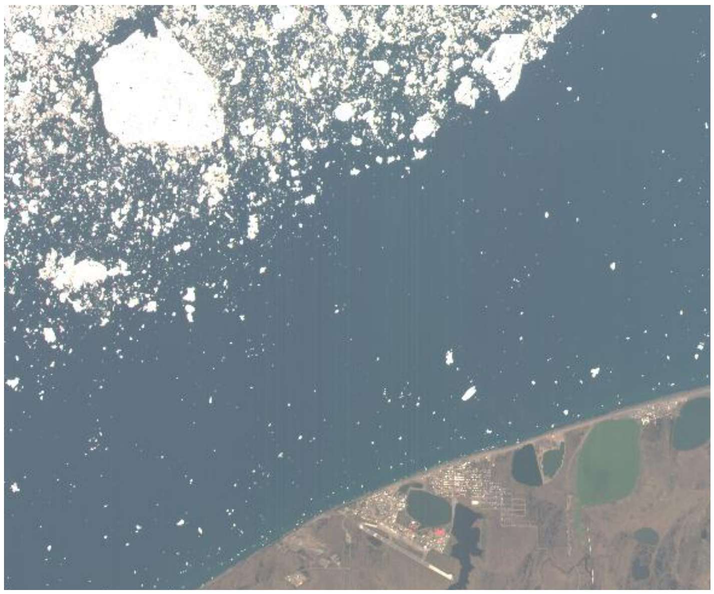


**Figure 4-10.** True color MTI image of free sea-ice near Barrow, Alaska.

Disaster monitoring for prevention and mitigation is expected to increase in importance in the Arctic due to an increase in future human activity, such as Arctic oil drilling, with warming. The potential for accidents and the degree of difficulty in responding to any that occur is seen to be greater in this region than in other areas where the environmental conditions are not as severe. Surveillance satellites have the ability to contribute during accidents on ocean oil platforms. Explosions and fires can be detected by IR sensors. With the exception of MTI and Landsat, there are few high-resolution thermal surveillance sensors available for civilian use. Multipurpose climate sensors like MODIS could be used in cases of large, hot fires. According to Brown and Fingas (2005), satellite imagery is used more for strategic planning in oil spills than for tactical planning. Brekke and Solberg (2005) have stated that many countries in northern Europe use a combination of satellite sensors and airborne sensors for oil-spill surveillance because airborne sensors are more useful for short-term, tactical response. Satellite data are best used for wide-area, synoptic viewing of the affected area. Figure 4-11 shows a MODIS true-color image with dozens of natural crude oil seeps from the deep sea floor in the central Gulf of Mexico. The streaks appear darker than the glinting sea surface because the oil decreases the roughness of the ocean surface, smoothing it out. Depending on the sun and sensor orientation, the oil streaks could appear brighter or darker than the ambient surface.

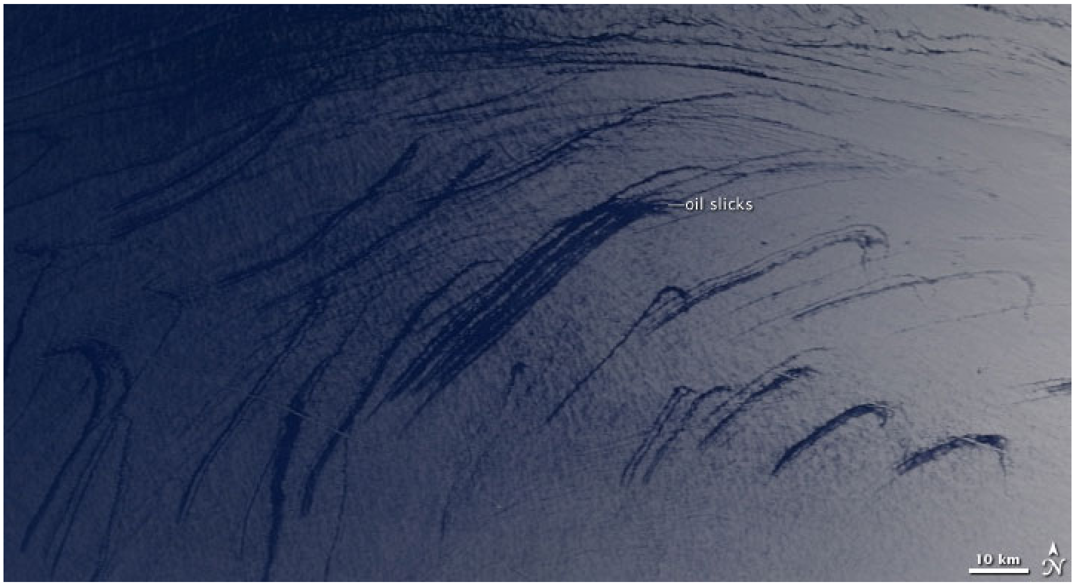



**Figure 4-11.** MODIS true-color image of the Gulf of Mexico on May 13, 2006. The bright surface on the right is due to sun glint. Dark streaks are oil slicks [Source: NASA Earth Observatory at http://earthobservatory.nasa.gov/IOTD/view.php?id=36873].

The detection and monitoring of oil spills and ocean seeps is performed by visible, IR, microwave, and radar satellite sensors. SAR systems seem to be the most reliable because they can be used at all times—day and night and in any weather condition. Despite this comprehensive capability of SAR systems, remote sensing of ocean surface phenomena remains a challenge. In an investigation using data from the RADARSAT-1 SAR, Simecek-Beatty and Pichel (2006) reported that oil-spill monitoring in Unalaska Island, Alaska, was plagued by false positives due to a large number of biogenic films present near the island. Further, tasking the early SAR systems in real time was also not possible. An emergency feature in RADARSAT-2 allows for the tasking of satellites to the site of an oil spill in less time. The radar backscatter is also very dependent on the sea-surface wind because of its influence on the ocean-surface wave pattern. Oil slicks are visible to SAR systems to different degrees for various ranges in wind speeds. A general overview of SAR sensitivity of oil spills for various wind speed ranges, as compiled by Bern et al. 1992 and Perez-Marrodan 1998, is given below in Table 4-6. It seems apparent that accurate detection of surface oil on the ocean from remote sensors is highly dependent on many aspects, including sensor proximity, environmental conditions, and having the ability to task the satellite.

### Table 4-6. Visibility of Oil Slicks in SAR Images (Bern et al. 1992; Perez-Marrodan 1998)

| Wind speed (meters per second [m/s]) | Slick signatures |
|---|---|
| 0 | No oil signal due to no SAR backscatter off flat ocean |
| 3 | High probability of false alarms due to local low-wind |

| Wind speed (meters per second [m/s]) | Slick signatures |
|---|---|
| | variations |
| 3–7 | Oil slick visible due to homogeneous high backscatter background |
| >7 | Only thick spills visible since thin spills are dispersed |

#### 4.4.2.4 Support for Communications Mission

Only a few current and near-term future satellites are planned to serve the growing communication needs of the Arctic. Due to the long distance of the remote polar regions over the horizon, communication is problematic. Satellite relays are needed to maintain consistent open channels of communication. The following excerpt from the CSA (Canadian Space Agency) website provides a good description of the communication problem in high latitudes:

> Telecommunication services are the backbone of a modern society. Currently, most of the telecommunication needs in remote areas are served by the geostationary communications satellites (GEO). … However, due to the orbit geometry, there are parts of the Canadian territory that cannot be covered at all by the GEO satellites. Also there are some limitations to what GEO satellites can offer in the High Arctic, particularly for mobile services such as ships, planes and Unmanned Aerial Vehicles (UAVs). That leaves a part of the Canadian territory in the Arctic region without access to secure, highly reliable and high capacity telecommunication solutions. (CSA 2014)

Improvement in polar communications will likely remain an issue for some time, but a few important efforts are under way. The Naval Research Laboratory (NRL) TacSat-4 satellite, the last of the Operational Responsive Space (ORS) experimentation, exists in a HEO-type orbit and has demonstrated that it can provide long-distance communication from the surface in the Arctic for half of its four-hour orbital period. TacSat-4 provides 10 UHF channels to support general communications, data linking (to arctic buoys), and Blue Force tracking simultaneously. The HEO position is being worked on to minimize the total number of satellites required for a constellation for continuous communication.

The Iridium communication constellation contains 66 satellites in six orbits at 780 km altitude.[21] Theoretically, this constellation offers continuous communications everywhere on the globe, even at the poles, using hand-held phones. Future satellites (Iridium Next) are planned with upgrades in bandwidth and possibly imaging capability. This next-generation system will not be fully functional until past 2020. To maintain connectivity, a clear line of sight (LOS) is required, causing problems if the operator is indoors, under

[21] Iridium facts are from webpage at http://www.iridium.com/About/IridiumGlobalNetwork/SatelliteConstellation.aspx (accessed on June 20, 2014).

canopy, or obscured by terrain. The primary users of the existing Iridium satellite constellation are military and those in remote areas, such as the ocean and polar regions. In 2011, the National Defense Budget Authorization Act rejected the budget proposal of $40.9 million for the High-Integrity Global Positioning System (HIGPS) (U.S. House 2010). The goal of HIGPS was to develop the technology required for demonstrating the capability of using the existing Iridium satellite constellation to enhance current ground-positioning-system navigation and timing capabilities. Improved communication in the high latitudes would have had important future implications for Arctic navigation because communications in the polar regions are susceptible to interruptions from solar storms (Bedingfield, Leach, and Alexander 1996). Satellite functionality is also put in significant jeopardy from strong solar activity. The U.S. Deep Space Climate Observatory (DSCOVR) satellite planned for launch in 2014 will be located at the $L_1$ Lagrangian point between the Earth and the Sun, where the gravitational forces of each are equal. This satellite will be able to detect the magnitude of solar activity and produce a warning 15 minutes before the event.

The most important future assets for future Arctic communications are the Canadian PCW (Polar Communications and Weather) satellites, previously discussed for their vital role in the polar weather-forecasting mission. Two satellites in high-altitude HEO will provide individual long-duration-communications infrastructure over the north polar region. This system should substantially improve weather forecasting, climate study, and communications in the Arctic. In particular, the primary telecommunications payload (utilizing the Ka-band frequency) will consist of a high-speed two-way system capable of providing continuous broadband services to users throughout the Arctic as far as the North Pole.

### 4.4.3 Classified Satellite Missions

Data from classified satellite systems could potentially provide important information to enhance the specific mission areas defined and discussed in the previous sections. Due to the classification level of this report, specific information will not be described here. Historically, there has been previous sensitive data support for environmental missions (see Section 9 of this report for more details). Sandia may be able to play a sizable role in orchestrating specific sensitive satellite tasking and data collections as well as in producing data products useful for Arctic activities.

## 4.5 Summary and Future Work

This section reviews the major findings of this brief study of satellite assets and their usefulness in supporting important missions in the Arctic. A summary of the key points made is followed by a short discussion on future work that would naturally follow this effort.

### 4.5.1 Key Points

A variety of satellites is currently orbiting the Earth, taking measurements of the Arctic for multiple reasons. The large number of sensor types and products that are sponsored by many agencies and countries makes it challenging to determine the overall effectiveness of the collected data in terms of specific mission utility. This effort has begun that process by outlining and correlating individual satellite sensors with specific Arctic-related missions. The major efforts and outcomes that resulted from this study are summarized in bullet points as follows:

- This study has identified four major mission areas in the Arctic that satellite data can support.
- This study has determined and summarized important issues pertaining to satellite measurements in polar regions that impact mission support.
- For this study, a thorough web-based survey was performed of all current and near-term approved and planned satellites with importance for Arctic remote sensing. Essential characteristics of each satellite have been identified to determine the utility of each system. Due to this arduous process, specific sensor-derived products have not been thoroughly investigated. Knowledge of these products will help to improve our understanding of their usefulness.
- A simple statistical assessment of current and future systems has been made based on general assumptions about mission utility for the purpose of identifying the state of mission-area support, limitations, and gaps.
- This study has discussed the utility of satellites for Arctic measurement with the following main points.
    - Satellites observing the polar region are primarily in LEO with high-overpass velocities (~7 km/sec) at intervals of 90–100 minutes.
    - Polar remote-sensing issues adversely affect satellite data in terms of the difficulty in producing quality products.
    - Polar coverage is generally low for single overpass. Most meteorology satellite systems include multiple satellites to increase coverage and data collection, but it is still insufficient for model input due to coverage and quality issues. The future Canadian HEO satellite system, PCW, will more closely resemble current GEO-operational satellites with improved spatial and temporal data coverage.
    - Science satellites can produce more sophisticated products but with less coverage. Multisatellite, multiagency, and multicountry cooperation is needed to increase the amount of useful data.

- Data assimilation issues (formats, timeliness, and quality) need to be given priority so that science products can be more easily transitioned for operational use.

- Surveillance satellites produce important data for closely monitoring the Arctic for security and environmental reasons; however, coverage, tasking, and harsh conditions still make this mission area challenging.

- Regular communication in the Arctic is difficult. The Iridium constellation offers the only option. Future military and Canadian satellites systems (PCW) offer real future communication options.

- This study has developed recommendations for improving satellite remote-sensing support to the various mission areas of interest based on the overall satellite assessment.

- This study has identified areas of future work, as discussed next.

### 4.5.2 Future Work

Due to project resources, only an initial assessment of the large number and wide variety of orbiting sensors could be made. This project does represent an excellent stepping off point for future work. Future efforts in the assessment of satellite data utility to support and enhance Arctic operations as well as research and development are given below.

- Further assessment of satellite sensors and derived products
  - Assess for separate day and night conditions.
  - Investigate product quality and frequency over the poles.
  - Identify the most important data needs for weather-forecasting models.
  - Leverage the Observing Systems Capability Analysis and Review (OSCAR) web-based tool that provides a brief summary about sensor and data usefulness.
- Further investigation of data assimilation issues
  - Attend Weather Research and Forecasting (WRF) model data-assimilation workshops to further understanding of issues and potential improvements.
  - Work closely with the modeling community to understand issues.
- More focus on classified systems
  - Create a special classified report.

– Implement special collections on certain classified systems in the Sandia sphere of influence.

## 4.6 References


Air Force Space Command. (2013). *Resiliency and Disaggregated Space Architectures*. White Paper. http://www.afspc.af.mil/shared/media/document/AFD-130821-034.pdf (accessed on June 19, 2014).

Bedingfield, K. L., R. D. Leach, and M. B. Alexander. (1996). *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment*. NASA Reference Publication 1390. http://maelabs.ucsd.edu/mae155/classes/wi_05/space%20envt_nasa%20rp1390.pdf (accessed on June 19, 2014).

Bélanger, S., J. K. Ehn, and M. Babin. (2007). “Impact of Sea Ice on the Retrieval of Water-leaving Reflectance, Chlorophyll a Concentration and Inherent Optical Properties from Satellite Ocean Color Data.” *Remote Sensing of Environment* 111, no. 1: 51–68.

Bern, T. -I., S. Moen, T. Wahl, T. Anderssen, R. Olsen, and J. A. Johannessen. (1992). *Oil Spill Detection Using Satellite Based SAR*. Completion report for Phase 0 and 1. Tech. rep., OCEANOR report no. OCN-R92071. Trondheim, Norway: OCEANOR.

Brekke, C., and A. H. S. Solberg. (2005). “Oil Spill Detection by Satellite Remote Sensing.” *Remote Sensing of Environment* 95, no. 1: 1–13.

Brown, C., and M. Fingas. (2005). “A Review of Current Global Oil Spill Surveillance, Monitoring and Remote Sensing Capabilities.” In *Proc. 28th Arctic and Marine Oil Spill Program (AMOP) Tech. Seminar,* Calgary, Canada, June 7–9, 2005, 789–798.

Buchwitz, M. (2012). Personal communication with John Roskovensky.

CEOS (Committee on Earth Observation Satellites) ESA (European Space Agency). (2014). CEOS EO Handbook Catalogue of Satellite Missions. [The CEOS Database]. http://database.eohandbook.com/database/missiontable.aspx (accessed on April 5, 2014).

Chouinard, C., and J. Hallé. (2003). “The Assimilation of AMSU-B Radiance Data in the Canadian Meteorological Centre Global Data Assimilation System: Their Difficulties Relative to the Assimilation of AMSU-A Radiances.” In *Proceedings of the 13th International TOVS Study Conference (ITSC-13)*, St. Adele, Canada, October 29–November 4, 2003, 1–14.

CPI (Computational Physics, Inc.). (2014). “Space Situational Awareness.” http://www.cpi.com/capabilities/ssa.html (accessed on April 5, 2014).

CSA (Canadian Space Agency). (2014). http://www.asc-csa.gc.ca/eng/satellites/pcw/ (accessed on April 7, 2014).

Dimotakis, P. E., B. C. Walker, K. K. Jonietz, and D. A. Rotman. (2011). *A Greenhouse-Gas Information System, Monitoring and Validating Emissions Reporting and Mitigation*. A report prepared for the Department of Energy Office of Science, published by Los Alamos National Laboratory, LA-UR 11-05512. http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-11-05512 (accessed on April 7, 2014).

DOD (U.S. Department of Defense). (2011). *Report to Congress on Arctic Operations and the Northwest Passage*. DOD Report 5-750938C. Washington DC: Department of Defense. www.defense.gov/pubs/pdfs/Tab_A_Arctic_Report_Public.pdf (accessed on April 7, 2014).

GAO (U.S. Government Accountability Office). (2012). *Arctic Capabilities, DOD Addressed Many Specified Reporting Elements in Its 2011 Arctic Report but Should Take Steps to Meet Near- and Long-term Needs.* GAO-12-180. Washington, DC: Government Accountability Office.

GOES-R. (2014). "Advanced Baseline Imager." http://www.goes-r.gov/ (accessed on June 20, 2014).

GOSAT (Global Greenhouse Gas Observation by Satellite) Project. (July 2013). 6th Edition 4th Revision. http://www.gosat.nies.go.jp/eng/GOSAT_pamphlet_en.pdf (accessed on June 20, 2014).

Hill, V. J., and R. C. Zimmerman. (2010). "Estimates of Primary Production by Remote Sensing in the Arctic Ocean: Assessment of Accuracy with Passive and Active Sensors." *Deep-Sea Research Part I-Oceanographic Research Papers* 57, no. 10: 1243–1254.

JPSS. (2014). National Environmental Satellite, Data, & Information Service Joint Polar Satellite System. http://www.corporateservices.noaa.gov/nbo/fy11_budget_highlights/JPSS_Budget_Highlights.pdf (accessed on July 16, 2014).

Liu, Y., J. R. Key, R. A. Frey, S. A. Ackerman, and W. P. Menzell. (2004). "Nighttime Polar Cloud Detection with MODIS." *Remote Sensing of Environment* 92, no. 2: 181–194.

Liu, Y., S. A. Ackerman, B. C. Maddux, J. R. Key, and R. A. Frey. (2010). "Errors in Cloud Detection over the Arctic Using a Satellite Imager and Implications for Observing Feedback Mechanisms." *Journal of Climate* 23, no. 7: 1894–1907.

Martin, J., J. É. Tremblay, J. Gagnon, G. Tremblay, A. Lapoussière, C. Jose, M. Poulin, M. Gosselin, Y. Gratton, and C. Michel. (2010). "Prevalence, Structure and

Properties of Subsurface Chlorophyll Maxima in Canadian Arctic Waters." *Marine Ecology-Progress Series* 412: 69–84.

NASA. (2014). "Orbiting Carbon Observatory (OCO-2)." http://oco.jpl.nasa.gov/ (accessed on June 20, 2014).

NASA Images. (2014). https://archive.org/details/ge_07378 and https://ia600500.us.archive.org/25/items/ge_07378/polar_tmo_2006172.jpg (accessed on June 20, 2014).

National Research Council. (2000). "Atmospheric Soundings." In *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part I. Science and Design*, 17–24. Committee on Earth Studies. Washington, DC: National Academy Press. http://books.nap.edu/openbook.php?record_id=9963&page=17 (accessed on June 20, 2014).

Pabi, S., G. L. Van Dijken, and K. R. Arrigo. (2008). "Primary Production in the Arctic Ocean, 1998-2006." *Journal of Geophysical Research: Oceans* 113, no. C8, C08005. Doi:10.1029/2007JC004578.

Perez-Marrodan, M. (1998). "ENVISYS—Environmental Monitoring Warning and Emergency Management System." In *Proceedings of the AFCEA Kiev Seminar*, Kiev, Ukraine, May 28–29, 1998, 122–132.

Perrette, M., A. Yool, G. D. Quartly, and E. E. Popova. (2011). "Near-Ubiquity of Ice-Edge Blooms in the Arctic." *Biogeosciences Discussion* 7, no. 2: 515–524.

Quarkology.com. (2014)."9.2.C - Orbits." http://www.quarkology.com/12-physics/92-space/92C-orbits.html (accessed on May 16, 2014).

Shindell, D., and G. Faluvegi. (2009). "Climate Response to Regional Radiative Forcing during the Twentieth Century." *Nature Geoscience* 2, no. 4: 294–300.

Simecek-Beatty, D., and W. Pichel. (2006). "W. RADARSAT-1 Synthetic Aperture Radar Analysis for M/V Selendang Ayu Oil Spill." In *Proceedings of the Twenty-ninth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, Vancouver, British Columbia, Canada, June 6–8, 2006, 931–949.

U.S. House. (2010). *National Defense Authorization Act For Fiscal Year 2011, Report of The Committee On Armed Services House Of Representatives On H.R. 5136 Together With Additional Views [Including Cost Estimate Of The Congressional Budget Office]*. 111th Cong., 2d sess., H. Rept. 111-491. http://www.gpo.gov/fdsys/pkg/CRPT-111hrpt491/html/CRPT-111hrpt491.htm (accessed on June 20, 2014).

Wang, M. H., and W. Shi. (2009). "Detection of Ice and Mixed Ice-Water Pixels for MODIS Ocean Color Data Processing." *IEEE Transactions on Geoscience and Remote Sensing* 47, no. 8: 2510–2518.

WMO (World Meteorology Organization). (2013). *Integrated Global Observing System Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP)*. Technical Report No. 2013-4. http://www.wmo.int/pages/prog/www/OSY/Publications/EGOS-IP-2025/EGOS-IP-2025-en.pdf (accessed on June 19, 2014).

# 5 Arctic Atmospheric Measurements by Unmanned Aircraft Systems and Tethered Balloons

Among twenty snowy mountains,
The only moving thing
Was the eye of the blackbird.

(Wallace Stevens, “Thirteen Ways of Looking at a Blackbird”)

Arctic visitors flying north from Fairbanks must transit the Brooks Range, a vast and desolate chain of mountains that extend across northern Alaska, marking the southern edges of the North Slope of Alaska. The snows of the Brooks Range are often lit in winter by brilliant and glowing aurora borealis but very rarely by lights of human origin, as this region of frozen rivers and boreal forests is essentially uninhabited during the Arctic winter. Seen from an airplane window, this view of an untouched and frozen wilderness is a stark reminder that scientific campaigns in these regions are performed without the reassuring availability of nearby civil infrastructure, emergency responders, or even basic services such as reliable terrestrial communications. Section 5 explores the scientific motivations for atmospheric measurements in the Arctic, describes how these measurements could be made with unmanned aircraft systems (UASs) or tethered (moored) balloons, identifies the primary drivers for unmanned systems, and discusses why unmanned systems are the best option when personnel safety is a priority.

## 5.1 Scientific Motivations for Arctic Atmospheric Measurements

Significant, interrelated atmospheric, oceanic, and terrestrial changes have been occurring in the Arctic in recent decades (SEARCH SSC 2001; ACIA 2005; NAS 2006; IPCC 2007; Overland 2009). Arctic temperatures have risen at almost twice the rate compared to the rest of the world for the last few decades (Serreze et al. 2009), resulting in broad-ranging land and ocean changes. Observations reveal reductions in perennial sea ice and summer sea ice extent (Markus, Stroeve, and Miller 2009), increased permafrost melt (Hinzman et al. 2005), and shifts in ecosystems (Prowse et al. 2009)—all indicators of changes in the Arctic with potential global repercussions. As a result, there has been a sustained interest in studying processes that might contribute to these accelerated changes in the Arctic. Various contributing factors have been identified, but in all likelihood, multiple factors contribute in a complicated, nonlinear way to changes in perennial and summer sea ice (Roberts et al. 2010). As a consequence, the variability in the prediction of climate trends is much greater in the Arctic than anywhere else on Earth.

This uncertainty in predicting climate trends derives from the important contribution of ice and snow in higher latitudes to climate trends through the ice-albedo feedback. Ice-albedo positive feedback is the phenomenon whereby an increase in ice melt leads to additional ice melt since solar radiation, normally reflected by ice, is absorbed by open, ice-free water leading to ocean temperature rise that in turn leads to additional ice melt. The magnitude of this feedback remains uncertain because the ice-albedo feedback is strongly coupled to Arctic cloud processes (Inoue, Liu, and Curry 2006; Tjernstrom, Sedlar, and Shupe 2008; Kay and Gettelman 2009). Clouds and atmospheric aerosols also play a dominant role in determining the regional radiation budget in the Arctic and the ice-albedo phenomenon. Clouds can produce a negative feedback in the ice-albedo phenomenon. Clouds, much like ice, can reflect incoming solar radiation and thereby reduce ice melt rates. Cloud formation can be further influenced by increased humidity levels resulting from the melting of sea ice. In addition, downwelling long-wave radiation from clouds in winter months appears to be an important and significant factor in sea-ice reduction (Burt, Randall, and Branson 2014; Kay et al. 2012).

The region in which clouds form is predominantly in the lower tropospheric layers, the structure of which is characterized by strong temperature inversions for most of the year. The properties that determine cloud impact on the surface energy budget and thermal structure of the atmosphere depend on aerosol layers that interact with the clouds. These aerosol layers, and indeed the water vapor necessary for cloud formation, may originate locally or may be advected into the local area from distant sources. Because all these factors are so strongly coupled with many of the processes not fully understood, they are not well represented in climate models. Indeed, assessments of the Community Climate System Model (CCSM4), one of the contributing models to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, reveal that the model still has large biases in the strength of the lower troposphere inversion, resulting in significant biases in clouds and their radiative impacts (de Boer et al. 2012). Moreover, model predictions of sea-level pressures in the Beaufort Sea area north of Alaska show monthly biases of up to 13 millibars, which is a large quantity and a further indicator of significant model error. Boé, Hall, and Qu (2009) pointed out that stronger inversion strengths in the Arctic lead to excessive negative long-wave feedback and hence reduced climate sensitivity.

Analysis of data from previous intensive observation periods with manned aircraft revealed clouds that were embedded in complex thermal and water vapor fields with large spatial and temporal variability. Most studies thus far have focused on a few "golden days" close to land, the conclusions of which yet have to converge to accepted interpretations (Avramov et al. 2011; Solomon et al. 2011) for relatively simple atmospheric structures such as a single-layer decoupled from the surface. Our knowledge of the structure and processes of the atmosphere in the deep Arctic (far from the land-sea interface) during winter come primarily from SHEBA (Surface Heat Budget of the Arctic Ocean) (Morrison et al. 2011). Conversations with Arctic atmospheric modelers (cloud resolving, regional climate and climate models) suggest that a zeroth-order problem for the modeling community is a lack of routine, long-term, distributed measurements of the atmospheric structure (Tjernstrom 2007). Such measurements are critical to resolving simple questions such as these: Do models routinely produce realistic atmospheric structures for the right reasons? What are the separate sources of water vapor and aerosol in the Arctic?

Achieving these goals in the Arctic will require spatially and temporally distributed observations of atmospheric state and surface conditions. Two types of observational data sets are needed:

1. Intensive, shorter-duration data sets with detailed characterization of surface-ice state, atmospheric thermodynamic state profiles, cloud properties, and short- and long-wave radiation measurements

2. Climate-scale observations for regional evaluation of the mean atmospheric and surface state and its temporal and spatial variability

Measurements of the first type of observational data set may best be obtained by intensive aircraft campaigns of relatively short duration that are focused on resolving identified needs for improving parameterizations in climate models. Such campaigns are best performed by large manned aircraft capable of carrying comprehensive sets of observing systems. Such campaigns are typically conducted close to the shore and airport facilities and can be done most efficiently by manned aircraft. Manned flights enable better in-flight decision making to achieve science mission objectives.

The type of observational data sets needed for assessments of climate models requires regular measurements over multiple seasons far offshore into the Arctic Ocean basin, with flights extending northward from the North Slope coastal plains and across the marginal ice zone. These data are needed to capture the seasonal, interannual, and spatial variability (or “Large System Variability”) of atmospheric and surface states. These measurements are essential for assessments of climate model performance and provide the basis for deciding which focused short-term campaigns will yield the highest impacts on climate simulations. Such observations can best be conducted by small, unmanned aircraft with measurements of the atmospheric and surface states. Mixed-phase clouds are of particular interest to the scientific community but are notoriously dangerous for manned flight systems. Safety and risk considerations for manned flight operations necessitate the use of twin-engine aircraft for flying into the potential icing conditions associated with mixed-phase clouds. For atmospheric measurements above the North Slope, these larger twin-engine aircraft are typically based in Fairbanks because North Slope hangar space is not readily available. The resulting long flights between Fairbanks and Barrow or Deadhorse add significantly to total flight hours and overall science-mission costs. The use of unmanned aircraft systems (UASs) is a safe alternative for probing these particular cloud conditions. These aircraft can be launched and controlled locally, and the personnel hazards associated with manned flight are eliminated with their use. Note that UASs are also referred to as unmanned aircraft vehicles (UAVs) in parts of this discussion.

Summarizing these observational requirements:

- Large system changes are observed in the Arctic, the magnitude of which are not captured well by any of the models used in the IPCC Fourth Assessment Report (AR4).

- Clouds play a dominant role in determining the regional radiation budget in the Arctic and are intimately linked to the ice-albedo feedback phenomenon.

- Analyses of CCSM4, one of the contributing models to the Fifth Assessment Report (AR5) of the IPCC, suggest that the atmospheric state is still poorly represented in that model, with particularly large biases over the Beaufort Sea.

- The physics of coupling between the clouds in the lower troposphere, characterized by strong stability for most of the year, and surface state is not captured well in models.

- Because the processes responsible for the structure of the lower troposphere are not well understood, the extent of the contribution of the negative cloud feedback on the ice-albedo feedback is not certain.

- These processes must be understood in the context of the strong seasonal changes in surface conditions over the Beaufort Sea.

- The highest priority need is for climate-scale (long-term) observations out over the off-shore Arctic basin to evaluate model processes and inform decisions for focused, short-term field campaigns to address understanding of specific processes. These climate-scale observations can be safely achieved by using small UASs.

Tables 5-1 and 5-2 match desired atmospheric observations to operational characteristics of manned and unmanned aircraft, using legends placed in the upper-left corner of each table. Science mission planners must consider safety, cost, availability, payload maturity, and other factors in choosing a measurement platform.

**Table 5-1. Selection of Aerial Measurement Platform Based on Climate Science Questions**

Legend: Yes; Often; Possible; Marginal; Not Practical

| Aerial Measurement Platform's Ability to Satisfy Science Questions | Arctic Atmosphere - High Priority Climate Science Questions | | | | | |
|---|---|---|---|---|---|---|
| | Large System Variability | Clouds and Ice-Albedo Feedback | Atmospheric State | Surface State Coupling to Lower Troposphere | Seasonal/ Spatial Variability | Model Process Evaluation |
| Small UAV's | Yes | Possible | Often | Often | Yes | Possible |
| Medium UAV's | Possible | Possible | Often | Often | Possible | Possible |
| Small Manned Aircraft | Marginal | Often | Often | Possible | Marginal | Yes |
| Large Manned Aircraft | Not Practical | Possible | Possible | Possible | Not Practical | Yes |

**Table 5-2. Selection of Aerial Measurement Platform Based on Suitability**

Legend: To a High Degree; Reasonably; To Some Degree; Marginally; Not Practical

| Aerial Measurement Platform | Arctic Offshore and Near-Shore Mission Suitability | | | | | |
|---|---|---|---|---|---|---|
| | Meets Safety and Regulatory Requirements | System Costs are Affordable | Good Mission Availability | Instruments are Mature | Operations and Maintenance Costs are Manageable | Satisfies Overall Science Questions |
| Small UAV's | Reasonably | Reasonably | Reasonably | Reasonably | Reasonably | Reasonably |
| Medium UAV's | Reasonably | To Some Degree | Reasonably | Reasonably | To Some Degree | Reasonably |
| Small Manned Aircraft | Marginally | Reasonably | To Some Degree | To a High Degree | Marginally | To Some Degree |
| Large Manned Aircraft | Reasonably | Marginally | Marginally | To a High Degree | Not Practical | Reasonably |

## 5.2 Measurements and UAS Payloads

Great strides could be taken toward making the desired observations and addressing the science questions posed above by using measurement payloads that have been previously demonstrated in polar regions mounted on "small" UASs. Small UASs in this case are defined as having a total weight of less than 55 pounds. Several key points with respect to small UASs are noteworthy and are listed below. Additional discussion is found in later sections.

1. The Federal Aviation Administration (FAA) has recently committed to changing flight and operational rules for UASs of less than 55 pounds (FAA 2013a).

2. The FAA is in the process of enacting rules that will simplify requirements (and thereby reduce mission costs) for scientific missions in the Arctic using UASs.

3. Payloads capable of measuring atmospheric variables and surface characteristics (including basic meteorological payloads; IR and optical imaging; as well as LIDAR, radiometric, and aerosol samplers) have been successfully demonstrated many times in polar regions over the last decade.

4. New, lightweight, highly functional payloads for small UASs are under development by multiple research and development (R&D) organizations.

5. Military UAS development and deployments have resulted in the creation of organizations that provide UAS services, including the provision of UASs under lease arrangements, pilots, payload integration, testing, and FAA permitting.

6. Formations of simultaneously flown multiple small UASs would be simpler logistically and very likely less expensive than employing a single medium-sized UAS, large UASs, or manned aircraft.

Many successful science missions have used unmanned aircraft in the Arctic. Crowe et al. (2012) include a list of science operations of UASs starting in 1999 (see Appendix C of this report). Judy Curry and others flew small UASs (Aerosondes) over the Barrow Atmospheric Radiation Measurement (ARM) site in 2004 and 2005. Mark Ivey and Bernie Zak successfully operated a small tethered balloon at Oliktok Point as part of the ARM Mixed-Phase Arctic Cloud Experiment (MPACE) field campaign in 2004 (Arm Climate Research Facility 2013).

Efforts to use UASs for atmospheric science missions would indirectly benefit from the highly successful use of unmanned aircraft during military operations in Afghanistan and Iraq in a number of ways. UAS technology has advanced significantly as a result of defense spending in this technology area. Many UAS operators trained by the military will be available to support climate research missions. In addition, surplus military UASs (both ground and aerial components) are now or will soon be available to the Department of Energy (DOE) and other federal agencies. The U.S. Geological Survey (USGS) is one example of a federal agency benefiting from surplus UASs. As explained by UAS Vision (2013), the USGS uses UASs for wildlife and land management work.

Existing organizations in both the public and private sectors can provide turnkey UAS operations, including ground and aerial systems, trained pilots, and FAA permitting assistance. Examples include New Mexico State University (NMSU), University of Alaska Fairbanks, University of Colorado, the National Oceanic and Atmospheric Administration (NOAA), BAE Systems (formerly Advance Ceramics), the VT Group, the ISR Group, and Altavian. NMSU has a unique UAS test facility in southern New Mexico that could be used to test UASs and payloads prior to deployment. (See the capabilities briefing for the NM State Physical Sciences Laboratory UAS Facility in

Davis 2011). The NMSU UAS test facility is operated under a cooperative research and development (CRADA) agreement with the FAA. This agreement may serve as the model for the additional UAS centers that the FAA has been directed to establish.

A phased approach to identifying and acquiring instruments and payloads for UASs for deployment in Arctic operations would reduce programmatic risk. The order of priority and acquisition would be roughly as follows:

- Atmospheric state parameters (temperature, relative humidity, pressure, wind direction) and position/speed (GPS)
- Broadband radiometric measurements (up and down) for short wave and long wave with options for stabilized platforms
- Extinction measurements and atmospheric aerosol particle sizing
- Gaseous species starting with $CO_2$ and methane
- LIDARs and imagers

Clearly, UAS payloads weighing 10 pounds or less will not deliver the detailed atmospheric, aerosol, or cloud information that payloads weighing hundreds of pounds will provide (see Table 5-1, presented previously). However, we believe that information essential for Arctic cloud- and climate-modeling purposes, such as measurements of atmospheric structure performed offshore on a routine basis, can be obtained on an acceptable cost-and-safety basis by unmanned aircraft with small payloads.

## 5.3 Regulatory Drivers and Changes

The Arctic's importance was recognized by the U.S. Congress when it included special provisions for unmanned aircraft operations in recently signed FAA reauthorization legislation. The following excerpts were taken from the FAA Modernization and Reform Act of 2012.

- 4 (d) EXPANDING USE OF UNMANNED AIRCRAFT SYSTEMS IN ARCTIC.—

  IN GENERAL.—Not later than 180 days after the date of enactment of this Act, the Secretary shall develop a plan and initiate a process to work with relevant Federal agencies and national and international communities to designate permanent areas in the Arctic where small unmanned aircraft may operate 24 hours per day for research and commercial purposes. The plan for operations in these permanent areas shall include the development of processes to facilitate the safe operation of unmanned aircraft beyond line of sight. Such areas shall enable over-water flights from the surface to at least 2,000 feet in altitude, with ingress and egress routes from selected coastal launch sites.
- (3) AIRCRAFT APPROVAL.—

> Not later than 1 year after the entry into force of an agreement necessary to effectuate the purposes of this subsection, the Secretary shall work with relevant national and international communities to establish and implement a process, or may apply an applicable process already established, for approving the use of unmanned aircraft in the designated permanent areas in the Arctic without regard to whether an unmanned aircraft is used as a public aircraft, a civil aircraft, or a model aircraft.
>
> (U.S. Congress. House. 2012)

Further, the FAA recently announced that new rules governing the use of unmanned aircraft of **less than 55 pounds total weight** will be enacted soon, possibly within the next few months (FAA 2013a). These new rules will reduce the cost to operate small unmanned aircraft, reduce requirements for approvals, and simplify ground operations. In December 2013, the FAA (2013b) announced the selection of six public entities who will develop UAS research and test sites across the United States. These entities are University of Alaska, State of Nevada, New York's Griffiss International Airport, North Dakota Department of Commerce, Texas A&M University – Corpus Christi, and Virginia Polytechnic Institute and Statue University (Virginia Tech).

Sandia has obtained approval for a DOE User Facility at Oliktok Point that includes the use of UAS systems for test and evaluation. This facility provides an established framework for dealing with issues such as proprietary or nonproprietary users, liability, flight-safety approvals, and related operational concerns.

## 5.4 Safety and Cost Drivers for UASs

Safety is one of the primary drivers for the use of UASs to study Arctic clouds. The following information from UAS veteran Jim Maslanik (University of Colorado) sheds light on the complex manned vs. unmanned cost and related safety questions:

> For our UAV projects, rather than trying to justify UAVs based on cost advantages (if any, and it's often the other way around), we try to focus on tasks that, when safety, aircraft availability and other issues are taken into account, realistically can only be done with UAVs, Sustained 20-hour missions, many flights per week, flights under relatively poor flying conditions, operations over ocean that would require a twin-engine manned aircraft at minimum, etc. A second aspect is the fact that UAVs can be configured as "science platforms" with suites of instruments that would be difficult to install on leased aircraft due to regulatory issues, cost, flexibility. Part of our thinking is to also take up some of the workload that might otherwise involve using NASA's large manned aircraft (P-3, DC-8), which are in short supply and usually fully committed to projects.
>
> I was talking to one of the oil company folks the other day about this cost issue, and his comment was to the effect that cost isn't an issue for them; air-crew safety is paramount.[22]

Risk analyses for flight missions typically include a review of the “4D’s: Duration, Dirty, Dull, Dangerous.” For missions where these four factors rank high collectively, the argument for use of UASs over manned aircraft becomes compelling.

The plot in Figure 5-1 shows fuel consumption rates (one important component of operations costs) for various UASs and manned aircraft by NOAA and the National Aviation and Space Administration (NASA). HALE, MALE, and LALE mean high-, medium-, and low-altitude, long endurance, respectively; “SE” stands for “short endurance.”

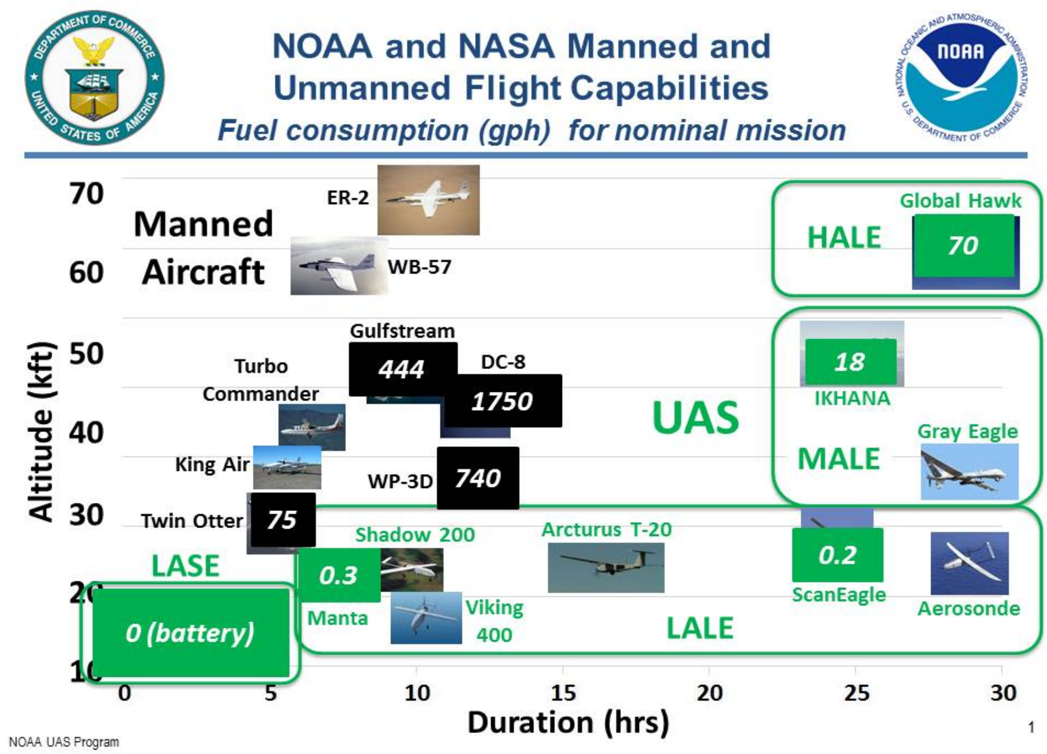



**Figure 5-1.** Fuel-consumption of manned and unmanned flights for nominal NOAA and NASA missions [Source: Hood 2012].

## 5.5 Scientific Motivations for Arctic Tethered Balloon Measurements

Multiyear surface-based measurements and associated in-cloud data retrievals for low (less than 2-kilometer) clouds are needed by the atmospheric modeling community to improve the representation of Arctic clouds in regional and global-scale models. Included in this set are cloud macrophysical properties (cloud base and top heights [Clothiaux et al. 2000]) and microphysical properties (liquid water path [Westwater et al. 2001; Dong and Mace 2003a]; profiles of liquid water content, droplet effective radius, and droplet number [Frisch, Fairall, and Snyder 1995]; column integrated water path, optical depth,

[22] Email correspondence between Jim Maslanik and Mark Ivey, April 2012.

and effective radius of the ice and water components of mixed-phase clouds [Turner 2005]; and ice water content [Matrosov 1999; Matrosov et al. 2002; Wang et al. 2004; Shupe, Uttal, and Matrosov 2005]).

The skill with which the cloud radiative forcing or heating rates can be calculated with cloud macro- and microphysical properties depends critically on the accuracy and precision of the cloud properties used to determine the radiative properties of the atmospheric column. Mace, Benson, Sonntag et al. (2006), and Mace, Benson, and Kato (2006) derived uncertainties in associated heating rates in terms of the root-mean-square (RMS) differences and biases in the downwelling fluxes at the surface (SFC) and in the upwelling fluxes at the top of the atmosphere (TOA). Using an eight-year data set collected at the ARM Climate Research Facility (ACRF) Southern Great Plain site that used published retrieval algorithms to derive cloud microphysical properties from ARM data, Mace and Benson (2008) show that biases in the boundary fluxes are small with scatter ranging from 2% to more than 30% (Table 5-3). This statistical uncertainty results in errors in the forcing and heating rates. Table 5-3 contains a subset of data extracted from Table 1 of Mace and Benson 2008 and is edited minimally for use in this report. These data represent a comparison with observations of radiative flux quantities calculated from cloud-property retrieval algorithms with TOA (top-of-atmosphere) and surface radiation measurements. The averaging time was 20 minutes for all comparisons. The averaged period was from January 1, 1997, through December 31, 2004, for a data set collected at the ACRF Southern Great Plain site. All fractional values were reported relative to the mean of the observations. Units of all nonfractional values are in watts per square meter (W $m^{-2}$). Statistics include only overcast nonprecipitating cloud scenes.

**Table 5-3. Boundary-Flux Bias Based on Long-Term Surface and Cloud-Top Model Predictions and Observations**

| Location | Parameter | Median Fractional Difference | Fractional Offset | Correlation Coefficient | RMS Difference | Slope of Linear Fit | Number of Observations |
|---|---|---|---|---|---|---|---|
| TOA | Upwelling Solar Flux | 0.13 | +0.02 | 0.81 | 64 | 0.91 | 5665 |
| | Upwelling Longwave Flux | 0.07 | +0.05 | 0.75 | 19 | 0.69 | 10542 |
| SFC | Solar Forcing | 0.25 | -0.09 | 0.75 | 0.21 | 0.87 | 6665 |
| | Downwelling Longwave Flux | 0.02 | -0.04 | 0.94 | 14 | 0.95 | 10264 |

Data from Mace and Benson 2008, Table 1

The contents of Table 5-4 were extracted (in their entirety) from Table 2 of Mace and Benson 2008 and were edited minimally for use in this report. As noted by Mace and Benson, the table contains uncertainties in the indicated quantities for approximate averaging times. The acronym CRE means cloud radiative effect, which the researchers define as the W $m^{-2}$ difference between the all-sky and clear-sky fluxes at the surface and TOA. The acronym CRF means cloud radiative forcing, which the researchers define as the vertical convergence of radiant flux or heating rate into a volume that is typically expressed in kelvins (K) per day. The values in the table were derived from the complete data set used to prepare the summary data presented in Table 5-3.

**Table 5-4. Boundary-Flux Uncertainties Based on Model Predictions and Observations**

| | 1 hour | 1 day | 1 Week | 1 Month |
|---|---|---|---|---|
| TOA Solar CRE (W $m^{-2}$) | 53 | 11 | 4.1 | 2.0 |
| TOA IR CRE (W $m^{-2}$) | 16 | 3.3 | 1.2 | 0.6 |
| Atmospheric Solar CRE (W $m^{-2}$) | 55 | 11 | 4.2 | 2.1 |
| Atmospheric IR CRE (W $m^{-2}$) | 21 | 4.5 | 1.6 | 0.8 |
| Surface Solar CRE (W $m^{-2}$) | 15 | 2.8 | 1.0 | 0.5 |
| Surface IR CRE (W $m^{-2}$) | 14 | 2.9 | 1.1 | 0.6 |
| Solar CRF (K $day^{-1}$) | 16 | 3.4 | 1.2 | 0.6 |
| IR CRF (K $day^{-1}$) | 25 | 5.1 | 1.9 | 0.9 |

Data from Mace and Benson 2008, Table 2

Table 5-4 above quantifies the error presented previously in Table 5-3 in terms of averaging periods over which the forcing is calculated. For averaging times of one hour (typical of process studies and direct validation of cloud-resolving models), the uncertainty in Table 5-4 is nearly as large or larger than the forcing and heating rates that can be expected with most cloud types. These results highlight the need for better cloud-property retrieval algorithms and meaningful validation of those algorithms. Our goal is to reduce the uncertainty in the forcing and heating rates to values that are meaningful on hourly time scales to approximately one-tenth of the values we are now obtaining. This goal can only be accomplished with a statistically significant set of observed *in situ* cloud properties for validation of retrieval algorithm results.

One could reasonably ask for a given cloud type just how many measurements are needed to meet the specified accuracy and precision requirements. Translating desired uncertainty in heating rates to errors in Arctic stratus cloud properties has not been examined specifically. However, Dong and Mace (2003a) show that errors in effective solar transmission in optically thick Arctic stratus on the order of 10% require effective cloud droplet radii measurements with an accuracy that ranges between 1 and 3 micrometers, depending on the surface albedo and liquid water path. For process studies, one could argue that precision in solar flux on the order of 10%–20% might be sufficient, while for monitoring global change and validating cloud parameterizations in climate models, much more stringent levels of precision would be necessary. Following the arguments presented by Wielicki et al. 2000, consider, for instance, that the effective cloud droplet radii in nonprecipitating Arctic stratus vary naturally over approximately 10 micrometers between spring and summer (Dong and Mace 2003a) and that the precision with which we can retrieve effective radii are on the order of 20% (Dong and Mace 2003b). Precision in the data ensemble on the order of 1%–2% is needed to ascertain accurately the presence of any retrieval biases and the effects of algorithm assumptions.

If we assume reasonably independent samples, then roughly 100 independent events are required to decrease the uncertainty of the comparison by a factor of 10 and down to 2%, assuming that the precision of the comparison is improved as the inverse square root of the number of independent samples (we are neglecting the uncertainty in the *in situ* measurements in this argument).

The only realistic option for obtaining these in-cloud measurements is the use of a tethered balloon system. Experience has shown that the tethered system needs to be of superior quality and designed to endure sudden, strong wind changes with altitude. The ARM program has been developing miniaturized cloud instrumentation that can be included in a tethered balloon package. For example, the Arctic Lower Troposphere Observed Structure (ALTOS) measurement campaign utilized a tethered balloon with a 17-kilogram (kg) lift capacity, as shown in Figure 5-2. In deployments like these, careful attention must be given to the carrying capacity of the balloon, the potential stress on the tether, and the desired instrumentation. Ideally, two balloons are needed: The first would be a small balloon capable of carrying a basic environmental-sampling package and able to survive adverse environmental conditions. The second, larger-lift balloon would be the cloud-physics balloon that would carry the more-expensive cloud-physics instrumentation and only be flown when conditions are known to be within the safe-operation envelope.

**Figure 5-2.** The ALTOS tethered balloon with a 17 kg lift capacity as deployed during a 2010 North Slope measurement campaign.

Tethered balloons are now widely recognized as a safe and economically feasible means for making routine measurements of low-level Arctic stratus clouds. Tethered balloons have advantages over research aircraft for the following reasons:

1. Tethered balloons can conduct long-duration vertical profiles through Arctic clouds from the surface all the way to cloud top.

2. Slow particle-impact speeds negate the problematic issue of ice crystals shattering on cloud particle probe inlets.

3. Tethered balloon operations are inexpensive compared to manned and unmanned aircraft.

4. Tethered balloon operations present a much lower personnel safety and overall mission risk than manned aircraft operations.

The photographs in Figure 5-3 show the tethered balloon and winch system used to measure cloud microphysical and radiative properties in Svalbard, Norway, between May and June of 2008. The balloon volume is 43 $m^3$ and will carry a 15 kg instrument package from sea level to nearly 2 kilometers in calm wind conditions. The custom tether line provides continuous power to the package and allows it to operate for extended periods, i.e., greater than 24 hours.

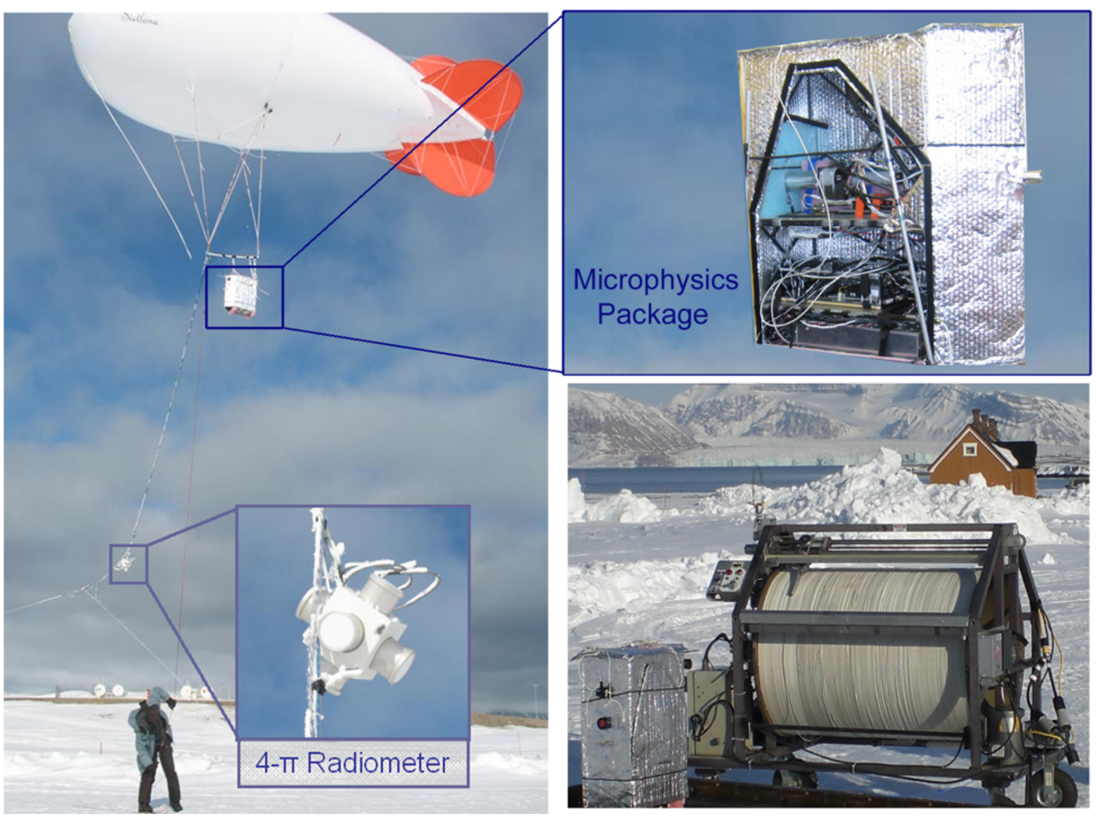



**Figure 5-3.** Photographs of tethered balloon and winch system for measuring cloud microphysical and radiative properties in Svalbard, May and June 2008.

A schematic illustration of the tethered balloon and winch system used in Svalbard is shown in Figure 5-4.

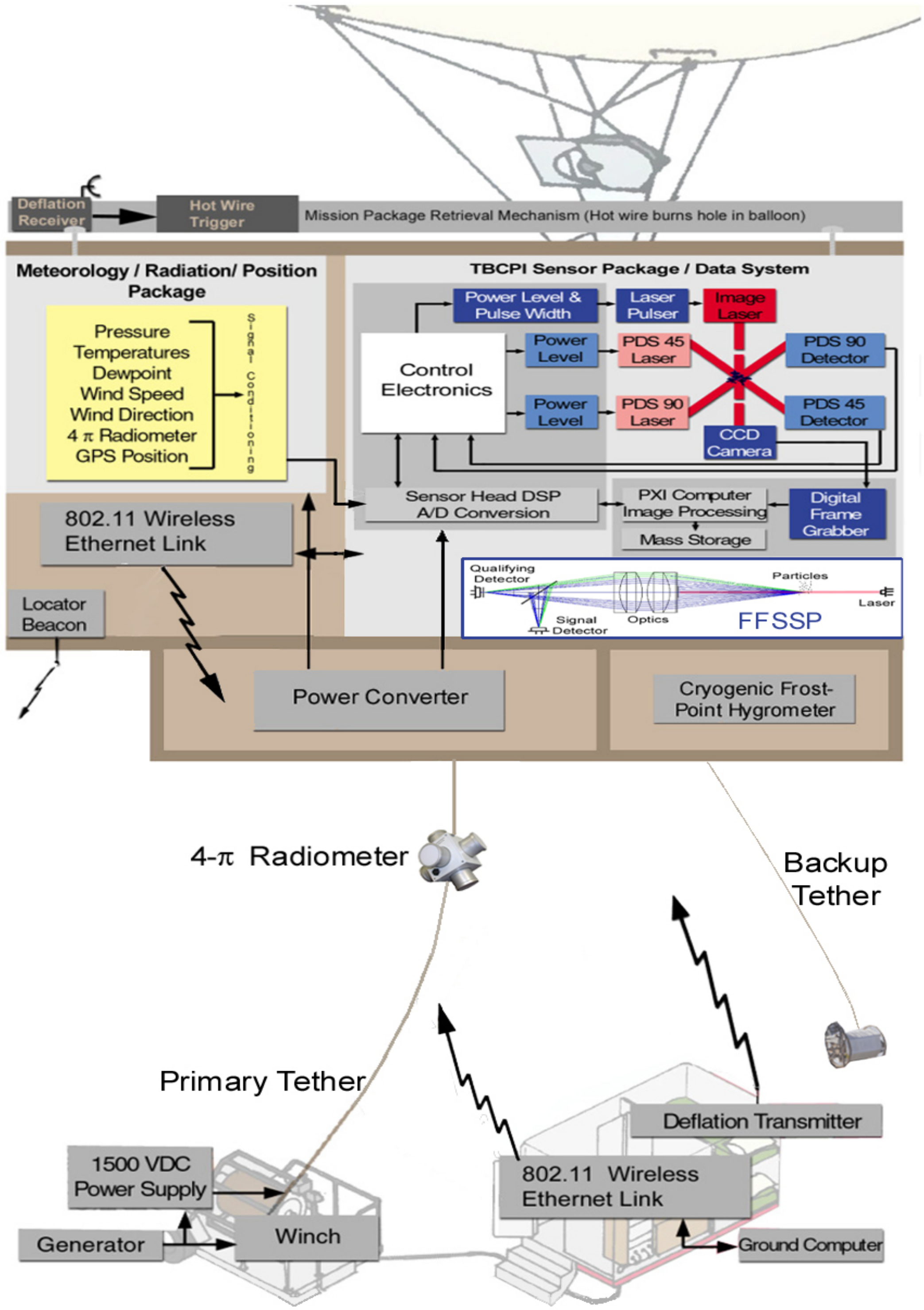



**Figure 5-4.** Principal components of the tethered balloon and winch system.

## 5.6 Summary and Conclusions

The significant atmospheric, oceanic, and terrestrial changes occurring in the Arctic in recent decades have produced a sustained interest in studying the various atmospheric processes that may contribute to these accelerated climatic changes in the Arctic. Various contributing factors have been identified, and it is becoming increasingly apparent that these factors contribute in a complicated, nonlinear way to changes in perennial and summer sea ice and Arctic climatic trends. Climate-modeling efforts for the Arctic region thus far have indicated considerable biases in important atmospheric parameters like heat flux that are predictive of climatic trends. To better understand and model these key parameters, extensive in-cloud measurements of key cloud physical properties are needed.

Section 5 has examined the advantages and disadvantages of in-cloud measurement approaches that include both manned and unmanned aircraft as well as tethered balloon systems. A number of UAS and tethered-balloon Arctic atmospheric science missions have been successfully carried out, and new developments in miniaturized, lightweight measurement systems offer much potential for additional growth in these new measurement techniques.

Regulatory changes in agencies like the FAA with respect to UASs also reveal that UAS operations for science missions and other commercial endeavors are being systematically addressed and that UASs are moving toward sharing national airspace with manned flight operations. While manned aircraft Arctic atmospheric science missions will continue to play a key role in the evolving science understanding of Arctic climate, new technologies associated with UASs and tethered balloon systems offer distinct advantages in terms of mission cost, flexibility, and personnel risk.

## 5.7 References


ACIA. (2005). *Arctic Climate Impact Assessment*. Cambridge University Press. http://www.acia.uaf.edu (accessed on May 21, 2013).

Arm Climate Research Facility. (2013). "UAV Campaigns." http://www.arm.gov/sites/aaf/uavcampaigns (accessed on May 20, 2013).

Avramov, A. E., A. S. Ackerman, A. M. Fridlind, B. van Diedenhoven, G. Botta, K. Aydin, J. Verlinde, A. Korolev et al. (2011). "Toward Ice Formation Closure in Arctic Mixed-Phase Boundary Layer Clouds during ISDAC." *Journal of Geophysical Research: Atmospheres* 116, no. D1, D00T08.

Boé, J., A. Hall, and X. Qu. (2009). "Current GCMs' Unrealistic Negative Feedback in the Arctic." *Journal of Climate* 22, no. 17: 4682–4695.

Burt, M., D. A. Randall, and M. Branson. (2014). The role of downwelling infrared radiation in Arctic amplification. Submitted for publication.

Clothiaux, E. E., T. P. Ackerman, G. G. Mace, K. P. Moran, R. T. Marchand, M. A. Miller, and B. E. Martner. (2000). "Objective Determination of Cloud Heights and Radar Reflectivities Using a Combination of Active Remote Sensors at the ARM CART Sites." *Journal of Applied Meteorology and Climatology* 39, no. 5: 645–665.

Crowe, W., K. D. Davis, A. la Cour-Harbo, T. Vihma, S. Lesenkov, R. Eppi, E.C. Weatherhead, P. Liu, M. Raustein, M. Abrahamsson, K-S. Johansen, and D. Marshall. (2012). *Enabling Science use of Unmanned Aircraft Systems for Arctic Environmental Monitoring*. AMAP Technical Report No. 6. Oslo, Norway: Arctic Monitoring and Assessment Programme (AMAP).

Curry, J. A., J. Maslanik, G. Holland, and J. Pinto. (2004). "Applications of Aerosondes in the Arctic." *Bulletin of the American Meteorological Society* 85, no. 12: 1855–1861.

Davis, D. (2011). New Mexico State University PSL Capabilities Briefing.

De Boer, G., W. Chapman, J. E. Kay, B. Medeiros, M. D. Shupe, S. Vavrus, and J. Walsh. (2012). "A Characterization of the Present-Day Arctic Atmosphere in CCSM4." *Journal of Climate* 25, no. 8: 2676–2695.

Dong, X. Q., and G. G. Mace. (2003a). "Profiles of Low-Level Stratus Cloud Microphysics Deduced from Ground-Based Measurements." *Journal of Atmospheric and Oceanic Technology* 20, no.1: 42–53.

Dong, X. Q., and G.G. Mace. (2003b). "Arctic Stratus Cloud Properties and Radiative Forcing Derived from Ground-Based Data Collected at Barrow, Alaska." *Journal of Climate* 16, no. 3: 445–461.

FAA (Federal Aviation Administration). (2013a). *Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap.* Washington, DC: U.S. Department of Transportation, Federal Aviation Administration. http://www.faa.gov/about/initiatives/uas/media/uas_roadmap_2013.pdf (accessed on June 25, 2014).

FAA (2013b). "Press Release – FAA Selects Unmanned Aircraft Systems Research and Test Sites." http://www.faa.gov/news/press_releases/news_story.cfm?newsid=15576 (accessed on June 25, 2014).

Frisch, A. S., C. W. Fairall, and J. B. Snyder. (1995). "Measurements of Stratus Cloud and Drizzle Parameters in ASTEX with a Ka-band Doppler Radar and Microwave Radiometer." *Journal of the Atmospheric Sciences* 52, no. 16: 2788–2799.

Hinzman, L., et al. (2005). "Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions." *Climatic Change* 72, no. 3: 251–298.

Hood, R. (2012). “Planning for Success – An Operational Test Program for Unmanned Observing Strategies.” Washington, DC: National Oceanic and Atmospheric Administration, NOAA Unmanned Aircraft System (UAS) Program.

Inoue, J., J. Liu, and J. A. Curry. (2006). “Intercomparison of Arctic Regional Climate Models: Modeling Clouds and Radiation for SHEBA in May 1998.” *Journal of Climate* 19, no. 17: 4167–4178.

IPCC (Intergovernmental Panel on Climate Change). (2007). *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by S. Solomon et al. Cambridge, UK: Cambridge Univ. Press.

Ivey, M., J. Verlinde, W. Ferrell, J. Voyles, and R. Petty. (2012). *Oliktok Point, AMF3, and Unmanned Aerial Vehicles.* DOE/Office of Science ARM Program Report DOE/SC-ARM-TR-135.

Kay, J., and A. Gettelman. (2009). “Cloud Influence on and Response to Seasonal Arctic Sea Ice Loss.” *Journal of Geophysical Research: Atmospheres* 114, no. D18204, doi:10.1029/2009JD011 773.

Kay, J. E., M. M. Holland, C. M. Bitz, E. Blanchard-Wrigglesworth, A. Gettelman, A. Conley, and D. Bailey. (2012). “The Influence of Local Feedbacks and Northward Heat Transport on the Equilibrium Arctic Climate Response to Increased Greenhouse Gas Forcing.” *Journal of Climate* 25, no. 16: 5433–5450.

Mace, G. G., S. Benson, and S. Kato. (2006). “Cloud Radiative Forcing at the Atmospheric Radiation Measurement Program Climate Research Facility: 2. Vertical Redistribution of Radiant Energy by Clouds.” *Journal of Geophysical Research: Atmospheres* 111, no. D11S91, doi:10.1029/2005JD005922.

Mace, G. G., S. Benson, K. L. Sonntag, S. Kato, Q. Min, P. Minnis, C. H. Twohy, M. Poellot, X. Dong, C. Long, Q. Zhang, and D. R. Doelling. (2006). “Cloud Radiative Forcing at the Atmospheric Radiation Measurement Program Climate Research Facility: 1. Technique, Validation, and Comparison to Satellite Derived Diagnostic Quantities.” *Journal of Geophysical Research: Atmospheres* 111, no. D11S90, doi:10.1029/2005JD005921.Mace, G. G., and S. Benson. (2008). “The Vertical Structure of Cloud Occurrence and Radiative Forcing at the SGP ARM Site As Revealed by 8 Years of Continuous Data.” *Journal of Climate* 21, no. 11: 2591–2610.

Markus, T., J. Stroeve, and J. Miller. (2009). “Recent Changes in Arctic Sea Ice Melt Onset, Freezeup and Melt Season Length.” *Journal of Geophysical Research: Oceans* 114, no. C12024.

Matrosov, S. Y. (1999). “Retrievals of Vertical Profiles of Ice Cloud Microphysics from Radar and IR Measurements Using Tuned Regressions between Reflectivity and Cloud Parameters.” *Journal of Geophysical Research* 104, no. D14: 16741–16753.

Matrosov, S. Y., A. V. Korolev, and A. J. Heymsfield. (2002). "Profiling Cloud Ice Mass and Particle Characteristic Size from Doppler Radar Measurements." *Journal of Atmospheric Oceanic Technology* 19, no. 7: 1003–1018.

Morrison, H., P. Zuidema, A. S. Ackerman, A. Avramov, G. de Boer, J. Fan, A. M. Fridlind et al. (2011). "Intercomparison of Cloud Model Simulations of Arctic Mixed-Phase Boundary Layer Clouds Observed during SHEBA/FIRE-ACE." *Journal of Advances in Modeling Earth Systems* 3, no. 2, Art: MO6003.

NAS (National Academy of Sciences) (2006). *Toward an Integrated Arctic Observing Network*. Committee Report. Washington, DC: National Academies Press.

Overland, J. E. (2009). "The Case for Global Warming in the Arctic." In *Influence of Climate Change on the Changing Arctic and Sub Arctic Conditions*, edited by J. C. J. Nihoul and A. G. Kostianoy, 13–23. Dordrecht, The Netherlands: Springer.

Prowse, T. D., C. Furgal, F. J. Wrona, and J. D. Reist. (2009). "Implications of Climate Change for Northern Canada: Freshwater, Marine, and Terrestrial Ecosystems." *Ambio* 38, no. 5: 282–289.

Roberts, A., et al. (2010). *A Science Plan for Regional Arctic System Modeling, A Report to the National Science Foundation from the International Arctic Science Community*. International Arctic Research Center Technical Papers 10-0001. Fairbanks, AK: International Arctic Research Center, University of Alaska Fairbanks.

SEARCH SSC. (2001). *SEARCH: Study of Environmental Arctic Change, Science Plan*. Seattle, WA: Polar Science Center, Applied Physics Laboratory, University of Washington.

Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland. (2009). "The Emergence of a Surface-Based Arctic Amplification." *The Cryosphere* 3, no. 1: 11–19.

Shupe, M. D., T. Uttal, and S. Y. Matrosov. (2005). "Arctic Cloud Microphysics Retrievals from Surface-Based Remote Sensors at SHEBA." *Journal of Applied Meteorology* 44, no. 10: 1544–1562.

Solomon, A., M. Shupe, O. Persson, and H. Morrison. (2011). "Moisture and Dynamical Interactions Maintaining Decoupled Arctic Mixed-Phase Stratocumulus in the Presence of a Humidity Inversion." *Atmospheric Chemistry and Physics* 11, no. 19: 10127–10148.

Tjernstrom, M. (November 2007). Poster Presentation and Private Communications, Sustaining Arctic Observing Networks Meeting, sponsored by the Arctic Council, Stockhom, Sweden.

Tjernstrom, M., J. Sedlar, and M. D. Shupe. (2008). "How Well Do Regional Climate Models Reproduce Radiation and Clouds in the Arctic? An Evaluation of ARCMIP

Simulations." *Journal of Applied Meteorology and Climatology* 47, no. 9: 2405–2422.

Turner, D. D. (2005). "Arctic Mixed-Phase Cloud Properties from AERI-Lidar Observations: Algorithm and Results from SHEBA." *Journal of Applied Meteorology and Climatology* 44, no. 4: 427–444.

UAS Vision. (2013). "U.S. Geological Survey Plans Deer Counting Mission North of Las Vegas." http://www.uasvision.com/2013/06/11/u-s-geological-survey-plans-deer-counting-mission-north-of-las-vegas/ (accessed on June 25, 2014).

U.S. Congress. House. (2012). *FAA Modernization and Reform Act of 2012*. HR 658. 112 Cong. 2nd session. Public Law 112–95, 126 STAT. 11.

Wang, Z., K. Sassen, D. N. Whiteman, and B. B. Demoz. (2004). "Studying Altocumulus with Ice Virga Using Ground-Based Active and Passive Remote Sensors." *Journal of Applied Meteorology and Climatology* 43, no. 3: 449–460.

Westwater, E. R., Y. Han, M. D. Shupe, and S. Y. Matrosov. (2001). "Analysis of Integrated Cloud Liquid and Precipitable Water Vapor Retrievals from Microwave Radiometers during the Surface Heat Budget of the Arctic Ocean Project." *Journal of Geophysical Research: Atmospheres* 106, no. D23: 32019–32030.

Wielicki, B. A., B. A. Baum, L. H. Chambers, T. P. Charlock, R. N. Green, S. Gupta, M. Haeffelin, D. P. Kratz et al. (2000). *CERES Validation Plan Overview, Release 4, 10/20/00*. Hampton, VA: NASA Langley Research Center. http://asd-www.larc.nasa.gov/ceres/validation/ceresval_r4.0_over.pdf (accessed on May 20, 2013).

# 6 Uncertainty Quantification Methods for Arctic Data and Models

In Section 6, the uncertainty associated with weather prediction tools for the Arctic region is described, motivating the need for new simulation and analysis capabilities. This section focuses on the development of numerical tools to help guide data acquisition programs. Current data acquisition strategies have not particularly produced higher-quality climate forecasts. This section argues the need for a strong coupling of numerical analysis and acquisition strategies. We leverage numerical tools developed at Sandia (e.g. "Trilinos"and the "Peopt" library) from which we demonstrate the development of relevant prototypes capable of large-scale optimization, which is a critical component of a coupled approach. We implemented prototypes with different physics to emulate ice sheet dynamics and atmospheric transport. These prototypes are designed not only to perform forward predictions but also to solve large-scale inversion problems. The opportunity for Sandia is to take a leading role in high-resolution numerical simulation and analysis guiding data acquisition programs in the Arctic region in support of national security. Through design-of-experiments theory and selection of the appropriate optimality conditions, the most informative data can be measured in a cost-effective and timely manner.

## 6.1 Introduction

The environment of the Arctic region is changing rapidly with significant national-security consequences, such as coastline erosion, border changes, the opening of shipping lanes, the emergence of submarine tracks, access to natural resources, and a host of environmental issues. In addition, the feedback between the Arctic region and the lower latitudes has been determined to be a critical component of the overall climate dynamics.

In support of national security, accurate numerical simulation and analysis capabilities are required and validated through measurements and data. Despite data acquisition efforts throughout the last decade, weather and climate numerical predictions continue to exhibit considerable uncertainty. A significant body of research has been accumulated that discusses observations from flask measurements to satellite readings and draws conclusions about various components that contribute to changing climate dynamics. The basic underlying reason for the continuing uncertainty, however, is associated with the highly nonlinear characteristics, complex nonlinear physics, sparse data coverage, and the need for parameterization of subgrid phenomena. These factors are especially relevant in the Arctic, where the changes in climate dynamics are accelerating and are more complicated in comparison with other regions. Furthermore, data acquisition in the Arctic is logistically more complicated and has much higher associated costs.

To reduce uncertainty, the typical strategy is simply to acquire more data. As history has demonstrated, however, this strategy will not necessarily improve numerical forecasts. It is our opinion that numerical simulation and data acquisition must be closely coupled to each level of the analysis, acquisition, and forecasting. This coupling requires implementation of large-scale analysis tools that, in turn, require the embedding of algorithms throughout the code structure. For instance, sensitivity analysis needs chain-rule–based methods wherever the independent variables occur in the code. Other examples include the need for preconditioning, Hessians, polynomial chaos propagation, singular-value decompositions, and matrix projections. Unfortunately, to accommodate efficient large-scale analysis, significant changes will have to be made in existing code. Considering the inflexible software structure of many of the community climate models, implementing these changes may not be a viable option.

Consequently, it is critically important to develop a computational program to help guide the growth of the measurement program in addition to starting the characterization of Arctic dynamics. A range of acquisition techniques is being considered from satellites, field stations, radio soundings, remote-controlled vehicles to manual sampling. Determining an optimal strategy for acquiring more data presents numerous challenges—from finding the best location to deciding the priority of measurement types. Ultimately, numerical models will be used to characterize and predict the dynamics associated with the national security issues, and as such, data will be used to calibrate the numerics. This process will entail an inversion process whereby the difference between model predictions and observations is reconciled. Once model parameters are determined, accurate predictions can be issued. Data errors and model approximations will have to be addressed by coupling stochastic techniques to the inversion process. A statistical characterization then can provide a measure of certainty of the solution.

Highlights of the remainder of the discussion on uncertainty follow. In Section 6.2, we provide background information to inform the reader with some perspective on the sources of uncertainty in the Arctic. This is followed in Section 6.3 by a discussion of numerical characterization in which climate and weather modeling are evaluated and then related to Arctic dynamics. The community models are also discussed with a specific focus on the quality of the forecasting. Sources of uncertainty in the Arctic are listed. Section 6.4 presents the major issues associated with data acquisition and identifies the "when, where, how, and what" questions. In Section 6.5, we discuss large-scale design of experiments and point to a critical need that perhaps only Sandia can address with our unique skill set and set of numerical tools. Through Section 6.6, we demonstrate the viability of a prototype that considers the coupling of numerical analysis and data acquisition and, in particular, the efficiency of the implementation is emphasized. Section 6.7 provides a summary of Sandia opportunities, followed by acknowledgments in Section 6.8 and a list of references in Section 6.9.

## 6.2 Background

This section briefly discusses background material that is relevant to weather and climate numerical modeling, the Arctic area, and data acquisition. The intent of this section is to touch on the important issues and is not meant to be a comprehensive literature review.

Significant changes in our climate are occurring and have been predicted to become worse as greenhouse gases continue to accumulate (Meehl et al. 2007). Atmospheric blocking events cause persistent anomalous weather patterns, such as drought, cold spells, prolonged precipitation, and heat spells. Slower progression of upper-level waves causes more-persistent weather conditions that can increase the likelihood of certain types of extreme weather. Previous studies support this idea: weaker zonal-mean, upper-level wind is associated with increased atmospheric blocking events in the northern hemisphere (Barriopedro et al. 2006) as well as with cold-air outbreaks in the western United States and Europe (Thompson, Wallace, and Hegerl 2000). Palmer (2012) discusses weather and climate numerical prediction and points out that we do not understand the level of uncertainty associated with climate.

During the past few decades, the Arctic has warmed approximately twice as rapidly as has the entire northern hemisphere, a phenomenon called *Arctic amplification* (Screen and Simmonds 2010; Serreze et al. 2009). Francis and Vavrus (2012) discuss the link between Arctic amplification and extreme weather in midlatitudes. In particular, both observational and modeling studies have identified a variety of large-scale changes in the atmospheric circulation associated with sea-ice loss and earlier snow melt that, in turn, affect precipitation, seasonal temperatures, storm tracks, and surface winds in midlatitudes (Budikova 2009; Honda, Inoue, and Yamae 2009; Francis et al. 2009; Overland and Wang 2010; Petoukhov and Semenov 2010; Deser et al. 2010).

Over time, sea ice reflects the fast-changing circumstances of weather. It is driven principally by changes in surface temperature, forming and melting according to the seasons, the winds, cloud cover, and ocean currents. In 2010, for example, sea ice extent recovered dramatically in March, only to melt again by May. Sea ice is subject to powerful short-term effects, so that while we cannot conclude anything about the health of the ice from just a few years' data, an obvious trend emerges over the space of a decade or more that shows a decrease of about 5% of average sea-ice cover per decade.

To some extent, the high level of uncertainty is a simple consequence of the smaller spatial scale of the Arctic, as climate simulations are reckoned to be more reliable at continental and larger scales (Meehl et al. 2007; Randall et al. 1998). The uncertainty is also a consequence of the complex processes that control the ice and the difficulty of representing these processes in climate models. The same processes that make Arctic sea ice highly sensitive to climate change, the ice-albedo feedback in particular, also make sea ice simulations sensitive to any uncertainties in model physics (e.g., the representation of Arctic clouds). Quantifying cloud feedback in climate change in any area is a challenging problem that is even more problematic in the Arctic, where clouds can be difficult to differentiate from snow and ice captured in satellite images.

The natural variability of climate systems is a known problem (Ghil 2003). The atmosphere, ocean, and sea ice compose a nonlinear chaotic system with a high level of natural variability that is unrelated to external climate forcing. Even if climate models contained a perfect representation of all climate-system physics and dynamics, inherent unpredictability would prevent us from issuing detailed forecasts of climate change beyond about a decade. Unpredictability is especially important in model-observation comparisons, as the large natural variability of Arctic sea ice must be distinguished from the effects of external climate forcing.

## 6.3 Numerical Characterization and Uncertainty

We next discuss the numerical characterization for global climate and weather predictions dynamics, in addition to requirements for the Arctic region. The discussion is organized in three parts, numerical characterization, community models, and uncertainties in the Arctic.

### 6.3.1 Numerical Characterization

Two types of numerical forecasting are necessary to enable numerical support to guide data acquisition. First, climate modeling is needed to forecast the general and average dynamical behavior of the environment over large regions and long periods of time. This is a boundary-value problem with a need to characterize accurately the external and internal conditions that drive the overall behavior. Boundary conditions range from the strength of the sun and the reflectivity of the surface to the opacity of the atmosphere to terrestrial radiation as a result of greenhouse gases. Second, weather-prediction capabilities are needed to forecast the dynamics locally and in near real-time. This is an initial-value problem that relies critically on accurate initial conditions. In this case, conditions, such as temperature, wind speed, wind direction, and precipitation rate, are required throughout the area of interest.

There are fundamental differences in mechanisms between weather and climate predictions. For example, accurate weather predictions require accurate characterization of processes that lead to precipitation from clouds that is relevant to rain predictions for spatial and temporal locations. For climate predictions, the specifics of the cloud-to-rain process are less important than the reflective properties of the cloud because these properties affect the planet's long-term energy budget.

There are several key physics in the Arctic that need to be coupled to predict the dynamics, specifically atmospheric transport, ocean, and ice-sheet modeling. Sea ice plays an important role in the climate system through reflection from high-surface albedo, insulating the ocean and influencing the salinity of the ocean through brine rejection when ice forms and surface freshening when ice melts. For these reasons, it is important that climate models include a good representation of sea ice processes. Salinity in ice and the process of brine rejection require microscale parameterization. The heat loss to the atmosphere is dependent on the thickness of the ice.

Recognizing the need to incorporate Arctic oscillation variability into considerations of recent sea ice decline, Lindsay and Zhang (2005) used an ocean–sea ice model to reconstruct the sea ice behavior of the satellite era and identify separate contributions from ice motion and thermodynamics. These researchers proposed a three-part explanation of sea ice decline that incorporates both natural Arctic oscillation variability and an overall warming climate.

Climate-model projections are unanimous that temperatures will continue to rise throughout the twenty-first century under the influence of enhanced greenhouse-gas forcing. The projections also agree that the warming will be largest in the high-northern latitudes and will be accompanied by large reductions in Arctic sea ice, particularly at the end of the summer melt season (Meehl et al. 2007).

In weather and climate models, the interaction between the atmosphere and the land surface is simulated by land surface models. These land surface models are designed to represent the physical processes that control the exchange of heat and moisture to solve the surface energy balance, typically by partitioning the available energy between evaporative, sensible, and ground heat fluxes. There has been a growing recognition in climate science that different parts of the Earth system affect one another and that these feedbacks, which often involve land ecosystem–atmosphere interactions, need to be included in the models to achieve improved projections for the future. Consequently, the land surface models have grown in complexity in an effort to include processes such as changes in vegetation cover, carbon cycling in terrestrial ecosystems, and the direct effect of rising carbon dioxide ($CO_2$) concentrations on plant physiology.

An additional important feature of coupled physics models and data acquisition is the disparity of spatial and temporal resolutions. Dynamics in the atmosphere are sensitive to diurnal cycles, unlike sea ice. From a predictive standpoint, this difference may not be as critical; however, from a data-acquisition-support standpoint, this difference clearly needs to be taken into account.

### 6.3.2 Community Models

The atmospheric community has a long history of developing numerical capabilities to predict climate change and forecast weather patterns. Our society, in terms of security, infrastructure, and logistics, depends on the accuracy of these models and, depending on the location, we are accustomed to large variations in the accuracy. Community models are in a continuous state of flux as physics and parameterization improve. It is this process of evolution, however, that has caused a complex software infrastructure with little flexibility to embed large-scale analysis algorithms, such as optimization, uncertainty quantification, or reduced-order modeling.

According to Mass (2012), the United States has fallen behind in numerical weather prediction in comparison to the rest of the world. Codes like Global Forecast System (GFS) and North American Mesoscale (NAM) Forecast System have shown to be less reliable than the European Union's European Center for Medium Range Weather Forecasting (ECMWF) code and codes from the UK Met Office as well as from the Canadian Met office. A recent study conducted by the University Corporation for Atmospheric Research (UCAR) confirms these conclusions (UCAR 2009).

The Weather Research and Forecasting Model, referred to as WRF, is one of the more advanced numerical capabilities to simulate atmospheric dynamics. WRF was developed by the National Center for Atmospheric Research (NCAR) to support operational models and serve as a research platform. For instance, WRF is capable of high spatial resolution with complete large-eddy-simulation (LES)–based turbulence modeling. It has sophisticated cumulus schemes, advanced time integration, and complex boundary condition handling. A range of data assimilation tools has been implemented, including

3DVar and ensemble Kalman filters. There is also a range of specialized models to handle trace gas transport and chemistry (WRF-CHEM), and there are specific capabilities to handle complex weather patterns, such as hurricanes. WRF also has global simulation capabilities and can be used for climate modeling.

We reviewed WRF in detail to determine the viability of this model to perform accurate numerical characterization, be extended to support embedded algorithms, and perform in an efficient manner. Our first experience with WRF was a porting exercise to different platforms. We were not able to port this code to many of our capability machines (like redsky) because there are dependencies on third-party libraries, compilers, and Message-Passing Interface (MPI). Only under very specific conditions will this code compile, link, and run properly. Our second experience was to extend the code to enable a scalar tracer. This activity was successful and not too time consuming. Although the code structure is designed to handle such extensions, adjoint and matrix projections are not. In addition, it takes quite a bit of computing resources to run relatively modestly sized data sets, meaning that if scalar transport were incorporated, it would depend on the velocity calculations. We decided that it was more efficient to have a stand-alone convection diffusion module. On a positive note, very advanced physics have been implemented, and the code is capable of achieving high-resolution simulations of complex weather dynamics. There are several modules and procedures that one must execute to run WRF, and this appears to be an artifact from a historical development process of adding Fortran code and leveraging previous developments. Our conclusion is that WRF is the right code to create accurate velocity and pressure fields at any resolution, but WRF cannot be modified or extended to accommodate embedded large-scale analysis algorithms.

### 6.3.3 Uncertainties in the Arctic

Climate models use the laws of physics (e.g., conservation of mass, momentum, and energy) to simulate the main components of the climate system: the atmosphere, ocean, land surface, and sea ice. Many different capabilities currently exist, but it is not clear whether any one in particular provides higher-quality forecasts. In 2001, leading researchers conducted a numerical experiment to compare the predictability of the leading numerical climate codes (Cubasch et al. 2001). Figure 6-1, reproduced from the report by Cubasch and his colleagues, demonstrates the quality of the prediction of state-of-the-art models from that era. The graph represents the change in globally averaged surface temperatures as a result of doubling the $CO_2$ concentration. Although the quality of numerical models has been improved since the report was published, the history of climate models (Weart and American Institute of Physics 2014) shows that the focus of numerical model development during the last decade has been on parameterizations of contributing phenomena (clouds, vegetation, etc.) in an attempt to improve the accuracy. The complexities of the models continue to increase. To some extent, the increasing complexities have the potential to introduce new forms of uncertainty, and as a recent study shows, there is still considerable disparity between models (Lobell, Bonfils, and Duffy 2007). This recent study evaluates the minimum and maximum temperatures for a period of time as a function of different $CO_2$ concentration scenarios.

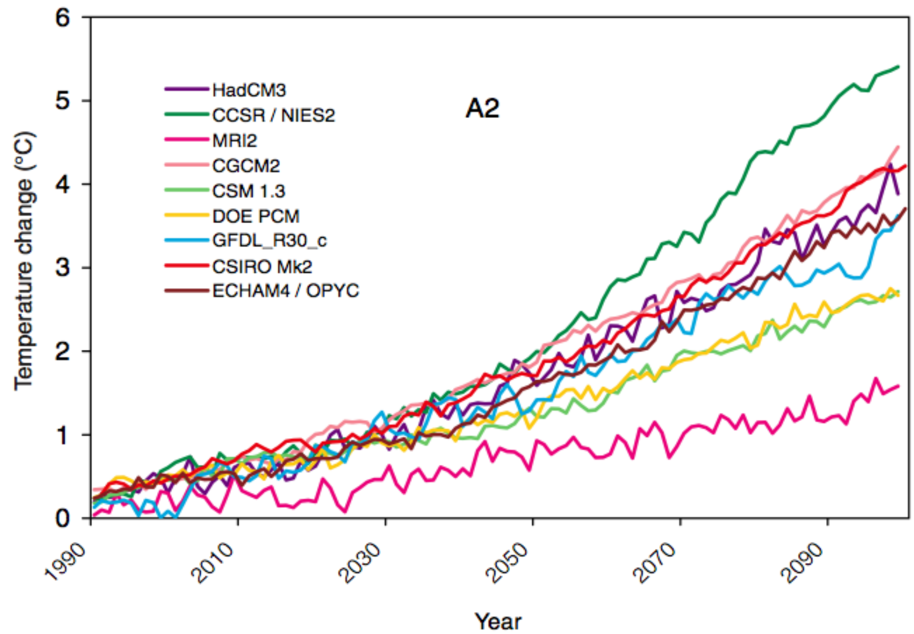



**Figure 6-1.** A selection of climate models and their prediction of globally averaged surface air temperature change in response to emissions scenario A2 of IPCC Special Report on Emission Scenarios. $CO_2$ is approximately doubled present concentrations by year 2100 [Source: Cubasch et al. 2001].

Many of the issues in climate models are exacerbated in the Arctic where higher spatial resolution is needed, less information is available, and additional parameterizations need to be considered. A range of phenomena can be identified that are responsible for the large amount of uncertainty associated with numerical predictions in the Arctic. Following are several key issues associated with these phenomena:

- On a resolved scale, motion is a key determinant of regions of thick and thin ice within the Arctic and accounts for much of the error in simulations of the Arctic thickness. Sea ice modes respond to top and bottom stresses exerted by the atmosphere (surface wind stress) and ocean, the tilt of the ocean surface, the Coriolis force, and internal stress within the ice cover (Washington and Parkinson 1986; Kattsov et al. 2005).

- In atmospheric models, certain factors strongly influence the sea ice simulation. Examples are the temperature profile of the atmospheric boundary, vertical resolution of the atmospheric component model being too coarse to capture the strong but shallow temperature inversions, and surface wind. Such factors in many atmospheric models are sufficient to cause large errors in the pattern of sea ice thickness across the Arctic.

- The presence of an anticyclonic surface-wind pattern circulating around an erroneous Arctic high-pressure center is a common problem in climate models and was documented for the 20C3M simulations (Chapman and Walsh 2007).

- Various Arctic-specific dynamics complicate the characterization of clouds. Cloud errors are particularly significant for sea ice simulation because clouds regulate the amount of sunlight at the surface during summer and provide a source of downwelling infrared radiation during the winter. Thus, the Arctic-specific dynamics substantially moderate both the growth and melting of the ice.

- In the literature of natural Arctic climate variability, two forms of variability feature prominently: (1) long-term wind fluctuations associated with the Arctic oscillation; and (2) variations in ocean heat flux due to incursions of Atlantic water, together with reductions in the buffering effect of the cold halocline layer.

- The Arctic oscillation is the most prominent mode of atmospheric variability in high-northern latitudes, and it exhibited a pronounced trend toward higher values from 1970 to the mid-1990s (Thompson, Wallace, and Hegerl 2000).

- Flux adjustments represent a trade-off in modeling: the adjustments are not desirable, as they do not represent real physical processes, yet they may be necessary to prevent the climate model from drifting to an unrealistic climate. This requires several hundred years' worth of simulation.

- Holland, Bitz, Hunke, et al. (2006) found that abrupt loss events, which are simulation studies that showed the abrupt end of sea ice at certain times, are preceded by pulselike incursions of warm Atlantic water into the Arctic. The pulses are essentially the same as the Atlantic Water incursions described by Polyakov et al. 2005 as a form of natural, unpredictable Arctic climate variability. Thus, even in global-warming simulations in which climate change is strongly driven by external forcing, natural variability is still a prominent factor in the year-to-year and decade-to-decade changes in sea ice cover.

- Holland, Bitz, and Tremblay (2006) examined a number of other present-day predictors, including winter cloud cover, ocean heat transport, and snow cover on land, and found statistically significant associations between these factors and simulated climate change.

Some researchers are arguing that an ensemble of models is necessary to capture in some manner the uncertainty associated with these numerical predictions. Anisimov (2009) suggests using a stochastic-modeling approach to account for the high spatial variability in large-scale permafrost models. Palmer (2012) discusses uncertainties of numerical weather and climate predictions and argues that, on time scales where verification data exist, stochastic methods are beginning to outperform conventional multisimulator ensembles. However, it is our contention that the emphasis of our effort has to be on maximizing information (or reducing uncertainty) and making the numerical forecasts more robust.

## 6.4 Data Acquisition

Historically, the measurement strategies in the Arctic have been targeted to improve qualitatively the understanding of the dynamics but mostly uncoupled from numerical predictions. More recently, certain observations are being used to validate models (McLaren et al. 2006).

The following are questions that a data acquisition strategy must answer:

- Where should measurements be taken and what are required accuracies?
- How many samples are sufficient?
- Which data types are most important?
- When should measurements be taken?
- How should inhomogeneous data be used and prioritized?
- How should the acquisition geometry be designed (paths, frequency)?

Arctic data acquisition programs encompass a tremendous range of data measurements for many different purposes. Weather models need data to establish initial conditions, climate models need boundary conditions and internal forces, and pollution models need trace gas measurements. For the Arctic region, additional information is required, such as sea ice thickness, ice concentration, sea surface temperature, reflection coefficients, velocities, permafrost material properties, ocean temperatures, air temperatures, water salinities, surface air temperature, sea ice thickness, cloud and aerosol properties and profiles above the surface, precipitation, paleoclimate information (ice cores to measure oxygen isotope ratio as a proxy for temperature), sea level rise, water vapor, thermodynamics measurements, cloud extent, cloud type, ice volume, and other geophysical parameters.

As mentioned in earlier chapters, Sandia manages atmospheric research facilities on the North Slope of Alaska that perform year-round monitoring of temperature, humidity, pressure, wind velocities, radiation, precipitation, ice thickness, cloud observations, ozone, black carbon, and trace gas concentrations. As part of this measurement program, we are beginning manned and unmanned flights that record data and complement our single-point measurements. Also, Sandia has a history of satellite deployment that needs to be coordinated with the overall program.

Furthermore, other agencies collect data such as sea ice concentration, thickness, velocity, and albedo. Ice concentration (and possibly velocity) can be obtained from satellite images, but other data depend on *in situ* measurements. A recent realization of the carbon and nitrogen release from a rapidly thawing permafrost has prompted additional measurements in nontraditional areas.

## 6.5 Coupling Data Acquisition and Numerical Analysis via Design of Experiments

One of the reasons why numerical climate and weather models have not made more progress is because data acquisition programs are not integrated or coupled into numerical simulation and analysis tools. The goal of experiment planning and design is to optimize a desired outcome of an experiment by choosing the best combination of parameters. For instance, in the Arctic we may ask where sea ice thickness should be measured, how many methane measurements should be taken, what trace gases need to be detected, whether ice cores are more important than black carbon measurements, or how many precipitation measurements are necessary. Although measurements in general provide valuable insight, it is not clear which measurements are more important to climate predictions. All these questions combined with the complicated logistics, harsh environment, and rapidly changing dynamics warrant the support of numerical analysis tools to prioritize measurements.

Traditionally, experiments are conducted by changing one factor at a time and assessing the outcome. For a small set of factors, an optimal value can be determined by inspection, but clearly for high-dimensional spaces, the manual inspection quickly becomes intractable. An optimization process can automate this process and determine the sensitivity of parameters on the overall dynamics. But when the design space is very large and highly nonlinear, the solution of an optimization problem requires special algorithms and implementation strategies.

If the goal is to improve the accuracy of numerical forecasting, the design of experiments can be cast into several stages. First, an inverse problem needs to be solved in which the goal is to improve model parameters. For climate dynamics, this poses a large-scale optimization problem and therefore requires adjoint-based formulations with partial differential equation (PDE)-constrained optimization techniques (Akcelik et al. 2006). Second, an optimization and sampling problem can be solved to develop a data acquisition design. The brute-force approach would be to consider a full-factorial approach where each point in the design space is interrogated. However, for climate-type or weather-type data acquisition, such an approach would be intractable. Instead, a D-Optimality criteria approach would address several constraints and would maximize information. Third, a real-time evaluation of the acquired data needs to be performed. In real time, the quality of the data must be assessed, which requires an online evaluation capability. This capability would consist of reduced-order modeling to perform the analysis in real time. Finally, the entire process needs to be repeated which would eventually produce high-quality prediction and an optimal data-acquisition strategy. We define this process as ”large-scale design of experiments” because the “large scale” pertains to not only the large data targets but also the complex dynamics. Large-scale design of experiments can be applied to any level of complexity, from the evaluation of a single data type to eventually a host of data types.

The second stage (as well as the third) of large-scale design of experiments requires the selection of an appropriate design-criteria target. A brute-force approach is to perturb each point of the design space in a factorial fashion. However, this can be intractable for high-dimensional spaces, as well as for irregular geometries, and does not necessarily produce the highest quality of information. Design of experiment theory offers more efficient approaches, in particular optimal design.

For a linear least-square problem, we can formulate the following objective function:

$$f(x) = \frac{1}{2}||Jx - y||^2$$

where *y* can represent observations and *Jx* can represent a numerical simulation. According to optimization theory, the gradient to *f(x)* set to zero results in an optimal solution $x^*$:

$$\nabla f(x) = J^T(Jx - y) = 0$$

$$x^* = (J^T J)^{-1} J^T y$$

This last equation is known as the normal equation, and $J^T J$ is known as the normal matrix or the information matrix. In general, the different approaches of optimal design attempt to maximize information. A popular choice is the D-optimality condition that seeks to minimize the determinant of this matrix. Other choices are the A-optimality for the trace of the matrix or the E-optimality that minimizes the largest eigenvalue of the matrix.

Solving these equations for a small number of design parameters is a trivial exercise. However, when large numbers of design parameters are involved where *J* depends on finite element discretization of multiple PDEs, then the solution requires so-called adjoint-based PDE-constrained optimization methods. The optimization algorithm then requires access to a specific linear-algebra object from the forward simulator. Section 6.6 discusses this issue in more detail and provides a concrete example.

Because of the high cost and urgency associated with gathering data in the Arctic, it will be critical to evaluate the quality of the measurements in the field so that slight modifications to the acquisition strategy can be considered or the repeat of certain measurements can be made if errors are identified. To support data acquisition in real time, a reduced-order modeling capability is required. Although creating a real-time simulation capability for weather and climate physics is still a research topic, certain approaches have been demonstrated on relatively complicated models. Proper orthogonal decomposition is a relatively straightforward method but still needs access to the Jacobian for projection and is therefore not easily implemented in the traditional community models. Once the highest-energy modes are identified, the forward coefficient matrix (Jacobian) can be projected to a much smaller dimensional space. However, this also poses an implementation challenge that cannot be readily solved in the context of community-based climate or weather numerical models

## 6.6 Sandia Capabilities and Numerical Prototype

A key feature that differentiates Sandia from other laboratories, universities, or commercial companies is our development of numerical simulation and analysis components for high-performance computing. Through many years of developing sophisticated software tools and infrastructure targeted to complex simulation goals of the nuclear stockpile, several key capabilities have emerged that provide an efficient and very powerful set of C++ based components from which multiphysics simulations can be built with embedded analysis capabilities. Capabilities such as Trilinos, Sierra, DGM, and Peopt provide a foundation from which embedded analysis can be implemented and exercised in a timely manner. Such capabilities, combined with decades of experience in large-scale simulation and analysis, position Sandia with a unique skill set to enable numerical guidance for data acquisition in the Arctic.

We discuss in the following paragraphs the implementation of multiphysics simulations combined with large-scale inversion algorithms, which is one of the components for large-scale design of experiments. An adjoint-based optimization prototype was developed at Sandia developed using the Sandia software tools Trilinos and Peopt adjoint-based optimization. The primary purpose of this demonstration was to report on the feasibility and the efficiency of using these tools with an eye toward eventually making significant contributions to field measurement programs.

The author of this part of the report (Section 6) in collaboration with a summer student developed several simulation components to prototype certain climate and weather dynamics. The goal was to assess the feasibility of creating simulation models interfaced with embedded algorithms in a short period of time. Large-scale inversion algorithms within a design-of-experiments process was the focus of the embedded algorithms. We also evaluated different software designs to determine most efficient access.

The mathematical formulation of the source inversion problem is as follows:

$$\underset{f}{min} \int_{\Omega} (c - c^*)^2 \delta(x - x^*) dx + \frac{\beta}{2} \int_{\Omega} c^2 dx$$

and is constrained by different type of physics, namely, a Poisson operator, convection-diffusion (CD), and Stokes physics:

$$\text{Poisson:} \quad -D\Delta c = f \quad \in \Omega$$

$$\text{CD:} \quad -D\Delta c + v \cdot \nabla c = f \quad \in \Omega$$

$$\begin{aligned} \text{Stokes:} \quad -D\Delta u + \nabla p &= f \quad \in \Omega \\ \nabla \cdot u &= 0 \end{aligned}$$

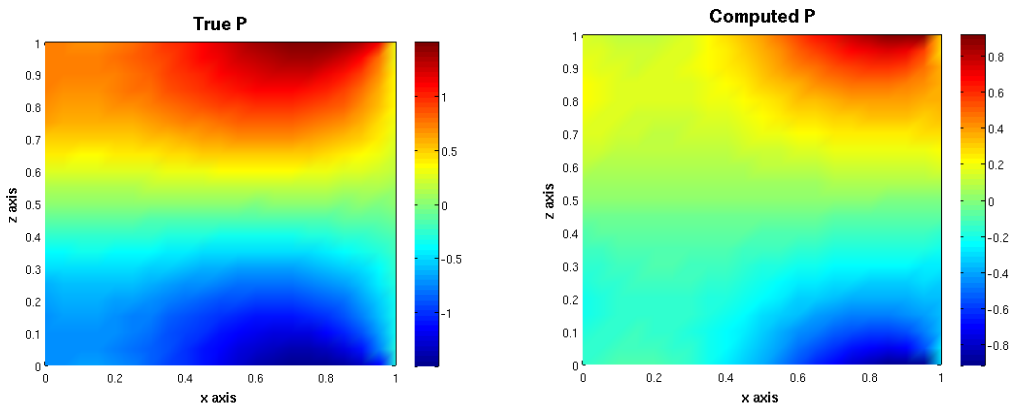
The choice of these physics formulations was based on our eventual goal of performing design of experiments for ice sheet modeling in which data measurements of temperature (Poisson), trace gas (CD), and ice velocity (Stokes) are considered.

To solve the above-described inversion problem, which is the model calibration phase of design of experiments, a large constrained optimization problem must be solved. The solution of this so-called PDE-constrained optimization problem requires that a Lagrangian function be formed where the objective function is combined with the constraints multiplied by the adjoint variables. Variations are then taken with respect to the states, adjoints, and inversion parameters and set to zero. The resulting optimality condition can be solved for the states, adjoint variables, and finally the inversion parameters. See Akcelik et al. 2006 for additional details on different approaches and methods. We implemented a continuous adjoint, meaning that we derived the optimality conditions in infinite dimensional space and then discretized the adjoint equations. Only in the limit when the mesh spacing approaches zero will the continuous adjoint be equivalent to the discrete adjoint, which ultimately is the correct operator needed to solve the optimization problem.

We first targeted a finite-element discretization and steady-state implementation for a Laplace operator. Trilinos's automatic differentiation module (Sacado) was used to create the Jacobian, which could easily be generated analytically. Anticipating the ultimate goal of implementing complex multiphysics capabilities, the purpose of using automatic differentiation for this very simple operator was to explore the implementation requirements, implementation efficiency, and performance behavior. Using automatic differentiation, the future generation of Jacobians for more complex physics is anticipated to be seamless. We designed our implementation to accommodate the necessary linear algebra needed for optimization, such as objective function, adjoints, inner products, scaling, Hessians, and inequality constraint.

Our initial working simulator was a Laplace operator (steady-state heat) with large-scale inversion capabilities to invert for source terms. The source inversion problem is a convenient initial step for any other inversion scheme because the optimization problem remains linear, meaning that the solution only requires first-order derivatives. However, it is a logical first step because adjoints are required to handle sensitivities associated with large numbers of inversion parameters. In subsequent implementations, we generated the source inversion problem for both convection-diffusion and Stokes flow.

In Figure 6-2(a) we show a two-dimensional (2D) forward simulation with a Gaussian source term. Figure 6-2(b) shows the inversion result for a synthetic experiment in which synthetic observations at sparse locations are used to reconstruct the original source term. In this synthetic experiment, the inversion makes no assumption about the original source term other than that at least one term can be located anywhere in the computational domain.




(a) (b)

**Figure 6-2.** Simulation results: (a) true pressure field Stokes flow and (b) reconstructed pressure field.

In less than three months we were able to create a 2D, parallel multiphysics capability using adjoints with interfaces to leverage large-scale inversion capabilities from a few key Trilinos modules and an independent (Peopt) optimization solver library. This development suggests that with modest efforts, certain aspects of climate and weather prediction could be developed with the necessary interfaces to perform large-scale analysis and provide numerical analysis support to data acquisition programs.

## 6.7 Conclusions and Sandia Opportunities

Sandia has traditionally not contributed to climate or weather forecasting efforts beyond that required for internal projects, typically involving modeling. However, with a series of national security issues associated with the rapidly changing Arctic regions, Sandia has a legitimate reason to engage in climate- and weather-model development and analysis. Our entry point could be the refactoring of certain numerical-simulation capabilities to help characterize Arctic-specific dynamics but more importantly to provide the infrastructure to support data acquisition with simulation and analysis tools.

Sandia has the opportunity to provide numerical support for data acquisition strategies. To handle the very large parameter space, efficient algorithms are required that interact with specific linear-algebra objects within the numerical simulation codes. Unfortunately, because most community models are not conducive to embedded algorithms, this would require a potential rewrite of critical simulation components. Although this task seems daunting, we have state-of-the-art tools that can recreate most physics modules in short periods of time with the necessary interfaces to state-of-the-art algorithms.

We have an established presence in arctic data acquisition via the DOE Atmospheric Radiation Measurement (ARM) facilities in Barrow and Oliktok Point; participation in the research community in situ measurement program; the use of satellite remote sensing; and manned and unmanned aircraft systems for making remotely sensed measurements. This data acquisition experience coupled with our numerical simulation capabilities

provides a unique opportunity for Sandia to make significant contributions to the overall characterization of the Arctic region.
The necessary coupling of data acquisition and numerical analysis encompasses a series of algorithms, including inversion, reduced-order modeling, and design of experiments. Design of experiments provides well-established methods but not in the context of large-scale optimization constrained by complex physics. We have the tools and experience to undertake large-scale design of experiments and have demonstrated in a short period of time relatively sophisticated prototypes.

Sandia is in a unique position to take responsibility for national security issues in the Arctic and simultaneously impact global climate forecasting through the coupling of large-scale analysis to data acquisition.

## 6.8 Acknowledgements

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## 6.9 References

Akcelik, V., G. Biros, O. Ghattas, J. Hill, D. Keyes, and B. van Bloemen Waanders. (2006). "Parallel Algorithms for PDE-constrained Optimization." In *Parallel Processing for Scientific Computing*, edited by M. Heroux, P. Raghaven, and H. Simon. Philadelphia, PA: Society for Industrial and Applied Mathematics (SIAM).

Anisimov, O. A. (2009). "Stochastic Modelling of the Active-Layer Thickness under Conditions of the Current and Future Climate." *Earth's Cryosphere* 3: 36–44.

Barriopedro, D., R. Garcia-Herrera, A. R. Lupo, and E. Hernández. (2006). "A Climatology of Northern Hemisphere Blocking." *Journal of Climate* 19, no. 6: 1042–1063.

Budikova, D. (2009). "Role of Arctic Sea Ice in Global Atmospheric Circulation: A Review." *Global and Planetary Change* 68, no. 3: 149–163.

Chapman, W. L., and J. E. Walsh. (2007). "A Synthesis of Antarctic Temperatures." *Journal of Climate* 20, no. 16: 4096–4117.

Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, et al. (2001). "Projections of Future Climate Change." In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 525–582. Cambridge, UK: Cambridge University Press.

Deser, C., R. Tomas, M. Alexander, and D. Lawrence. (2010). "The Seasonal Atmospheric Response to Projected Arctic Sea Ice Loss in the Late 21st Century." *Journal of Climate* 23, no. 2: 333–351.

Francis, J. A., W. Chan, D. J. Leathers, J. R. Miller, and D. E. Veron. (2009). "Winter Northern Hemisphere Weather Patterns Remember Summer Arctic Sea Ice Extent." *Geophysical Research Letters* 36, no. 7, L07503, doi:10.1029/2009GL037274.

Francis, J. A., and S. J. Vavrus. (2012). "Evidence Linking Arctic Amplification to Extreme Weather in Mid-latitudes." *Geophysical Research Letters* 39, no. 6, L06801, doi:10.1029/2012GL051000.

Ghil, M. (2003). "Natural Climate Variability." In *Encyclopedia of Global Environmental Change, Volume 1, The Earth System: Physical and Chemical Dimensions of Global Environmental Change*, edited by M. C. MacCracken and J. S. Perry. Chichester, England: John Wiley & Sons.

Holland, M. M., C. M. Bitz, and B. Tremblay. (2006). "Future Abrupt Reductions in the Summer Arctic Sea Ice." *Geophysical Research Letters* 33, no. 23, L23503, doi:10.1029/2006GL028024.

Holland, M. M., C. M. Bitz, E. C. Hunke, W. H. Lipscomb, and J. L. Schramm. (2006). "Influence of the Sea Ice Thickness Distribution on Polar Climate in CCSM3." *Journal of Climate* 19, no. 11: 2398–2414.

Honda, M., J. Inoue, and S. Yamane. (2009). "Influence of Low Arctic Sea-Ice Minima on Anomalously Cold Eurasian Winters." *Geophysical Research Letters* 36, no. 8, L08707, doi:10.1029/2008GL037079.

Kattsov, V. M., E. Källén, H. Cattle, J. Christensen, H. Drange, I. Hanssen-Bauer, T. Jóhannesen, I. Karol, J. Räisänen, G. Svensson, et al. (2005). "Future Climate Change: Modeling and Scenarios for the Arctic. In *Arctic Climate Impact Assessment*, edited by C. Symon, L. Arris, and B. Heal. Cambridge, UK: Cambridge University Press.

Lindsay, R. W., and J. Zhang. (2005). "The Thinning of Arctic Sea Ice, 1988–2003: Have We Passed a Tipping Point?" *Journal of Climate* 18, no. 22: 4879–4894.

Lobell, D. B., C. Bonfils, and P. B. Duffy. (2007). "Climate Change Uncertainty for Daily Minimum and Maximum Temperatures: A Model Inter-comparison." *Geophysical Research Letters* 34, no. 5, doi:10.1029/2006GL028726.

Mass, C. (March 18, 2012). "The U.S. Has Fallen Behind in Numerical Weather Prediction: Part I." Cliff Mass Weather Blog. http://cliffmass.blogspot.com/2012/03/us-fallen-behind-in-numerical-weather.html (accessed on March 28, 2014).

McLaren, A. J., H. T. Banks, C. F. Durman, J. M. Gregory, T. C. Johns, A. B. Keen, J. K. Ridley, M. J. Roberts, W. H. Lipscomb, W. M. Connolley, and S. W. Laxon. (2006). "Evaluation of the Sea Ice Simulation in a New Coupled Atmosphere-Ocean Climate Model (HadGEM1)." *Journal of Geophysical Research: Oceans (1978–2012)* 111, no. C12, DOI: 10.1029/2005JC003033.

Meehl, G. A., et al. (2007). "Global Climate Projections." 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*, edited by S. Solomon et al. Cambridge, UK: Cambridge University Press.

Overland, J. E., and M. Wang. (2010). "Large-Scale Atmospheric Circulation Changes Are Associated with the Recent Loss of Arctic Sea Ice." *Tellus A* 62, no. 1: 1–9.

Palmer, T. N. (2012). "Towards the Probabalistic Earth-System Simulator: A Vision for the Future of Climate and Weather Prediction." *Quarterly Journal of the Royal Meteorological Society* 138, no. 665: 841–861.

Petoukhov, V., and V. A. Semenov. (2010). "A Link between Reduced Barents-Kara Sea Ice and Cold Winter Extremes over Northern Continents." *Journal of Geophysical Research – Atmospheres* 115, no. D21111, doi:10.1029/2009JD013568.

Polyakov, I. V., A. Beszczynska, E. C. Carmack, I. A. Dmitrenko, E. Fahrbach, I. E. Frolov, R. Gerdes, et al. (2005). "One More Step toward a Warmer Arctic." *Geophysical Research Letters* 32, no. 17, L17605, doi:10.1029/2005GL023740.

Randall, D., J. Curry, D. Battisti, G. Flato, R. Grumbine, S. Hakkinen, D. Martinson, R. Preller, J. Walsh, and J. Weatherly. (1998). "Status and Outlook for Large-Scale Modeling of Atmosphere-Ice-Ocean Interactions in the Arctic." *Bulletin of the American Meteorological Society* 79, no. 2: 197–219.

Screen, J. A., and I. Simmonds. (2010). "The Central Role of Diminishing Sea Ice in Recent Arctic Temperature Amplification." *Nature* 464, no. 7293: 1334–1337.

Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland. (2009). "The Emergence of Surface-based Arctic Amplification." *Cryosphere* 3, no. 1: 11–19.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl. (2000). "Annular Modes in the Extratropical Circulation. Part II: Trends." *Journal of Climate* 13, no. 5: 1018–1036.

UCAR (University Corporation for Atmospheric Research). (2009). *2009 Community Review of the NCEP Environmental Modeling Center*. http://www.ncep.noaa.gov/director/ucar_reports/EMC_Report_UCAR_Final.pdf (accessed on March 27, 2014).

Washington, W. M., and C. L. Parkinson. (1986). *An Introduction to Three-Dimensional Climate Modeling*. Oxford, England: Oxford University Press.

Weart, S., and American Institute of Physics. (2014). "General Circulation Models of Climate." http://www.aip.org/history/climate/GCM.htm (accessed on March 26, 2014).

# 7 Uncertainty Analysis for Climate Models

Section 7 discusses aspects of uncertainty analysis that impact its use for climate models. First, we outline some of the needs and challenges involved in performing uncertainty analysis for climate models. Next, we discuss Sandia's past and current activities in uncertainty analysis for climate models and then highlight Sandia's capabilities in this area. Note that the material in this section is applicable to Arctic models as well as to other components of climate simulations such as atmosphere and land models. Finally, we identify some topics for future work. The section concludes with a list of references.

The term "uncertainty analysis" is used broadly throughout Section 7 to cover sensitivity analysis, model calibration, and uncertainty quantification (UQ). Sensitivity analysis includes identification of the most important parameters and phenomena driving the responses of climate models. Model calibration covers, for example, parameter estimation and identification of parameters that yield results that agree well with experimental data. An example of UQ is the forward propagation of uncertain input parameters to understand the uncertainty in the responses.

## 7.1 Needs and Challenges

Climate models face needs in sensitivity analysis, model calibration, and UQ that are common to those faced by many computational simulations. These needs are presented in Section 7.1.1. Climate models also face significant challenges in computational cost, calibration, and model prediction. These challenges are described in Sections 7.1.2 through 7.1.4.

### 7.1.1 Common Needs

Climate models such as CESM, the Community Earth System Model (UCAR 2014), are sophisticated computational simulations involving multiple physical phenomena (e.g., advection and radiation) on multiple scales. The needs faced by climate models similar to those of many computational simulations include the following:

1. ***Sensitivity Analysis***. Methods are needed to analyze the global and local response and sensitivity of given quantities of interest with respect to uncertain input parameters, including methods to rank and screen uncertain input parameters in terms of their influence.

2. ***Model Calibration***. Methods are needed for statistical calibration and tuning of uncertain input parameters given observations (inverse UQ), including methods that account for observation errors and structural errors in the process.

3. ***Prediction and Model UQ***. Methods are needed to characterize the predictive accuracy of a quantity of interest by propagating input uncertainty through the model and account for additional structural error (forward UQ). This includes

methods to validate the predictions, and to select and/or average predictions from competing models.

### 7.1.2 Computational Cost Challenge

A major challenge posed by climate models is their computational cost. For example, performing the current CESM using CAM5 and a one-degree–nudged model for a nine-month run, which is a short run, takes about 2,250 central processing unit (CPU) hours. With this cost, it is not possible to perform a large number of samples, referred to as an ensemble of runs. With relatively few samples, especially given the large number of model parameters, it is necessary to develop surrogate models, such as metamodels or response surface models based on these samples. The surrogate models are simplified models that are usually very fast to evaluate (e.g., a linear regression model that specifies the output as a linear function of input parameters). Surrogate models can then be queried extensively to perform some of the methods in items 1–3 (of Section 7.1.1) outlined above. Surrogate methods must play a major role in sensitivity analysis, model calibration, and model prediction because of the cost of the climate simulations. Yet surrogate models themselves present issues because their error needs to be estimated and included in the analyses. In addition, although one may build a surrogate model over a small number of parameters, the underlying uncertainty in the model may be a function of many more parameters that are not explicitly treated in the surrogate model. Regression models may be expanded fairly easily to hundreds or thousands of input parameters, but the more advanced surrogate methods, such as Gaussian process models, polynomial chaos, or spline models, usually handle a maximum of a few dozen input parameters.

### 7.1.3 Calibration Challenges

Calibration is especially challenging in climate models for several reasons, First, a wide variety of physical observations are recorded in climate models, ranging from the commonly known temperature and precipitation measurements to satellite observations to light detection and ranging (LIDAR). These observations are often high frequency, being recorded multiple times per day at multiple locations over the Earth. There may be a significant amount of missing data, and the observations may be inconsistent. For example, there are significant differences in the rates and precipitation amount information recorded over the United States by the Next-Generation Radar (NEXRAD), the Tropical Rainfall Measuring Mission (TRIMM), and the National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center.

Second, the calibration problem in climate models is nonunique. That is, with hundreds of parameters, running the model at several different combinations of parameter values may result in the same values of model outputs, such as global mean temperature or precipitation. If parameter settings A and parameter settings B give the same answer or nearly the same answer, this makes the optimization problem challenging: we are searching a high-dimensional space for multiple local optima, and it may be hard to determine the relative merit of one local optima over another in terms of being more "physically correct."

Third, the calibration problem in climate models is ill posed. As much as the climate models have evolved, they are still imperfect representations of our world. In some cases, it may not even be possible to find parameterizations that are consistent with different types of quantities of interest. For example, one problem Sandia is addressing in the Climate Science for a Sustainable Energy Future (CSSEF) program (discussed in Section 7.2.2) is to calibrate the atmosphere model parameters that control the diurnal cycle over the central United States. This calibration problem has been very difficult: the model predicts that it rains in the day, but the actual data show it rains in the night, meaning that the model is about 12 hours out of phase. However, calibrating cloud parameters and other atmospheric parameters may not be the best method to employ (and we may not even find combinations of parameters that can characterize the phase correctly) because part of the problem is that the orographic details over the Rocky Mountains is not modeled correctly to a high-enough resolution. Thus, in this case, tuning parameters is not necessarily the right answer to providing a more physically accurate model.

The fourth reason calibration is challenging in climate models is related to the issue of modeling structural error (part of the prediction and model UQ item listed in Section 7.1.1). Some computational statisticians favor the identification and explicit treatment of a structural error term to treat incomplete physics, systemic biases in the models, etc. (Kennedy and O'Hagan 2001) This approach has its advantages and disadvantages: it is useful for climate modelers to understand the size of the structural error and the parameters that tend to influence the error. The disadvantage is that a structural error term is another term that must be estimated; it can have complicated dependencies on parameters and be a function of space and time; and the calibration results are confounded with the estimation of the structural error. An example of estimating structural error that was performed as part of the CSSEF project is provided in Johannesson and Lucas 2014.

The fifth reason that calibration is challenging in climate models is the need to aggregate the sheer number of observations in space and time, requiring that calibration be performed, for example, with respect to averages in weeks or months versus hourly data. Furthermore, there is significant noise in both the observations and in the climate models, making the calibration problem more difficult.

The sixth reason that calibration is challenging in climate models is that typically we want to perform calibration on a model that is verified, meaning a model for which we can quantify some error metrics for the mathematical models used in solution of the governing equations for the model. Historically, Sandia and the Advanced Simulation and Computing (ASC) program have emphasized that the physics models used for weapons applications be verified. The verification process may involve several steps, such as using the method of manufactured solutions and performing studies at three or more mesh sizes (typically doubling the mesh successively) to estimate the order of convergence. Such steps are simply not possible at this time with climate problems. We can go from grid resolutions at two degrees to one degree to one-eighth degree, but the parameterizations (especially atmosphere and cloud parameterizations) differ as the resolution increases. In effect, we are not in the same regime when resolution increases with climate models as we are in many engineering applications. For climate models, we want to perform calibration on models that would not be considered to have undergone rigorous solution verification in the computational science community. Note that in this context, solution verification refers to the estimate of numerical error in the solution and also to an estimate of the convergence rate of the model as the model is refined.

### 7.1.4 Model Prediction Challenges

In terms of model prediction, the climate-modeling community has typically taken the results of 20 or more different climate models that were all generated for a particular scenario (e.g., doubling atmospheric carbon dioxide [$CO_2$] by 2100) and plotted the results (e.g., mean global temperature predictions out to 2100) on a single plot. This type of analysis is a between-model or intermodel uncertainty analysis. That is, the analysis does not include the quantification of uncertainty within a model (i.e., intramodel). The UQ tools that Sandia uses focus on intramodel uncertainty analysis. Within a particular climate model, there still may be questions, for example, about which particular turbulence model to use and which particular microphysics cloud model to use. Sandia has some tools to address this "model selection" problem. Overall, we discuss the capabilities that Sandia can bring to this problem in Section 7.3.

## 7.2 Current and Past Activities in Climate UQ

The activities presented in Sections 7.2.1 and 7.2.2 do not address all of the climate work done by Sandia. The discussion here is limited to UQ and limited to a sampling of recent activities.

### 7.2.1 Climate Science for a Sustainable Energy Future

In 2010, the Climate and Environmental Sciences Division, in the Office of Biological and Environmental Research at the Department of Energy (DOE) put out a call for a large climate-science initiative referred to herein as CSSEF (Climate Science for a Sustainable Energy Future). A large consortium of national laboratories (Oak Ridge, Argonne, Brookhaven, Lawrence Berkeley, Lawrence Livermore, Pacific Northwest, Los Alamos, and Sandia) conducted a proposal writing session in July 2010 and submitted a proposal. The proposal was awarded, and the funding started in June 2011.

The CSSEF program has several goals, but the overarching theme is to develop capabilities for the next generation of climate models. The following was taken from the CSSEF proposal (Bader et al. 2010):

> CSSEF will undertake several unique and potentially transformative research directions, including
>
> - The capability to thoroughly test and understand the uncertainties in the overall model and its components as they are being developed;
>
> - Major scientific advances in the components that will achieve greater fidelity in modeling feedbacks in the climate system;

- Development of model evaluation procedures that allow the rapid ingest of observational data for model and component evaluation;
- Flexible dynamical cores that enable fine-scale simulations; and
- Early adaptation of the model algorithms and code to the next generation of computers.

A large part of the CCSEF work focuses on advancing the code capabilities for the major thrust areas of land, ocean, and atmosphere models. In addition to these thrust areas, there are "cross-cutting" capability teams, specifically in (1) data and test beds and (2) UQ. The CCSEF program is divided among eight laboratories. At the time this report was finalized, there were two CCSEF UQ teams at Sandia: Sandia California supports land UQ activities; Sandia New Mexico supports atmosphere UQ efforts.

Both CSSEF UQ teams at Sandia (the land group and the atmosphere group) have focused on generating ensembles of runs and performing sensitivity analysis on these runs. These teams have also explored surrogate models. The atmosphere team has relied on Lawrence Livermore National Laboratory to generate the CAM5 ensemble on their machines. In 2011, the analysis focused on some CAM4 and early CAM5 two-degree runs. The 2012 efforts involved sensitivity analysis of more two-degree and then one-degree–nudged runs (Johannesson et al. 2014). We currently are trying to calibrate the two-degree model using "simulated" observational data, with the simulated data generated from the model as well. Even this task is proving difficult, because of the large number of quantities of interest we are investigating (400 responses, including the first four harmonics of the diurnal cycle in four seasons in six regions of the United States, and various precipitation percentiles) and because of the noise in the model. For example, even if we generate surrogate models for each of the 400 responses based on the original two-degree data and sample the surrogate models at a million points, we do not get predictions matching the simulated experimental quantities of interest within a 30% error bar for each quantity of interest. To address this issue, we are developing an iterative filtering method that may circumvent the need to match all the data at once.

The Sandia team performing sensitivity analysis and calibration for the Community Land Model focused on Bayesian compressive sensing. This is an approach that picks the "most important" parameters from a larger set. A surrogate model is constructed using a set of polynomial basis functions. The optimal polynomial coefficients are inferred within a Bayesian framework, given a certain number of model training runs at some randomly selected inputs. The result is a sparse representation of a higher-order response surface, containing only the terms that matter. Bayesian compressive sensing has been applied to 80 parameters in the Community Land Model, successfully reducing the number of important parameters down to a dozen (Sargsyan et al. 2014).

### 7.2.2 SciDAC PISCEES Program

In 2012, the Office of Biological and Environmental Research within DOE's Office of Science issued a call for Scientific Discovery through Advanced Computing (SciDAC) application proposals. Three proposals were funded in climate: (1) land-ice modeling, (2) atmospheric tracer transport, and (3) variable-resolution atmospheric modeling. The work funded for land-ice modeling has the most Sandia involvement. The project is called PISCEES (Predicting Ice Sheet and Climate Evolution at Extreme Scales). The project will include uncertainty analysis as part of its focus. PISCESS's main goal is to develop improved models, and new tools will be implemented in the Community Ice Sheet Model (CISM) and CESM as a result of this work.

## 7.3 Sandia Capabilities

Sandia has many capabilities to address the needs of sensitivity analysis, model calibration, and model prediction in the climate community, as discussed in Sections 7.3.1 through 7.3.4. Note that many of these techniques have been developed over years, both at Sandia and at other DOE laboratories and organizations concerned with UQ on large computational simulations. For example, Ronald Iman of Sandia was one of the developers of Latin hypercube sampling, which is a stratified sampling method that improves the point placement in a high-dimensional space. Furthermore, the Design Analysis Kit for Optimization and Terascale Applications (DAKOTA, Adams et al. 2009) software framework developed by Sandia engineers has many algorithms for sensitivity analysis and UQ, as does the UQ Toolkit (UQTk). DAKOTA methods are included in the following discussion of Sandia capabilities as applicable.

### 7.3.1 Method Capabilities for Sensitivity Analysis

Sensitivity analysis is often categorized as local (e.g., derivatives) or global. Local methods are often considered "intrusive" to the code in the sense that we need to calculate analytic derivatives if possible. For components of the climate models, automatic differentiation offers the capability of efficient computation of local sensitivity information, which is particularly efficient for high-dimensional input spaces. Global methods are usually nonintrusive; that is, they do not require any modifications of the climate models, only evaluations of the climate models at different parameters sets. Nonintrusive sensitivity analysis (e.g., Saltelli, Chan, and Scott 2000) methods broadly fall in two classes: those that interact directly with the model and those that use fast statistical output emulators. The first class of methods is driven by input sampling schemes that are efficient in estimating given sensitivity indices (i.e., requiring as few simulations as possible), while the second class of methods is driven by (often adaptive) sampling schemes that produce accurate output emulators that can then, for example, be efficiently sampled as many times as needed to yield sensitivity indices. Further, the output emulator can be used in place of the simulator for informative graphical exploratory and statistical analysis of quantities of interest.

The following methods can be used with nonintrusive sensitivity analysis:

- Graphical data analysis: Scatter plots of inputs/outputs, joint density estimation of input/output relationships

- Statistical analysis: Correlation analysis, stepwise regression (for screening), and analysis of variance (ANOVA) to identify sources of variation

- Variance-based decomposition: Identifies the fraction of the variability in the output that can be attributed to an individual input variable alone or with interaction effects (Saltelli, Chan, and Scott 2000)

- Morris One-At-A-Time Sampling (MOAT): A “main effects” type of analysis that is performed by averaging over multiple sample trajectories, where each trajectory involves “large” derivative steps (e.g., more than half the domain) (Morris 1991)

The first two methods outlined above are available in most statistical analysis packages. The last two methods are available in a few toolkits, including DAKOTA. For local sensitivity analysis, Sandia has a package called Sacado in the Trilinos framework that can be used for automatic differentiation.

### 7.3.2 Method Capabilities for Surrogate Models

There are many methods that can be used for surrogate models (also called metamodels, emulators, or response surface models). These methods range from simple polynomial regression to neural networks to adaptive spline methods to more elaborate constructions involving careful choices of basis representations. Such surrogates can then be queried extensively for both forward and inverse UQ, detailed sensitivity analysis, or optimization purposes. Note that the quantities of interest from climate simulations include spatiotemporal summary statistics across multiple output variables. Having a toolbox of surrogates allows one to explore various options and improve robustness in analyses relying on surrogate models.

DAKOTA currently has the capabilities for polynomial regression (up to cubic terms), neural networks, and splines (an implementation called MARS, meaning Multivariate Adaptive Regression Splines [Friedman 1991]). MARS employs a partitioning of the parameter space into subregions. Forward and backward regression methods are used to create a local surface model in each subregion with its own basis functions and coefficients. MARS is a nonparametric surface-fitting method, and its regression component does not constrain the surface to pass through all of the response data values. Thus, it provides some smoothing of the data.

Two areas of current focus in surrogate modeling are Gaussian process (GP) models and stochastic expansion methods. GP interpolation (also known as “kriging” predictors) is based on the spatial statistics. The idea is that points close together in input space will have response values that are also close together. One advantage of the GP is that it can provide a probabilistic assessment of a response value at a “new” point for which the forward model has not been evaluated (Sacks et al. 1989; Rasmussen and Williams 2006; Santner, Williams, and Notz 2003). Most surrogates only provide an estimate of the response, but the GP provides an estimate of the uncertainty in the response, which is very useful in understanding how much to “trust” the prediction. For example: Is the uncertainty large, meaning there is not much data, or is it small, meaning the interpolation point falls close to some of the existing data points? DAKOTA has GP capabilities and additionally has adaptive sampling and optimization algorithms based on GP surrogates.

Stochastic expansions, such as polynomial chaos expansions (PCEs), use orthogonal polynomial representations of an output over the input space (Ghanem and Spanos 1991; Xiu 2010). Stochastic expansions can be employed as global- or local-element–based functional representations. They can be constructed using nonintrusive sampling methods, where the samples are used to provide numerical estimates of projection integrals for the PCE coefficients. Both random (Monte Carlo and various variants) and deterministic (quadrature and sparse-quadrature) sampling methods for PCE construction are available in DAKOTA. In addition, a stand-alone library of UQ components called UQTk (UQ Toolkit), developed at Sandia California, has capabilities for both intrusive and nonintrusive stochastic expansions (Sandia National Laboratories 2014).

### 7.3.3 Method Capabilities for Calibration

There are two major classes of methods for calibration: deterministic and nondeterministic. Deterministic methods include gradient- and nongradient-based optimization algorithms and typically result in a point estimate (i.e., one answer) of the best parameter set. Gradient-based algorithms, such as nonlinear least-squares algorithms, are tailored to minimize a "sum of squared error" terms. Nonlinear least-squares optimization algorithms have been designed to exploit the structure of a sum-of-the-squares objective function. By assuming the residuals (the difference between the observed data and the model) are close to zero near the solution, the Hessian matrix of the objective can be approximated using only the derivatives of the residuals. In this way, one obtains good convergence behavior. DAKOTA has three versions of gradient-based nonlinear least-squares algorithms specifically designed to minimize a sum-squared-error formulation. In addition, we can use nongradient-based approaches such as genetic algorithms. We have explored using a multiobjective genetic algorithm (MOGA) for situations where we are trying to find parameter sets that satisfy several sets of response quantities simultaneously (e.g., precipitation and temperature). MOGA attempts to satisfy a Pareto optimization problem and identify a Pareto front of optimal solutions. In this case, there are multiple solutions that represent the trade-offs between objectives: some parameterizations may do well on matching temperature, for example, but others may do better on matching precipitation. The Pareto front maps out these solutions. Our limited experience thus far suggests that Pareto optimization may work if there are not too many parameters or responses and the responses are not too noisy.

Nondeterministic methods include Bayesian methods. In nondeterministic methods, the representation of the optimal parameter value is a distribution, not a point estimate. For example, in Bayesian methods, the goal is to find posterior distributions on the parameters given prior distributions on these parameters, observed data, and a likelihood function that relates the data and model predictions. Bayesian methods are conceptually very attractive: the idea is that one updates an initial belief (the "prior") with observational data as the data are obtained, resulting in better (presumably narrower distributions) estimates that are called posterior distributions. There are many challenges of Bayesian calibration, however. The standard approach used for generating the posterior distribution is called Markov Chain Monte Carlo. It involves tens or hundreds of thousands of evaluations of the model, so surrogates must be used in Bayesian calibration. We do have an initial capability to perform Bayesian calibration in DAKOTA.

### 7.3.4 Method Capabilities for Prediction and Model UQ

Forward UQ refers to propagating uncertainties in the model inputs, such as initial and boundary conditions and model parameters, through the simulation model to assess the effect of those uncertainties on the model predictions. Typically, we use random sampling or deterministic sampling to perform this propagation.

Random sampling methods include Monte Carlo, a number of flavors of quasi–Monte Carlo sampling, such as Latin hypercube sampling and importance sampling, as well as Centroidal Voronoi tesselations, and classical experimental designs. We often use Latin hypercube sampling because it tends to give lower variance estimates of statistics and improves point placement over plain Monte Carlo methods. Given the cost of climate models, it may be desirable to use adaptive methods that add points to an initial sample to optimize some metric. Most sampling methods are not adaptive. We do have some initial implementations of adaptive methods in DAKOTA. One adaptive sampling method is driven by the predictive accuracy of a GP surrogate model: samples are taken in areas of the space that do not have many samples. Importance sampling can help with sample adaptivity: importance sampling preferentially samples “important” values of input variables to improve the estimation of a statistical response quantity. We have an importance sampling approach in DAKOTA that is adaptive and uses GP surrogates.

Broadly, Monte Carlo and quasi–Monte Carlo methods are attractive in that they are not very sensitive to input dimensionality, in contrast with deterministic sampling. Moreover, random sampling methods do not rely on any smoothness of the system response. With respect to analyzing climate-model uncertainties, we note that there are many regulatory precedents for using random sampling methods for large-scale risk analyses of high-consequence events such as nuclear waste repository performance (Helton, Swift, and Hansen 2014) and nuclear power safety (Rasmussen et al. 1975).

Deterministic sampling methods are commonly used in nonintrusive PCE methods for quadrature evaluation of projection integrals for PCE coefficients. In this context, forward-model simulations are evaluated at parameter values chosen at the quadrature points. While these integrals can also be evaluated using random sampling, quadrature methods are more efficient than Monte Carlo and Latin hypercube sampling methods for small-to-moderate dimensionality. By taking advantage of known or presumed smoothness in the response, these deterministic sampling methods can achieve fast convergence with generally fewer samples than Monte Carlo and quasi–Monte Carlo methods (Eldred and Burkardt 2009; Eldred, Webster, and Constantine 2008).

A major challenge with PCE methods is the strong sensitivity to dimensionality of the input space. Approaches to mitigate this curse of dimensionality include various variants of adaptive anisotropic sparse-quadrature methods, where important dimensions are sampled more extensively. These approaches are currently implemented in the DAKOTA toolkit (Adams et al. 2010) and can be made available to the climate toolkit framework. However, these techniques are computationally feasible up to moderate—say 10 to 20 dimensions—depending on the CPU cost of one model evaluation. Even after sensitivity analysis and down-selection of influential parameters, climate model or testbed input parameter spaces can exceed this regime. Dimension reduction methods, combined with sensitivity analysis, may need to be used.

## 7.4 Future Directions

This section outlines future directions for UQ efforts by the computational science community, including Sandia.

### 7.4.1 Coupling Model Components

CESM, the full-Earth system model, connects the various model components (e.g., atmosphere, ocean, sea ice, land ice, and terrestrial) to model climate. In principle, only fully coupled calibration and UQ is appropriate. However, some physical data are practically specific to certain model components because their information about model parameters is mostly insensitive to activity in the other model components (e.g., ocean temperature profiles versus terrestrial vegetation $CO_2$ flux). For these data sources, calibration of separate component parameters will likely be quite accurate. Model parameters that are sensitive to the coupling in the full-Earth system model will, in principle, require an ensemble of partially or fully coupled climate simulations. How these ensembles are constructed and how the coupling is accomplished are major challenges and can greatly impact the required computational burden for UQ.

### 7.4.2 Use of Low-Fidelity Models

Rather than allocate the entire computing budget to the highest-fidelity climate simulations, computational scientists can improve emulator accuracy (for a fixed computational budget) by augmenting the ensemble with simpler, faster versions of the model. If the entire computing budget was apportioned to producing more runs of crude, but fast, models, the resulting benefits could outweigh the corresponding loss in accuracy. With appropriate response-surface modeling, systematic errors in the crude models can be adjusted by tying them to a sparser landscape of high-fidelity model runs that are carried out at strategically selected input settings. A key challenge is how to set up the low-fidelity simulations to give the best information about the high-fidelity runs.

### 7.4.3 Codesign and Model-embedded UQ

Next-generation computing resources and climate models will evolve together toward exascale platforms, which will be hybrid and massively parallel. UQ will take a similar path to cope with the massive amount of streaming data that cannot be archived for postanalysis. Compared to most mature approaches, embedded UQ methods will reside closer to the simulations both methodologically and architecturally. Embedded UQ methods will be in a spectrum that spans two alternative approaches: running alongside simulations, and in extending the simulations for UQ purposes. Both of these approaches will require that UQ methods be conceptualized as highly parallel and compatible with the targeted hybrid systems.

## 7.5 References


Adams B. M., W. J. Bohnhoff, K. R. Dalbey, J. P. Eddy, M. S. Eldred, D. M. Gay, K. Haskell, P. D. Hough, and L. P. Swiler. (2009). *DAKOTA, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis: Version 5.0 User's Manual*. SAND2010-2183, December 2009. Updated December 2010 (Version 5.1), November 2011 (Version 5.2), February 2013 (Version 5.3), and May 2013 (Version 5.3.1). Albuquerque, NM: Sandia National Laboratories.

Bader, D. (2010). "Climate Science for a Sustainable Energy Future." ORNL FWP #ERKP791. Proposal to the Department of Energy's Office of Science, Office of Biological and Environmental Research. Contributing organizations: Argonne, Brookhaven, Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge, Pacific Northwest, and Sandia National Laboratories, and the National Center for Atmospheric Research.

Eldred, M. S., C. G. Webster, and Constantine, P. (2008). "Evaluation of Non-intrusive Approaches for Wiener-Askey Generalized Polynomial Chaos." In *Proceedings of the 10th AIAA Non-Deterministic Approaches Conference*, AIAA-2008-1892, Schaumburg, IL (Vol. 117, p. 189).

Eldred, M. S., and J. Burkardt. (2009). "Comparison of Non-intrusive Polynomial Chaos and Stochastic Collocation Methods for Uncertainty Quantification." In *Proceedings of the 47th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA-2009-0976, Orlando, FL (Vol. 123, p. 124).

Friedman, J. H. (1991). "Multivariate Adaptive Regression Splines." *Annals of Statistics* 19, no. 1: 1–67.

Ghanem, R., and P. Spanos. (1991). *Stochastic Finite Elements: A Spectral Approach*. New York: Springer-Verlag.

Helton, J. C., C. W. Hansen, and P. N. Swift. (2014). "Performance Assessment for the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, NV." *Reliability Engineering and System Safety* 122: 1–6.

Johannesson, G., and D. D. Lucas. (2014). *Detecting and Testing for Structural Error in Computer Models with Application to the Community Atmospheric Model*. LLNL-TR-652027. Livermore, CA: Lawrence Livermore National Laboratory.

Johannesson, G., D. Lucas, Y. Qian, L. P. Swiler, and T. M. Wildey. (2014). *Sensitivity of Precipitation to Parameter Values in the Community Atmosphere Model Version 5*. SAND2014-0829. Albuquerque, NM: Sandia National Laboratories.

Kennedy, M. C., and A. O'Hagan. (2001). "Bayesian Calibration of Computer Models." *Journal of the Royal Statistical Society* 63, no. 3: 425–464.

Morris, M. D. (1991). "Factorial Sampling Plans for Preliminary Computational Experiments." *Technometrics* 33, no. 2: 161–174.

Rasmussen, N. et al. (1975). *Reactor Safety Study*. WASH-1400. Washington DC: U.S. NRC.

Rasmussen, C. E., and C. K. I. Williams. (2006). *Gaussian Processes for Machine Learning*. Cambridge, MA: The MIT Press.

Sacks, J., W. J. Welch, T. J. Mitchell, and H. P. Wynn. (1989). "Design and Analysis of Computer Experiments." *Statistical Science* 4, no. 4: 409–435.

Saltelli, A., K. Chan, and E. M. Scott. (2000). *Sensitivity Analysis*. New York: Wiley.

Sandia National Laboratories. (2014). "UQ Toolkit." http://www.sandia.gov/UQToolkit/ (accessed on April 17, 2014).

Santner, T. J., B. J. Williams, and W. I. Notz. (2003). *The Design and Analysis of Computer Experiments*, New York: SpringerVerlag.

Sargsyan, K., C. Safta, H. Najm, B. Debusschere, D. Ricciuto, and P. Thornton. (2014). "Dimensionality Reduction for Complex Models via Bayesian Compressive Sensing." *International Journal for Uncertainty Quantification* 4, no. 1: 63–93.

UCAR (University Corporation for Atmospheric Research). (2014). "CESM Community Earth System Model." http://www2.cesm.ucar.edu/ (accessed on April 17, 2014).

Xiu, D. (2010). *Numerical Methods for Stochastic Computations: A Spectral Method Approach*. Princeton, NJ: Princeton University Press.

# 8 Data Needs for Arctic Modeling

The Arctic is changing rapidly and predictive models are essential for understanding the future trajectory of the ocean, atmosphere, sea ice, and ice sheets. Models for these physical systems require observational data for validation of model output and for model input. Unfortunately, much of the existing data is sparsely sampled both spatially and temporally in the Arctic. As a substitute, reanalysis products that assimilate the available data and use constrained models to generate approximations to these fields over the whole globe are often used. However, there are biases in the available reanalysis products, particularly at the poles, due to the lack of data for assimilation.

New observations are critical to understand the physical processes in the Arctic, provide a means for validation of models and parameterizations, and improve reanalysis data sets. In Section 8 we discuss important variables for climate and other models, limitations on existing reanalysis products, and ways in which Sandia can contribute to an improved characterization of the Arctic.

## 8.1 Modeling and Data

Models of physical processes in the Arctic span a wide range of spatial and temporal scales. At the large scale are global and regional climate models that can generally be divided into atmospheric, ocean, land, sea ice, and land-ice components. Examples of climate-scale models are the Community Earth System Model (CESM) (Gent et al. 2011) developed by the National Center for Atmospheric Research (NCAR) and the Department of Energy (DOE), and the Regional Arctic System Model (RASM) currently under development by a group of agencies and universities led by the Naval Postgraduate School (Roberts et al. 2011). The climate-scale models are designed to compute long-term trends over large areas and consequently are run at low spatial (on the order of tens to hundreds of kilometers) and temporal (on the order of hours) resolutions.

At intermediate scales are models developed for weather and sea ice forecasting. These models are run at finer scales (on the order of kilometers) and for shorter time periods of days to months. An example of a forecasting model is the Weather Research and Forecasting Model (WRF), which was developed by NCAR and the National Oceanic and Atmospheric Administration (NOAA) (Skamarock et al. 2005). Forecast models can be similar to climate-scale models because they generally solve the same underlying dynamical equations. However, finer scales can allow for resolution of additional physical processes.

At the finest scales are process-scale models that describe behavior that occurs over much smaller spatial scales and time scales, such as cloud nucleation and brine transport in sea ice. Often small-scale models are used to formulate parameterizations for important physical processes that occur at unresolved scales in the regional and climate models.

Observational data are extremely important for advancing understanding of fine-scale physical processes and for validating parameter values and trends in large-scale models.

Additionally, observational data are required as inputs for stand-alone models, such as an ocean model that requires boundary input from the atmosphere and sea ice. A working document, developed by members of the CESM community to formulate data needs for models in the polar regions, includes a discussion of some of the issues inherent in use of sparse Arctic data for climate modeling (Kay, deBoer, and Hunke 2012). In particular, a lack of broad spatial and temporal coverage makes it difficult to assess how well the model performs on seasonal, annual and decadal time scales. The data sets that have long temporal coverage, such as the DOE Atmospheric Radiation Measurement (ARM) facilities in Barrow and Oliktok Point, provide point measurements that may not generalize over a larger area, and many satellite observations of atmospheric properties have been available for less than a decade. Additionally, measurement uncertainties in the observational data are sometimes lacking, making it difficult to assess the performance of the climate models rigorously in comparison to the data.

As an example of modeling that relies on observational data, consider the modeling of Arctic sea ice. The sea ice forms a relatively thin layer over the ocean and has an important effect on heat transfer between the ocean and the atmosphere. The warming of the Arctic has brought significant changes in the sea ice extent and thickness, and it is important for models to capture the physical processes operating at the ice-ocean and ice-atmosphere boundary accurately in order to predict the future behavior of the sea ice and the overall Arctic. A set of important physical quantities needed to assess feedback effects at the sea ice boundary is given in Table 8-1. Data for some of these quantities are available from satellites, including ice concentration, which measures the fraction of ice in an area, and ice thickness. However, measurements for ocean quantities, such as sea surface salinity and atmospheric surface fluxes, are much more difficult to acquire. For sea ice models that are run independently, studies have found that changes in atmospheric forcing data, including atmospheric winds and fluxes, have a strong impact on the behavior of the sea ice (Hunke and Holland 2007). Therefore, it is important to have reliable data sets that include more of these critical surface quantities for use as inputs to sea ice models in uncoupled runs and for validation of atmospheric and ocean models.

**Table 8-1. Important Quantities for Atmosphere-Ice-Ocean Interface**

| Physical System | Quantity of Interest |
|---|---|
| Atmosphere | Surface winds |
| | Sea level pressure |
| | Air temperature |
| | Cloud fraction |
| | Precipitation |
| | Specific humidity |
| | Surface fluxes (short wave, long wave, latent and sensible heat) |
| Sea Ice | Ice thickness |
| | Snow thickness |
| | Velocity |
| | Albedo |
| | Ice concentration |
| Ocean | Surface temperature |

| Physical System | Quantity of Interest |
|---|---|
| | Surface salinity |
| | Surface currents |

## 8.2 Reanalysis Data Sets

When direct observations are lacking for validation of physical quantities and for forcing individual models, reanalysis products are generally used. Reanalysis data sets are generated from weather and climate models with data assimilation schemes to produce global fields of atmospheric or ocean variables. In general, these products produce a reasonable approximation to the state of the atmosphere or ocean over a given time frame. Reanalysis data sets are often used to study trends over time in variables such as surface air temperature. Additionally, these data sets are used as forcing data for individual component models.

However, the reanalysis data sets are themselves generated from models and not equivalent to observational data. Variations between reanalysis data sets and observational data occur primarily at locations with little data to assimilate. Therefore, errors in the reanalysis data sets tend to be greater at the poles than at other locations around the globe. In Section 8.2.1 we describe available atmospheric global reanalysis products and some of their known limitations in the Arctic. Section 8.2.2 discusses a newly available polar reanalysis data set. A thorough summary of available reanalysis products can be found at www.reanalysis.org.

### 8.2.1 Global Reanalysis Data Sets

Global atmospheric reanalysis data sets from a number of sources are available. Table 8-2 lists the main data sets that have minimum spatial and temporal resolution and time span. The National Center for Environmental Protection (NCEP)/NCAR reanalysis was the first product to cover a significant period and be continually expanded with monthly updates (Kalnay et al. 1996). After the release of NCEP/NCAR in 1997, other reanalysis products were developed and released, including the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) (Uppala et al. 2005) and the 25-year reanalysis (JRA-25) by the Japan Meteorological Agency and Central Research Institute of Electric Power Industry (Onogi et al. 2007). Recent advances in data assimilation systems and improvements in model parameterizations have led to the development of a new set of reanalysis products, including the ERA-Interim Reanalysis (Dee et al. 2011), the NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), and the NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Reinecker et al. 2011). Additionally, the 20th Century Reanalysis has been developed by NOAA for looking at long-term changes in the atmosphere (Compo et al. 2011).

**Table 8-2. Global Reanalysis Data Sets**

| Reanalysis | Spatial resolution* | Temporal resolution* | Years available |
|---|---|---|---|
| NCEP/NCAR | 2.5 x 2.5 degrees | 6 hours | 1948–present |
| ERA-40 | 2.5 x 2.5 degrees | 3 hours | 1958–2002 |
| ERA-Interim | 0.75 x 0.75 degrees | 3 hours | 1979–present |
| JRA-25 | 1.25 x 1.25 degrees | 6 hours | 1979–present |
| MERRA | 1.25 x 1.25 degrees | 6 hours | 1979–present |
| CFSR | 0.5 x 0.5 degrees | 1 hour | 1979–present |
| 20 C Reanalysis | 2 x 2 degrees | 6 hours | 1871–2010 |

* Minimum resolution of available data

In all cases, the reanalysis data are obtained by running an atmospheric model using data assimilation to constrain the state variables. Consequently, the errors in the atmospheric fields will depend on the amount and quality of the observational data available. Reanalysis data produced at times before the modern satellite era (1979) are known to have significant biases in data-poor regions, which is why many of the reanalysis data sets do not span the years prior to 1979.

A number of studies have looked at the accuracy of reanalysis data in the Arctic. In the satellite era, the correlation is generally good between reanalysis data and observations for atmospheric fields such as temperature, pressure, wind speed, and humidity in the Arctic (Bromwich and Wang 2005). However, studies have found biases in precipitation, particularly in the NCAR/NCEP reanalysis (Bromwich, et al. 2007), and in cloud fraction and surface radiative fluxes (Bromwich et al. 2007; Walsh, Chapman, and Portis 2009).

One of the main biases in reanalysis data in the Arctic is in total cloud fraction, where there is a large spread between the reanalysis products in the annual cycle of total cloud fraction. This bias is seen in both the early reanalysis products and the more modern reanalysis products (Zib et al. 2012; Chernokulsky and Mokhov 2012). This is shown graphically in Figure 8-1 where none of the reanalysis products successfully reproduces the observational seasonal cycle apparent in the surface approximations (red line) and in the majority of the satellite observations (blue lines). The bias causes significant errors in the computed surface fluxes, which in turn have a strong influence on sea ice growth and melt and ocean heating.

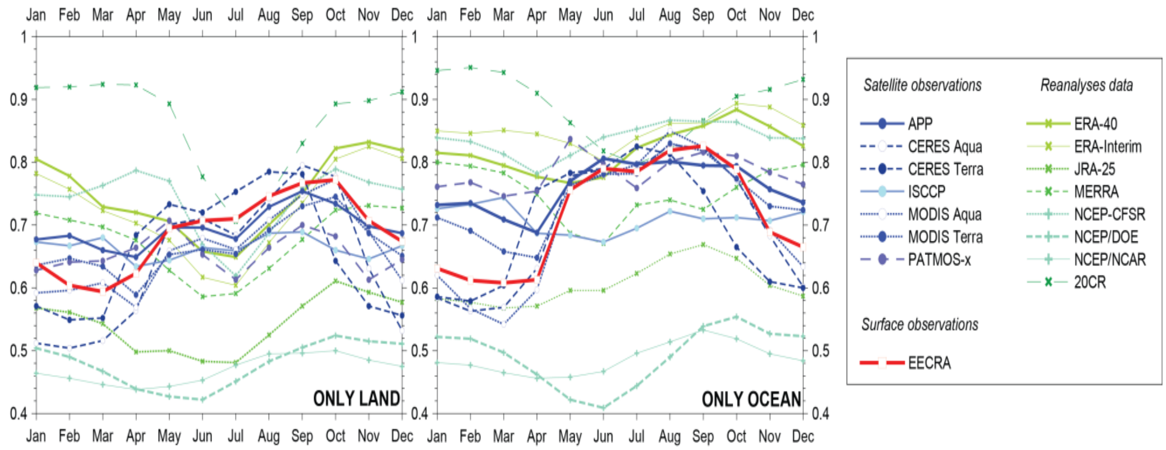


**Figure 8-1.** Total cloud fraction over land and ocean from satellite observations, surface observations, and reanalysis data sets in the Arctic (latitude > 70 degrees N) [Source: Chernokulsky and Mokhov 2012].

Additional observations over a broad set of locations of surface fluxes and clouds would contribute significantly in constraining the reanalysis data and aid in producing a better approximation of the atmospheric state.

## 8.2.2 Regional Polar Reanalysis

Recently, a polar reanalysis product developed by the Byrd Polar Research Center at Ohio State University became available (Polar Meteorology Group 2013). This regional reanalysis product, called the Arctic System Reanalysis (ASR), is much more finely resolved than the global reanalysis products, with a minimum resolution of 10 kilometers. It is produced using the Polar Weather Forecast Model (PWRF), the WRF-VAR system, and the High Resolution Land Data Assimilation System (HRLDAS) optimized for the Arctic. The domain of the ASR is shown in Figure 8-2. This product has the potential to improve the approximation of the atmospheric state in the Arctic, but as with the global reanalysis products, availability of more meteorological data is necessary to assess the accuracy of the product.

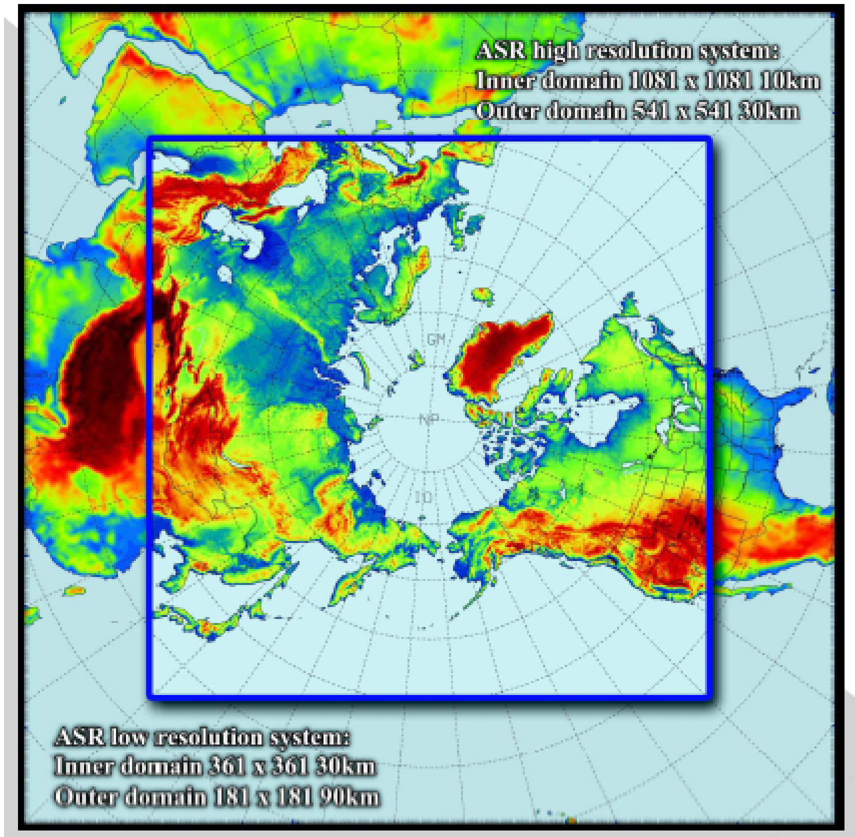


**Figure 8-2.** ASR domains [Source: Polar Meteorology Group 2013].

## 8.3 Potential Sandia Contributions

Overall, the lack of near-surface observations in the Arctic limits the ability to test and validate models. A smart data acquisition strategy is required to fill in the gaps in observational data for use in validating climate models, driving forecasting models, and generating reanalysis products with improved accuracy in the Arctic. Sandia can play an important part in the development of an optimized data acquisition strategy by leveraging expertise in climate modeling in combination with expertise in inverse modeling and uncertainty quantification.

In particular, Sandia has expertise in a number of model components important in the Arctic. Researchers at Sandia have led the development of the HOMME (High-order Method Modeling Environment) spectral element atmospheric dynamical core, which is now the default dynamical core for use in CESM (Taylor and Fournier 2010). Sandia researchers have also contributed significant numerical improvements to the Community Ice Sheet Model (CISM) in CESM and are involved in developing the next-generation Scalable, Efficient, and Accurate Community Ice Sheet Model (SEACISM) (Lemieux et al. 2011). Sandia researchers are also involved in the development and improvement of sea ice models (Peterson, Bochev, and Paskaleva 2010; Sulsky and Peterson 2011).

Additionally, Sandia is recognized as a leader in optimization and uncertainty quantification. The DAKOTA toolkit (Adams et al. 2011) developed at Sandia has been used for a broad range of sensitivity, optimization, and uncertainty studies and could potentially be used to assist in the design of an optimized data acquisition strategy.

## 8.4 References


Adams, B. M., W. J. Bohnhoff, K. R. Dalbey, J. P. Eddy, M. S. Eldred, D. M. Gay, K. Haskell, P. D. Hough, and L. P. Swiler. (2011). *DAKOTA, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis Version 5.2 User's Manual*. SAND 2010-2183. Albuquerque, NM: Sandia National Laboratories.

Bromwich, D., and S. Wang. (2005). "Evaluation of the NCEP-NCAR and ECMWF 15- and 40-Yr Reanalyses Using Rawinsonde Data from Two Independent Arctic Field Experiments." *Monthly Weather Review* 133, no. 12: 3562–3578.

Bromwich, D., R. Fogt, K. Hodges, and J. Walsh. (2007). "A Tropospheric Assessment of the ERA-40, NCEP, and JRA-25 Global Reanalyses in the Polar Regions." *Journal of Geophysical Research* 112, D10111, doi:10.1029/2006JD007859.

Chernokulsky, A., and I. I. Mokhov. (2012). "Climatology of Total Cloudiness in the Arctic: An Intercomparison of Observations and Reanalyses." *Advances in Meteorology*. Article ID 542093,15 pages. Doi:10.1155/2012/542093.

Compo, G. P., J. S. Whitaker, P. D. Sardeshmukh, N. Matsui, R. J. Allan, X. Yin, B. E. Gleason et al. (2011). "The Twentieth Century Reanalysis Project." *Quarterly Journal of the Royal Meteorological Society* 137, no. 654: 1–28.

Dee, D. P. S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kbayashi, U. Andrae et al. (2011). "The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System." *Quarterly Journal of the Royal Meteorological Society* 137, no. 656: 553–597.

Gent, P. R., G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence et al. (2011). "The Community Climate System Model Version 4." *Journal of Climate* 24, no. 19: 4973–4991.

Hunke, E. C., and M. M. Holland. (2007). "Global Atmospheric Forcing Data for Arctic Ice-Ocean Modeling." *Journal of Geophysical Research* 112, C04S14.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell et al. (1996). "The NCEP/NCAR 40-Year Reanalysis Project." *Bulletin of the American Meteorological Society* 77, no. 3: 437–472.

Kay, J., G. deBoer, and E. Hunke. (2012). On the observational needs for climate models in polar regions. Working document available at http://www.cesm.ucar.edu/working_groups/Polar (accessed on May 5, 2013).

Lemieux, J-F., S. Price, K. J. Evans, D. Knoll, A. G. Salinger, D. Holland, and T. Payne. (2011). "Implementation of the Jacobian-Free Newton-Krylov Method for Solving the First-Order Ice Sheet Momentum Balance." *Journal of Computational Physics* 230, no. 17: 6531–6545.

Onogi, K., J. Tsutsui, H. Koide, M. Sakamoto, S. Kobayashi, H. Hatsushika, T. Matsumoto et al. (2007). "The JRA-25 Reanalysis." *Journal of the Meteorological Society of Japan* 85, no. 3: 369–432.

Peterson, K., P. Bochev, and B. Paskaleva. (2010). *Development, Sensitivity Analysis and Uncertainty Quantification of High-Fidelity Arctic Sea Ice Models*. SAND 2010-6218. Albuquerque, NM: Sandia National Laboratories.

Polar Meteorology Group. (2013). The Arctic System Reanalysis (ASR). http://polarmet.osu.edu/ASR (accessed on April 30, 2013).

Rienecker, M. M., M. J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M.G. Bosilovich et al. (2011). "MERRA - NASA's Modern-Era Retrospective Analysis for Research and Applications." *Journal of Climate* 24, no. 14: 3624–3648.

Roberts, A., J. Cherry, R. Doscher, S. Elliott, and L. Sushama. (2011). "Exploring the Potential for Arctic System Modeling," *Bulletin of the American Meteorological Society* 92, no. 2: 203–206.

Saha, S., S. Moorthi, H-L Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp et al. (2010). "The NCEP Climate Forecast System Reanalysis." *Bulletin of the American Meteorological Society* 91, no. 8: 1015–1057.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers. (2005). *A Description of the Advanced Research WRF Version 2*. NCAR Technical Note, NCAR/TN-468+STR. Boulder, CO: National Center for Atmospheric Research, Mesoscale and Microscale Meteorology Division.

Sulsky, D., and K. Peterson. (2011). "Toward a New Elastic-decohesive Model of Arctic Sea Ice." *Physica D* 240, no. 20: 1674–1683.

Taylor, M., and A. Fournier. (2010). "A Compatible and Conservative Spectral Element Method on Unstructured Grids." *Journal of Computational Physics* 229, no. 17: 5879–5895.

Uppala, S. M., P. W. Kallberg, A. J. Simmons, U. Andrae, V. Da Costa Bechtold, M. Fiorino, J. K. Gibson et al. (2005). "The ERA-40 Reanalysis." *Quarterly Journal of the Royal Meteorological Society* 131, no. 612: 2961–3012.

Walsh, J., W. Chapman, and D. Portis. (2009). “Arctic Cloud Fraction and Radiative Fluxes in Atmospheric Reanalyses.” *Journal of Climate* 22, no. 9: 2316–2334.

Zib, B., X. Dong, X. Vaike, and A. Kennedy. (2012). “Evaluation and Intercomparison of Cloud Fraction and Radiative Fluxes in Recent Reanalyses over the Arctic Using BSRN Surface Observations.” *Journal of Climate* 25, no. 7: 2291–2305.

# 9 The MEDEA Program and Arctic Systems

MEDEA is a program designed to share intelligence community data with the climate and environmental science community. The program is concerned with global environmental change, but from its inception in 1992, there has been a strong focus on the Arctic. Section 9 briefly reviews the history of MEDEA, highlights Sandia's relationship with the program, identifies areas in which MEDEA can improve our understanding of the Arctic climate system, and suggests how Sandia can contribute to MEDEA and use its framework to leverage our existing Arctic research in the national interest.

## 9.1 History

MEDEA has its roots in 1992, when (then) U.S, Senator Al Gore approached Robert Gates, director of the Central Intelligence Agency (CIA), to explore the possibility of sharing classified intelligence information with the climate science community to better understand global warming. Gore and Gates, together, are widely credited with having conceived and executed the program. The original program was implemented in October 1992 with the creation of an environmental task force that included many scientists outside of the intelligence community, such as James Hansen (then director of NASA Goddard Institute for Space Studies). The original program was subsequently renamed MEDEA, meaning Measurements of Earth Data for Environmental Analysis. The acronym conveniently matched the name of the wife of Jason, of Greek mythology. "JASON" is also the name of a science advisory group that was consulted in the formation of MEDEA.

The original MEDEA program produced classified documents and declassified many satellite images. It grew when Bill Clinton became president (and Al Gore became vice president) in 1993. Although it enjoyed strong support from CIA director James Woolsey, the program was canceled in 2001 by President George W. Bush.

MEDEA was resurrected at the behest of Al Gore, beginning in 2008. In early 2009, the Obama administration took office, Leon Panetta became director of the CIA, and Senator Dianne Feinstein became chair of the Senate Intelligence Committee. Robert Gates was retained as secretary of defense by the new administration. With this configuration of supportive leaders, MEDEA was reconstituted with additional members and began working again.

The most complete summary of the reconstituted MEDEA was a news article in *The New York Times* on January 4, 2010, titled "C.I.A. is Sharing Data with Climate Scientists" (Broad 2010). The article focused primarily on Arctic climate change and featured a declassified satellite image (with degraded resolution) of sea ice in the East Siberian Sea. This image is reproduced in Figure 9-1.

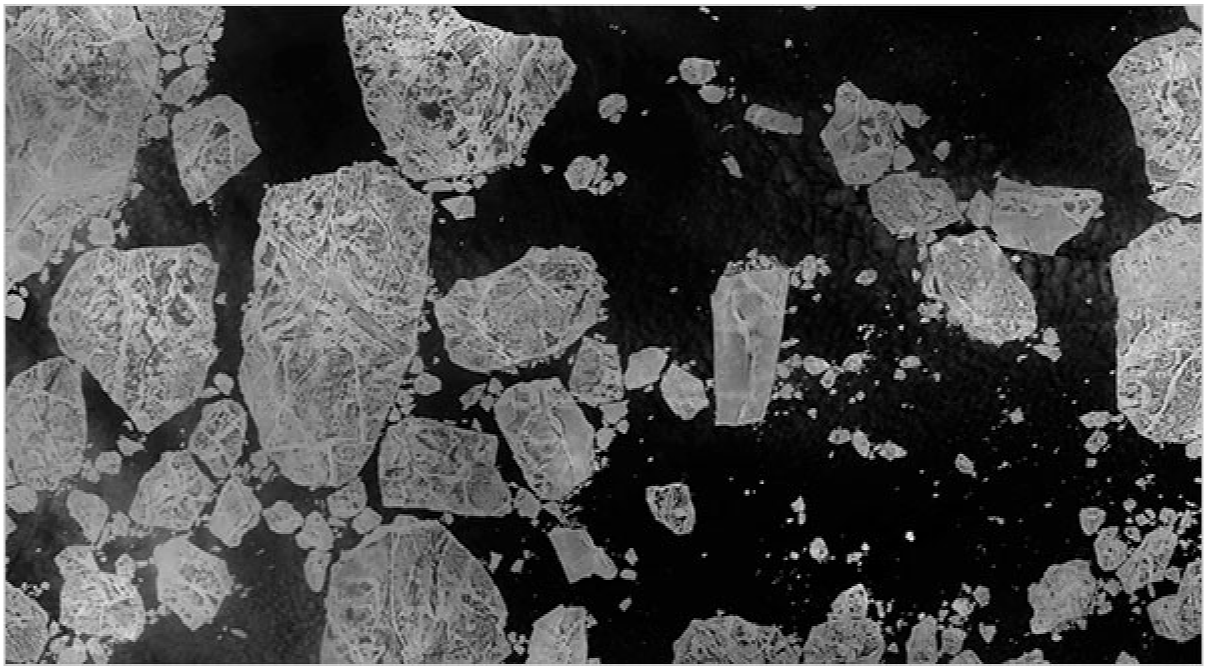

**Figure 9-1.** Declassified satellite image [Source: Broad 2010].

According to Broad (2010),

> The nation's top scientists and spies are collaborating on an effort to use the federal government's intelligence assets – including spy satellites and other classified sensors – to assess the hidden complexities of environmental change. They seek insights from natural phenomena like clouds and glaciers, deserts and tropical forest . . . In the last year, as part of the effort, the collaborators have scrutinized images of Arctic sea ice from reconnaissance satellites in an effort to distinguish things like summer melts from climate trends, and they have had images of the ice pack declassified to speed the scientific analysis.

Pointing out that "Scientists consider the Arctic highly sensitive to global warming and are particularly interested in closely monitoring its changes as possible harbingers," Broad extensively quoted MEDEA member Professor Norbert Untersteiner of the University of Washington (now deceased), an expert on polar ice:

> Scientists, Dr. Untersteiner said, 'have no way to send out 500 people' across the top of the world to match the intelligence gains, adding that the new understandings might one day result in ice forecasts.
>
> 'That will be very important economically and logistically,' Dr. Untersteiner said, arguing that Arctic thaws will open new fisheries and sea lanes for shipping and spur the hunt for undersea oil and gas worth hundreds of billions of dollars . . . Dr. Untersteiner said the federal government had already adopted one of the report's recommendations — have reconnaissance satellites follow particular ice floes as they drift through the Arctic basin rather than just monitoring static sites.

> For this summer, Dr. Untersteiner said he had asked that the intelligence agencies start the process sooner, ‘so we still see the snow cover, maybe in early May.’
>
> Such research, Dr. Untersteiner said, promised to promote understanding of the fundamental forces at work in global climate change, including the endless whorls and gyres of polar ice.
>
> ‘We still have a problem with ice mechanics,’ he said. ‘But the dynamics are very revealing.’

## 9.2 MEDEA Program Visit to Sandia

Primarily through Marty Carr, Sandia has maintained a strong connection to the CIA’s Office of the Chief Scientist. This group was the primary customer for Sandia’s 2009 report *Global Situational Awareness and Early Warning of High-Consequence Climate Change* (Boslough, Backus, and Carr 2009).

In 2010, Sandia invited Dr. Linda Zall, the program manager of the Global Climate Change Research Program (GCCRP) that manages MEDEA, to discuss the program. Dr. Zall visited Sandia on November 8, 2010, and presented an overview of MEDEA. During this visit, Dr. Zall was accompanied by Dr. Dan Pophin (Scitor GCCRP Program Manager) and Rob Graydon (Scitor Corporation, DOE Survey Task Lead). She was briefed by Sandians Dick Spalding, John Roskovensky, Brian Post, John Mitchiner, Theresa Brown, Mark Taylor, Jaideep Ray, Tim Trucano, Kent Schubert, and Bernie Zak.

## 9.3 Areas of Interest in MEDEA

One result of the meeting at Sandia in 2010 was the delivery of MEDEA documents to Sandia. GCCRP representatives provided Sandia with the following unclassified documents:

- *MEDEA Biography Book* (biographies of 26 MEDEA scientist/members)
- *MEDEA Program 1990-2000* (prepared by Dr. Linda Zall, January 2007)

Sandia also has possession of the following classified documents:

- (U) *Climate Treaty Monitoring Strategy Position Paper for the Intelligence Community* (April 2010, by the Office of the Chief Scientist and Center on Climate Change and National Security for DNI)

- (U) *The Contribution of National Security Systems to Understanding Climate Change* (June 2009). This report consists of two volumes: *Phase 1 Report Summary* and *Phase 1 Final Report*.

  The 2009 *Phase 1 Final Report* volume contains five appendices:

  – Appendix A: Key Climate Science Issues (68 pages) is a set of unclassified short papers by various authors.

- Appendix B: Indicators and Measurements for Climate Change (168 pages) is a collection of excellent summaries, focused primarily on conclusions by the Intergovernmental Panel on Climate Change (IPCC).
- Appendix C: Expanded Descriptions of Civil Remote Sensing Systems for Climate Monitoring (10 pages) contains classified information.
- Appendix D: Expanded Descriptions of National Security Systems for Climate Monitoring (36 pages) contains classified information.
- Appendix E: Global Fiducial Monitoring Program (3 pages) contains classified information.

### 9.3.1 Treaty Monitoring Report

Although the 2010 report (*Climate Treaty Monitoring Strategy Position Paper for the Intelligence Community*) is outside the scope of this Arctic systems study, it provides some insight into the charter of the MEDEA program. According to the report,

> (U) Climate change offers a new threat to global security. The response of nations to mitigate harmful effects of human interference in the climate system is called out in the UNFCCC to which the US is a part will lead to agreements that may bind nations to terms with significant economic implications. The seriousness of purpose and compliance of nations is a matter warranting independent analysis. The US intelligence apparatus can ensure the protection of the nation's interests. This study concludes that compliance monitoring is flexible and is within the technical and financial means of the intelligence community to begin this process.

### 9.3.2 National Security Systems Report

This two-volume 2009 report (*The Contribution of National Security Systems to Understanding Climate Change*) summarizes the history of the GCCRP, which was established in response to requests from Senator Dianne Feinstein, chair of the Senate Select Committee on Intelligence (SSCI) and Representative Anna Eshio of the House Permanent Select Committee on Intelligence (HPSCI). The focus is on the national overhead collection systems and archives of data from these and their predecessors. The national overhead collection systems are defined as reconnaissance satellites and systems operated by the National Reconnaissance Office (NRO). Follow-on was planned to include national security systems of the Navy, the National Security Agency, the Defense Intelligence Agency, and the Department of Energy (DOE). The GCCRP should not be confused with the USGCRP, which is a national program overseen by the Executive Office of the President.

The GCCRP currently has three attributes. The program is responsible for (1) documenting the state and trends of global climate, including natural disasters and hazards; (2) providing metrics needed for monitoring and verifying global climate treaties; and (3) assessing the national security implications of climate and global change.

Since the 1990s, the climate issue has become larger and more pressing. Collection systems have changed. For the reconstituted MEDEA program, there are 20 climate-related issues, including natural disasters, treaty monitoring, and 18 science indicators of climate change; 130 measurements; and 900 technical requirements. The indicators of climate change relate to radiation budget, atmosphere, cryosphere, oceans, and land surface. The greatest focus is on the least well-understood indicators that have the greatest uncertainty and the greatest impact (e.g., cloud albedo changes in tropical clouds, and sea ice).

The *Phase 1 Final Report* volume includes the following:

- Review of global climate change indicators
- National security implications of climate change
- Priority science issues associated with climate change
- Review of civil and commercial remote sensing

At the time of the report, there were 23 scientist members who served on four topical MEDEA panels: (1) atmosphere, (2) ocean, (3) cryosphere, and (4) land.

According to the report, "There have been suggestions that the [IPCC] Third Assessment Report is too conservative" (conservative meaning scientifically reticent: "erring on the side of least drama"[23]). The report argues that global climate change could develop sooner, more abruptly, and with greater impacts. The report contains numerous references to the potential for abrupt and large-scale climate events, in particular those that could be associated with the Arctic. For example, "observed natural phenomena such as rapid acceleration and movement of ice sheets cannot be explained with current physical models and understanding."

The report makes a strong argument for maintaining a repository of data. The surprising discovery of the springtime ozone hole is a compelling reminder of the need to maintain ready access to historical archives, including "raw data." Commercial systems do not provide such access.

Many indicators of climate change are listed in the report. One subset is closely associated with the Arctic:

- Sea ice variations (sea ice cover, thickness, albedo, melt pond formation, surface temperature, snow water equivalent)
- Land ice variations (land ice cover, topography, mass balance, surface velocity, albedo)
- Snow cover variations (snow cover, snow water equivalent)
- Permafrost (permafrost areal, active layer, temperature)

[23] For a discussion of the "erring …" term, see Brysse, K., N. Oreskes, J. O'Reilly, and M. Oppenheimer, "Climate Change Prediction: Erring on the Side of Least Drama?," *Global Environmental Change* 23 (2013): 327–337.

The report has four unclassified conclusions:

1. National security systems can provide unique value and perspective in addressing science questions and national security issues related to climate and the impact of climate change, natural disasters, and the monitoring of future climate treaties.

   National security systems can provide unique contributions in five areas:

   - Natural disasters
   - Treaty monitoring
   - Radiation balance
   - Ocean primary productivity
   - Sea ice

   National security systems can provide significant contributions in eight areas:

   - Treaty monitoring
   - Natural disasters
   - Radiation balance
   - Net primary productivity
   - Sea ice
   - Land ice
   - Snow cover
   - Land use and land cover
   - Atmospheric circulation

   In addition, national security systems can enhance the understanding of science and provide warning of natural disasters.

2. National security systems cannot address the climate problem in its entirety. Monitoring climate processes and climate change will ultimately depend on the architecture of civil and commercial systems designed for this purpose.

3. The unique capabilities of national security systems can be brought to bear on important climate problems in the near term to address areas of uncertainty in science understanding of the climate system. National security systems have the potential to support climate applications by providing new collection capabilities, augmenting civil and commercial collections, and supporting long-term trend analysis with historical data archives. Archives include (1) historical evidence of climate change and (2) the Global Fiducial Program (proposed in 1996 and undertaken in 1999 on a subset of sites with unclassified products, such as land snow cover).

4. The way nations of the world respond to climate change and extreme weather will bear upon U.S. national security interests (e.g., science, climate treaties, political instability).

The report has six unclassified recommendations:

1. There is a need to develop within the intelligence community (to the maximum extent consistent with priority national security objectives) the routine application of the national security systems and data to enhance the understanding of global climate change and its impacts.
2. Based on recommendations by the National Academy of Sciences and MEDEA, the Global Fiducial Program should be expanded to provide long-term records at critical sites that may reveal impacts of global climate change and sustainability. National security systems are maintained for a long time.
3. Because the national overhead collection systems examined in this study provide only a subset of the capability available from national security systems, the assessment should be broadened to encompass other valuable collection assets.
4. Unique indicators of classified imaging systems, such as persistence and resolution, enable novel science that may provide answers to some of the climate questions that currently perplex the science community and confound the performance of predictive models. Such questions should be identified by MEDEA, and selected experiments using classified systems should be undertaken. Examples of such questions could involve estimation of temporal albedo patterns in the Arctic "amenable to analysis with classified imagery," properties of Antarctic ice sheets and shelves, and qualification of tropical clouds.
5. The intelligence community should develop a national-security-system collection strategy for monitoring future international climate agreements and treaties, potentially incorporating key additions to collection capabilities.
6. The intelligence community should develop an "environmental indications and warning" capability that adds the impact of climate-induced environmental stress upon our traditional understanding of the political, economic, and social stability of states and nations.

#### 9.3.2.1 Appendix A

Appendix A: Key Climate Science Issues of the *Phase 1 Final Report* volume is a collection of short unclassified papers:

- McElroy: Earth radiation budget and atmospheric inputs
- Munk: Ocean inputs (global ocean observation system)
- Baker: Overhead systems – Ocean GOES Acidity Acoustics
- Gaffney: Ocean inputs
- Bindshandler: Urgent ice sheet dynamics and national overhead collection systems
- Untersteiner: Arctic sea ice
- Orcutt: NSF Ocean observatories initiative

- Shugart: Terrestrial surface – forest ecosystems
- Schlesinger: Desertification and national overhead collection systems
- Schlesinger: Human disease and national overhead collection systems
- Fuerth: Policy inputs
- Fuerth: Lessons learned from arms control
- Wofsy: Natural system observations and climate treaties
- Schlesinger and Shugart: Verification of $CO_2$ storage in vegetation and soil
- Brewer: Detection of methane emissions
- Dozier: Snow and ice panel notes

Of particular interest are the papers by McElroy, Bindshandler, and Untersteiner. McElroy provides a basic restatement of the IPCC Fourth Assessment Report (AR4) conclusions. Bindshandler states that a one-meter sea level rise (which cannot be ruled out) will displace 145 million people and cost $944 billion in lost gross domestic product (GDP). Untersteiner summarizes the Arctic global fiducial sites (see Section 9.3.2.2). Fuerth discusses the difference between monitoring (science analysis) and verification (politics).

#### 9.3.2.2 Arctic Global Fiducial Sites

According to Untersteiner's contribution to Appendix A (titled "Arctic Sea Ice"), in the summer of 1998, at the request of MEDEA, the NRO began to collect images of Arctic sea ice at five different locations in the Arctic basin. This collection, referred to as "quasi ground truth," consists of 450 images since 1998. Identified in Figure 9-2, there were five original sites that are now called "Untersteiner sites." These sites are listed below with the reason each was chosen.

- Beaufort Sea (two sites, most studied and best known)
- Canada (oldest and thickest sea ice)
- Fram Strait (exit route for ice from Arctic Sea)
- E. Siberian (most first-year ice).

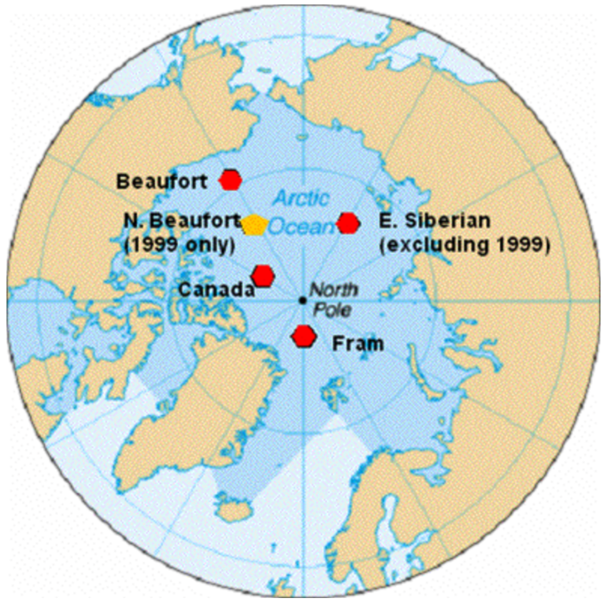


**Figure 9-2**. Locations of Arctic global fiducial sites [Source: NSIDC 2014].

Two more sites were added in 2005:

- Chukchi Sea (seasonal ice)
- Barrow (extensive monitoring of fast ice by the University of Alaska)

As of April 2010, 50 images had been released, and the remaining awaited approval. One additional site, the North Pole, has been recommended.

## 9.4 What Can Sandia Do?

Sandia has a unique combination of experts, facilities, and capabilities that put us in a position to make major contributions to MEDEA and use its framework to leverage our existing Arctic research in the national interest.

Unique capabilities:

- Sandia has subject domain experts in sea ice, uncertainty quantification, Arctic science, ice sheet modeling, atmospheric dynamics, monitoring systems, and remote sensing.

- Sandia has existing projects that involve both Arctic systems and climate change.

- Sandia has strong relationships with the intelligence and global-monitoring communities, as well as with the climate science community.

- Sandia has staff with security clearances and access to Sensitive Compartmented Information Facilities (SCIFs).

- Sandia has existing ties to the US Geological Survey. The U.S. Geological Survey's National Civil Applications Program manages the Global Fiducials Library (GFL), which is online for public access. The GFL archives images from U.S. national imagery systems, representing a long-term periodic record for selected sites that are important scientifically (USGS 2014). The GFL includes aerial sea ice images that were derived from previously classified images collected under the auspices of MEDEA (ARCUS 2009). These images could be a great asset to the broader research community if they were readily available.

Potential contributions:

- "Scientist in a SCIF": Sandia can work inside a SCIF to examine classified data and generate declassified products that go beyond dumbed-down images, e.g., validation of sea-ice dynamics that do not reveal classified capability.

- Data collection guidance: Sandia can help implement methods for the collection of data that would be most useful to the science community, e.g., "Lagrangian" observations of ice that track a point on the moving ice instead of current "Eulerian" images that point at the same spot and let the ice drift through.

- Panel participation: Sandia should seek opportunities for its staff members to serve on MEDEA panels. By serving on a MEDEA panel, a Sandia scientist could contribute to the panel's Arctic work and also benefit from the expertise of other panel members.

## 9.5 References

In addition to the MEDEA-specific references noted and discussed in the text, the following sources have been cited in Section 9.

Boslough, M., G. Backus, and M. Carr. (2009) *Global Situational Awareness and Early Warning of High-Consequence Climate Change*. SAND2009-4702. Albuquerque, NM: Sandia National Laboratories.

Broad, W. J. (2010). "CIA Is Sharing Data with Climate Scientists." *The New York Times*, January 4.

NSIDC (National Snow and Ice Data Center). 2014. "Arctic Sea Ice Melt Pond Statistics and Maps, 1999, 2000, and 2001." http://nsidc.org/data/docs/noaa/g02159_ponds/ (accessed on August 12, 2014).

# 10 Synthesis

This study has investigated current and future needs of the defense, scientific, energy, and intelligence communities for more comprehensive geophysical data products for the Arctic; assessed the current state of atmospheric measurement resources available for the Arctic; and identified how the capabilities at Sandia National Laboratories (Sandia) can be used to address the technological, data, and modeling needs for these three overlapping communities. Section 10 begins with summaries of the identified needs and Sandia opportunities in the eight areas investigated in the study. Next, we describe a meeting hosted by Sandia in 2013 whose purpose was to define further the type of research that might involve unmanned aircraft systems (UASs) on the North Slope of Alaska over the next few years. Finally, we present concluding remarks followed by the references used in Section 10.

## 10.1 Need and Opportunity Summaries

The eight summaries below correspond to the content presented in Sections 2 through 9, respectively.

### 10.1.1 Defense and Scientific Community Needs and Sandia Opportunities

Section 2 emphasizes four gap focus-areas that were identified by the U.S. Coast Guard (USCG) and the U.S. Northern Command (USNORTHCOM) for the Arctic: (1) communications, (2) maritime domain awareness, (3) search and rescue, and (4) environmental observation and forecasting. The needs across these areas are somewhat interdependent and overlapping, as the brief summaries below indicate. An additional infrastructure gap was identified by the Government Accountability Office (GAO).

- Only a limited number of installations in the Arctic allow defense-quality, high-speed communications. To address near-term communications needs, Sandia discussed with USNORTHCOM ways to use existing low-bandwidth commercial communications, satellites, and to modify existing radar installations.

- For maritime domain awareness, there are needs to understand present and forecasted atmospheric and ice conditions, to understand physical processes, and to monitor land and sea conditions continually. Sandia could support these needs through its climate and Arctic-specific modeling and simulation capabilities (as discussed in this report) as well as its expertise in terrestrial and space-based sensing in Division 1000 – Science and Technology, Division 5000 – Defense Systems and Assessments, and Division 6000 – Energy, Non-Proliferation and High-Consequence Security.

- For search and rescue operations, adequate weather and ice forecasts, adequate response assets, and knowledge of human activity are needed. To address these needs, Sandia's uncertainty methods, as applied to the maritime awareness needs, could be useful. Monitoring stations, which are used for forecasting, are likely to be limited in the future. The author of Section 2 suggests ways in which Sandia could help to reduce the number of monitoring stations necessary for making weather and ice forecasts with adequate spatial and temporal coverage, including using small UASs to take measurements and conducting uncertainty analyses to determine the minimal additional information that would most improve maritime data awareness. Sandia's uncertainty expertise could also be used to support USNORTHCOM's response to potential incidents involving Nobel Eagle missions.

- Environmental observation and forecasting serve as the scientific foundation for maritime data awareness. Through the Atmospheric Radiation Measurement (ARM) program, Sandia could provide many valuable avenues for enhanced observations that would support improved forecast modeling.

- With respect to the infrastructure needs, Sandia could assist in the assessment of infrastructure vulnerability, resilience, and environmental constraints with its expertise in Division 6000.

Section 2 also examines the needs, actions, and/or interests of several other entities in the defense and scientific communities. Objective 5 of the U.S. Navy's 2009 roadmap and several of its associated action items are deemed particularly relevant for Sandia's capabilities in environmental assessment and prediction. Sandia's experience in the ARM program, as well as its sensing and modeling expertise, could be useful to scientific efforts pursued in the Arctic by the National Oceanic and Atmospheric Administration (NOAA) and the Department of Interior, as directed by Executive Order 13580. The atmospheric measurement data taken by Sandia at the ARM facilities can be made available to a wider user base through incorporation in the Arctic Collaboration Environment (ACE), thereby supporting the service branches in their Arctic work.

Information included at the end of Section 2 may be helpful to Sandians who are interested in Arctic research programs and projects as well as in the federal strategy and planning documents that were published about the Arctic in 2013 and 2014.

### 10.1.2 Data Fusion Needs and Sandia Opportunities

Data collection and data fusion are the twin topics addressed in Section 3. Large volumes of data are available to characterize the current and future states of the climate in the Arctic. Currently, such data are collected at different times, in different locations, at different resolutions, and by different physical methods. As such, integrating or fusing the collected data in forms most accessible by and informative to users of these data becomes highly problematic, yet integrated data sets are essential needs for climate and weather models. This "data assimilation" problem is especially difficult in the Arctic where existing geophysical data sets are sparse.

The author of Section 3 questions the approach to the Arctic data collection process in general, focusing on the types of costs that such data collection incurs, in terms of both resources and safety. The author advocates that the process of data collection in the Arctic should be reconsidered and ultimately refined. The author promotes characterizing the Arctic climate region with minimum cost and a minimum of observational data.

To address the data fusion issue, the author proposes that the STDF statistical approach, which takes advantage of both temporal and special dependence in the data, be used with disparate Arctic data to reduce the uncertainty when these data are used in models. Sandia's use of the STDF approach, as part of its larger expertise in modeling and simulation, uncertainty quantification, and analysis of complex issues, provides future opportunities for work in the integration of Arctic data by multiple research institutions.

### 10.1.3 Satellite Needs and Sandia Opportunities

The assessment described in Section 4 classifies satellites by function into four mission areas: forecasting, climate, surveillance, and communications. For satellites used in weather forecasting, there is a strong need to have consistent spatial and temporal coverage of atmospheric state data; many sources of error affect the quality of weather forecasts. The needs for climate data are more specific and greater than those for weather prediction. In climate data, both the atmosphere and the surface are important. For satellites used in surveillance, there is a need for remote monitoring of the Arctic as human activity there increases. Such monitoring provides situational awareness to military and civilian commanders responsible for national security, disaster relief, and search and rescue. With respect to communication services, there are great needs for improvement, though only a few current and near-term future satellites are planned to serve the growing communication needs of the Arctic.

The satellite tables produced in Appendix A, which are based on the EO Handbook, can be helpful in getting a quick overview of current and future satellites. The survey revealed some important issues when mission area is considered. For example, by 2013, 70% of the forecasting satellites, 61% of the climate satellites, and 46% of the surveillance satellites were to have reached EOL, though there is planning to replace these satellites.

Many challenges impact remote sensing in the Arctic for the four mission areas. Coverage in the Arctic is limited because most of the satellites that observe the poles are in Low Earth Orbit (LEO) with high-overpass velocities (~7 kilometers per second) at intervals of 90–100 minutes. To increase coverage and data collection, most meteorological satellite systems (those used for weather forecasting) include multiple satellites, but that approach is still insufficient for model input in part because of problems associated with assimilating data from multiple sources. In general, producing quality products from satellite data is difficult because of polar remote-sensing issues. Compared with meteorology satellite systems, scientific satellites used to study climate can produce more-sophisticated products but with less coverage. For data from scientific satellites to be useful, multisatellite, multiagency, and multicountry cooperation is needed, and data assimilation issues need to be given priority. Though surveillance satellites produce important data for closely monitoring the Arctic for security and environmental reasons, coverage, tasking, and harsh conditions make this mission area challenging. Regarding the communications mission area, the Iridium constellation of satellites now offers the only option. Problems with communications in the Arctic include inability of coverage by Geostationary Orbit (GEO) satellites, degraded high-frequency communications about 70° N, availability, and bandwidth. In the future, the Canadian Polar Communications and Weather (PCW) satellites should substantially improve weather forecasting, climate study, and communications in the Arctic.

The initial satellite assessment presented in Section 4 represents a springboard upon which future Sandia efforts can be based. Some of the ideas put forth for future work include assessing separate day, night, and terminator conditions; investigating product quality and frequency over the poles; and identifying the most important data needs for weather-forecasting models. Sandia, through its extensive modeling and simulation, uncertainty, and data fusion and integration expertise could address some of the data assimilation issues that especially impact data collected for the forecasting and climate mission areas.

### 10.1.4 UAS and Tethered Balloon Needs and Sandia Opportunities

Changes in the Arctic in the past few decades have been a motivating force for climate scientists to study processes that may contribute to these changes, such as rising temperatures, reduction in sea ice and sea ice extent, and melting of permafrost. Currently, there is a major gap in the understanding of mixed-phase clouds and the thermodynamic structure of the Arctic atmosphere. To address this gap, in-cloud measurements of key cloud physical properties are needed. The author of Section 5 describes the problems involved in collecting data from clouds and representing these data in models and considers the advantages and disadvantages of manned and unmanned approaches to obtaining these measurements through comparative charts. The author provides evidence of the successful use of small UASs, with small payloads, to meet the needs of past science missions. Unmanned aircraft with small payloads of 10 pounds or less, the author notes, should be sufficient for taking the measurements needed for cloud- and climate-modeling purposes. To acquire Arctic observational data in the future, the author identifies a number of organizations, including universities and the military, that could play supportive roles in the data collection process. At the time of publication of this report, the FAA had just announced the selection of six new sites selected across the United States for UAS research and testing.

The author of Section 5 also describes the benefits of using a tethered balloon approach for obtaining certain in-cloud measurements. Photographs and component diagrams of tethered balloon systems are provided in Section 5. Appendix B contains specifications of UASs; characteristics of past Arctic science missions are documented in Appendix C.

Sandia's research experience in collecting measurements in the Arctic by various methods and its management of the ARM Climate Research Facility on the North Slope of Alaska offer valuable opportunities for collaborating with other Arctic researchers. As highlighted on the facility's fact sheet,[24] data gathered during normal operations or field campaigns can be accessed through the ARM Data Archive (http://www.archive.arm.gov/). Researchers can propose and conduct a field campaign (http://www.arm.gov/campaigns/propose) and also make in-person or virtual visits to the North Slope of Alaska site (http://www.arm.gov/sites/nsa/visit).

### 10.1.5 Uncertainty Quantification Method Needs and Sandia Opportunities

Section 6 identifies the need for numerical tools to help guide data acquisition programs, given the considerable uncertainty exhibited by weather and climate numerical predictions. The author of this section contends that the typical strategy of acquiring more data does not necessarily improve numerical forecasts. Instead, numerical simulation and data acquisition need to be closely coupled to each level of the analysis, acquisition, and forecasting. For that to occur, large-scale analysis tools with embedded algorithms throughout the code structure need to be implemented. Two types of numerical forecasting are needed in this approach: climate modeling for forecasting over large regions and long periods of time and weather-prediction capabilities for forecasting Arctic dynamics locally and in near real-time. Different levels of detail are required for these two types of prediction. In addition, several key geophysical systems need to be coupled to predict the dynamics, namely, atmospheric transport, ocean, and ice-sea modeling. Weather and climate models also need to include interaction between the atmosphere and the land surfaces. Further, the disparity of spatial and temporal resolutions of coupled physics models and data acquisition also needs to be taken into account.

A number of authors in this report discuss community models that are used to predict climate change and forecast weather patterns. For this study, the WRF model developed by the National Center for Atmospheric Research (NCAR) was reviewed in detail to determine its ability to perform accurate numerical characterization, be extended to support embedded algorithms, and perform efficiently. WRF was found capable of creating accurate velocity and pressure fields at any resolution but could not be modified or extended to accommodate large-scale analysis algorithms.

Using several of Sandia's numerical tools, the author of Section 6, with the assistance of a summer intern, developed and implemented relatively sophisticated prototypes with different physics to emulate ice sheet dynamics and atmospheric transport. The prototypes are capable of performing forward predictions and solving large-scale transport problems. In a short period of time, Sandia successfully demonstrated the coupling of data acquisition and numerical analysis via design-of-experiments theory. Sandia's numerical simulation capabilities, enhanced by our data acquisition experience in the ARM program, provide a unique opportunity for Sandia to make significant contributions to the overall characterization of the Arctic region and impact global climate forecasting.

[24] The ARM Fact Sheet is available at http://www.arm.gov/publications/fact-sheets/docs/doe-sc-arm-14-004.pdf?id=17 (accessed on June 30, 2014).

### 10.1.6 Uncertainty Analysis Needs and Sandia Opportunities

As discussed in Section 7, methods for sensitivity analysis, model calibration, and prediction and model uncertainty quantification are needed by climate models like the Community Earth System Model (CESM). Such models also have challenges, as summarized below:

- Computational cost is a significant challenge, as only a small number of samples can be performed. Thus, surrogate models must be developed to perform sensitivity analysis. Using surrogate models requires that the error be estimated in the analysis, and uncertainty becomes an issue in a surrogate model because of parameters that are not treated in the model.

- Calibration poses significant challenges in climate models. For example, the models contain large numbers of physical observations, but these observations are often high frequency and may be inconsistent. Other calibration challenges involve processes in the climate models that imperfectly represent the real-world phenomenon being modeled; estimation of the structural error term; the need to aggregate large numbers of observations in space and in time; and a lack of verified models on which to perform calibration.

- The need to quantify uncertainty within particular climate models (intramodel uncertainty analysis) is identified as a challenge area for model prediction. Typically, the climate-modeling community performs a between-model uncertainty analysis where it has taken the results of 20 or more different climate models that were all generated for a particular scenario and plotted the results.

Section 7 highlights Sandia activities that illustrate our involvement in uncertainty quantification for climate models. In one activity, Sandia performed Bayesian compressive sensing for a land model, where the number of model parameters was reduced from 80 to 12. In another example, Sandia provided improvements to a land-ice model for implementation in the Community Ice Sheet Model (CISM) and CESM.

The author of Section 7 provides a detailed discussion of methods about which Sandia is knowledgeable and has many years of experience in applying. Methods in the Dakota toolkit and the Sacado package in Trilinos are recommended for sensitivity analysis. For surrogate models, Dakota offers Gaussian process and stochastic expansion methods. With respect to calibration, Dakota contains deterministic methods as well as an initial capability to perform Bayesian calibration, a nondeterministic method. For prediction and model uncertainty quantification, Sandia typically uses random sampling or deterministic sampling to propagate uncertainties in the model inputs to assess their effect on the model predictions. Random sampling methods include Monte Carlo, varieties of Monte Carlo and classical experimental design. Adaptive methods may be advantageous, given the cost of climate models. Dakota has some initial implementations of adaptive methods. Deterministic sampling methods are commonly used in nonintrusive PCE (polynomial chaos expansion) methods. Such methods, however, are strongly sensitive to dimensionality of the input space. Dakota has some approaches that sample important dimensions more extensively.

### 10.1.7 Arctic Modeling Data Needs and Sandia Opportunities

The discussion in Section 8 addresses the needs by models of physical processes in the Arctic for observational data. The models span a wide range of spatial and temporal scales. At the large scale are global and regional climate models; at the intermediate scale are forecasting models; at finer and finest scales are process models. All these model types as well as standalone models need observational data describing properties of atmosphere, sea ice, and ocean systems. The author of Section 8 stresses, however, that the available observational data are sparsely sampled, both spatially and temporally.

To address the gaps in observational data, reanalysis data sets are typically used to approximate the state of the atmosphere or ocean at a particular time. However, reanalysis data sets are not equivalent to observational data, as these data sets are themselves generated from models. Further, errors in data sets generated at the poles have greater errors than those from other global locations. A table of reanalysis products for Arctic data is presented in Section 8 that includes the spatial and temporal resolution. Though good correlation between reanalysis data and observations has been found for parameters like temperature and pressure, biases have been found in parameters like precipitation, cloud fraction, and surface radiative fluxes. An example is provided of how the bias in total cloud fraction causes errors in computed surface fluxes that then influence the growth and melting of sea ice and ocean heating.

The author of Section 8 advocates the need for a smart data acquisition strategy for the Arctic. Participation in the development of this strategy is an opportunity for Sandia, building on Sandia's past and current modeling work for the Arctic and its expertise in uncertainty quantification. Significant Sandia accomplishments include developing the core of CESM (the Community Earth System Model), making numerical improvements to CISM (the Community Ice Sheet Model) in CESM, and developing and improving sea ice models. The Dakota toolkit, which Sandia developed, could be used in designing an optimized data acquisition strategy.

### 10.1.8 MEDEA Needs and Sandia Opportunities

The MEDEA documents reviewed for this study emphasize the need for developing a greater understanding of the current and future effects of climate on the environment, including those indicators that have particular relevance to the Arctic, such as variations in sea ice, land ice, snow cover, and permafrost. Sandia's unique combination of experts, facilities, capabilities, and partnerships with the defense, scientific, and intelligence communities positions us to make significant contributions to the Global Climate Change Research Program (GCCRP), which manages MEDEA, especially given our past and current projects involving both Arctic systems and climate change. In addition, Sandians can be involved in generating declassified products, in providing guidance for data that would be most useful to the science community, and in serving on MEDEA panels.

As mentioned earlier, the U.S. Geological Survey's National Civil Applications Program manages the Global Fiducials Library (GFL), which is online for public access. The GFL archives images from U.S. national imagery systems, representing a long-term periodic record for selected sites that are important scientifically (USGS 2014). The GFL includes aerial sea ice images that were derived from previously classified images collected under the auspices of MEDEA (ARCUS 2009).

## 10.2 Polar Research Meeting in 2013

Cooperation and collaboration among the different communities of interest in the Arctic are emphasized in several of the strategic efforts discussed in Section 2 of this report. An example of promoting cooperation and collaboration was advanced by Sandia in 2013. Ivey et al. (2013) describe a polar research meeting hosted by Sandia on July 24–26, 2013, in Washington, DC. The meeting's purpose was to define further the type of research that might involve UASs on the North Slope of Alaska over the next few years. In attendance were approximately 30 science experts who represented national laboratories, federal agencies and programs, research universities, and manufacturers of meteorological sensors. Participants primarily discussed the following topics: (1) what measurements are needed to improve the representation of clouds in Arctic atmospheric models, (2) how UASs can serve the observational needs of Arctic ecologists, and (3) how improved sensor technologies and UAS capabilities can be used to meet the observational needs of Arctic ecologists.

As Desilets, Ivey, and Zak (2013) recount, the atmospheric scientists participating in the polar research meeting agreed that there is a major gap in understanding of the thermodynamic structure of the Arctic atmosphere. In addition, these scientists agreed that basic process-oriented research is needed that emphasizes the structure of the lower layers as well as the energy and vapor fluxes through those layers. The group also agreed that higher temporal and spatial resolution is needed and that contemporaneous ground-based observations from the long-term deployment of the third ARM mobile facility, AMF3, would be of great benefit to airborne atmospheric research. Ecologists in attendance identified soil moisture, surface temperature, and elevation as three variables that could be advantageously measured by UASs. Existing sensor technology modified for UASs would be capable of implementing the needed observations.

It should be noted that much of the detailed discussion in this systems study served as the foundation for discussions conducted during the polar research meeting.

## 10.3 Concluding Remarks

It is our hope that this study of needs for Arctic information and Sandia's capabilities to meet these needs will serve as a guide for decision makers in the defense, scientific, and intelligence communities tasked with making financial investments in atmospheric measurement, data analysis, uncertainty quantification methods, and modeling capabilities for the Arctic. We also hope that this study will have a positive impact within the Energy & Climate Program Management Unit (EC PMU) to enable sound policy;

identify, create, and support Arctic-related competencies at Sandia; and identify areas in which Sandia can engage with other nations with borders or interests in the Arctic. We believe that EC PMU management can use this analysis to guide investment in program development and Laboratory-Directed Research and Development (LDRD).

## 10.4 References


ARCUS (Arctic Research Consortium of the United States). (2009).“PRB Study Leads to Release of Arctic Sea Ice Imagery.” *Witness the Arctic* 13, no. 3: 6. http://www.arcus.org/witness-the-arctic/2009/3/article/508 (accessed on June 13, 2014).

Desilets, D., B. D. Zak, and M. D. Ivey. (2013). New Capabilities for Arctic Research through the Use of Unmanned Aircraft.” *Eos* 94, no. 48: 461. http://onlinelibrary.wiley.com/doi/10.1002/2013EO480007/pdf (accessed on June 30, 2014).

Ivey, M., R. Petty, D. Desilets, J. Verlinde, and R. Ellingson. *Polar Research with Unmanned Aircraft and Tethered Balloons*. DOE/SC-ARM-TR-135. Washington, DC: U.S. Department of Energy, Office of Science. http://www.arm.gov/publications/tech_reports/doe-sc-arm-tr-135.pdf (accessed on June 30, 2014).

Polar Research Board. (2009). *Scientific Value of Arctic Sea Ice Imagery Derived Products*. Washington, DC: The National Academies Press. http://www.nap.edu/openbook.php?record_id=12631 (accessed on June 13, 2014).

USGS (United States Geological Survey). 2014. “Global Fiducials Library.” https://lta.cr.usgs.gov/GFL (accessed on June 13, 2014).

# Appendix A. Satellite Summary

This appendix contains two tables. Both Table A-1 and Table A-2 were compiled in September 2012, as explained in Section 4 of this report. The Nomenclature section at the beginning of the report includes many of the acronyms used in these tables.

## Table A-1. Current Satellites (2012) on-orbit with Arctic Mission Capability

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| AISSat-1<br>Automatic Identification System Satellite-1<br>NSC | L2010<br>E2013 | LEO SSO | Demonstrate and extend access to AIS (Automatic Identification System) signals beyond the land-based AIS system operated by the Norwegian Coastal Administration today. Observe ship traffic in the High North. | SDR | | Surveillance |
| Aqua<br>Aqua (formerly EOS PM-1)<br>NASA, JAXA, INPE | L2002<br>E2013 | LEO SSO<br>705 km<br>98.8 mins<br>98.2 deg | 6-year nominal mission life, currently in extended operations. Atmospheric dynamics/water and energy cycles, cloud formation, precipitation and radiative properties, air/sea fluxes of energy and moisture, sea ice extent and heat exchange with the atmosphere. | AIRS, AMSR-E, AMSU-A, CERES, HSB, MODIS | | Climate<br>Forecasting |
| ALOS<br>Advanced Land Observing Satellite<br>NASA | L2006<br>E? | LEO SSO<br>720 km<br>99 mins<br>98 deg | High Resolution imaging | | | Climate<br>Surveillance |
| Aura<br>Aura (formerly EOS Chemistry)<br>NASA, NSO, FMI, NIVR, UKSA | L2004<br>E2013 | LEO SSO<br>705 km<br>98.8 mins<br>98.2 deg | 5-year nominal mission life, currently in extended operations. Chemistry and dynamics of Earth's atmosphere from the ground through the stratosphere. | HiRDLS, MLS (EOS-Aura), OMI, TES | | Climate |
| CALIPSO<br>Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations<br>NASA, CNES | L2006<br>E2013 | LEO SSO<br>705 km<br>98.8 mins<br>98.2 deg | 3-year nominal mission life, currently in extended operations. Measurements of aerosol and cloud properties for climate predictions, using a 3 channel lidar and passive instruments in formation with Aqua and CloudSat for coincident observations of radiative fluxes and atmospheric state. | CALIOP, IIR, WFC | | Climate<br>Forecasting |
| CARTOSAT-1<br>Cartography Satellite - 1 (IRS P5)<br>ISRO | L2005<br>E2012 | LEO SSO<br>618 km<br>97 mins<br>97.87 deg | High precision large-scale cartographic mapping of 1:10000 scale and thematic applications (with merged XS data) at 1:4000 scales. | PAN (Cartosat-1) | S: 30 km<br>R: 2.5 m<br>C: 0.5%, 8.2% | Surveillance<br>Climate |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| CARTOSAT-2<br>Cartography Satellite - 2<br>ISRO | L2007<br>E2012 | LEO SSO<br>635 km<br>97.4 mins<br>97.87 deg | High precision large-scale cartographic mapping of 1:10000 scale and thematic applications (with merged XS data) at 1:4000 scales. | PAN (Cartosat-2) | | Surveillance<br>Climate |
| CARTOSAT-2A<br>Cartography Satellite - 2A<br>ISRO | L2008<br>E2013 | LEO SSO<br>635 km<br>97.4 mins<br>97.87 deg | High precision large-scale cartographic mapping of 1:10000 scale and thematic applications (with merged XS data) at 1:4000 scales. | PAN (Cartosat-2A/2B) | | Surveillance<br>Climate |
| CARTOSAT-2B<br>Cartography Satellite - 2B<br>ISRO | L2010<br>E2015 | LEO SSO<br>635 km<br>97.4 mins<br>97.87 deg | High precision large-scale cartographic mapping of 1:10000 scale and thematic applications (with merged XS data) at 1:4000 scales. | PAN (Cartosat-2A/2B) | | Surveillance<br>Climate |
| CBERS-2B<br>China–Brazil Earth Resources Satellite program (CBERS) | L2007<br>E? | LEO SSO<br>774 km<br>100.3 min<br>98.6 deg | High Resolution imaging<br>VNIR, SWIR,LWIR | WFI, CCD, IRMSS, HRC | HRC S: 27 km<br>HRC R: 2.7 m<br>HRC C: 0.5%, 7.4%<br>WFI S: 890 km<br>WFI R: 260 m<br>WFI C: 15%, 100%<br>other S: 120 km<br>other R: 20 m<br>other C: 2%, 33% | Climate<br>Surveillance |
| CloudSat<br>CloudSat<br>NASA, DoD (USA), CSA | L2006<br>E2013 | LEO SSO<br>705 km<br>98.8 mins<br>98.2 deg | 3-year nominal mission life, currently in extended operations. CloudSat will use advanced radar to "slice" through clouds to see their vertical structure, providing a completely new observational capability from space. One of first satellites to study clouds on global basis. Will fly in formation with Aqua and CALIPSO. | CPR (CloudSat) | Single LOS<br>R: 3 km<br>C: 0.05%, 0.8% | Climate<br>Forecasting |
| COSMIC-1/FORMOSAT-3 FM1<br>Constellation Observing System for Meteorology, Ionosphere and Climate-1<br>NSPO, NOAA, UCAR | L2006<br>E2013 | non-SSO<br>800 km<br>100 mins<br>72 deg | Meteorology, ionosphere and climate. | GOX | Solar Occultation | Climate<br>Forecasting |
| COSMIC-2/FORMOSAT-3 FM2<br>NSPO, NOAA, UCAR | L2006<br>E2013 | non-SSO<br>800 km<br>100 mins<br>72 deg | Meteorology, ionosphere and climate. | GOX | Solar Occultation | Climate<br>Forecasting |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| COSMIC-3/FORMOSAT-3 FM3<br>NSPO, NOAA, UCAR | L2006<br>E2013 | non-SSO<br>711 km<br>100 mins<br>72 deg | Meteorology, ionosphere and climate. | GOX | Solar Occultation | Climate<br>Forecasting |
| COSMIC-4/FORMOSAT-3 FM4<br>NSPO, NOAA, UCAR | L2006<br>E2013 | non-SSO<br>800 km<br>100 mins<br>72 deg | Meteorology, ionosphere and climate. | GOX | Solar Occultation | Climate<br>Forecasting |
| COSMIC-5/FORMOSAT-3 FM5<br>NSPO, NOAA, UCAR | L2006<br>E2013 | non-SSO<br>800 km<br>100 mins<br>72 deg | Meteorology, ionosphere and climate. | GOX | Solar Occultation | Climate<br>Forecasting |
| COSMIC-6/FORMOSAT-3 FM6<br>NSPO, NOAA, UCAR | L2006<br>E2013 | non-SSO<br>800 km<br>100 mins<br>72 deg | Meteorology, ionosphere and climate. | GOX | Solar Occultation | Climate<br>Forecasting |
| COSMO-SkyMed 1<br>COnstellation of small Satellites for Mediterranean basin Observation - 1<br>ASI | L2007<br>E2014 | LEO SSO<br>620 km<br>97.1 mins<br>97.8 deg | Environmental monitoring, surveillance and risk management applications, environmental resources management, maritime management, earth topographic mapping, law enforcement, informative / science applications. | SAR 2000 | S: 10–100 km<br>R: 5–500 m<br>C: 1.7%, 27% | Surveillance<br>Climate<br>Forecasting |
| COSMO-SkyMed 2<br>ASI | L2007<br>E2014 | LEO SSO<br>620 km<br>97.1 mins<br>97.8 deg | Same as other COSMO Satellites | SAR 2000 | S: 10–100 km<br>R: 5–500 m<br>C: 1.7%, 27% | Surveillance<br>Climate<br>Forecasting |
| COSMO-SkyMed 3<br>ASI | L2008<br>E2015 | LEO SSO<br>620 km<br>97.1 mins<br>97.8 deg | Same as other COSMO Satellites | SAR 2000 | S: 10–100 km<br>R: 5–500 m<br>C: 1.7%, 27% | Surveillance<br>Climate<br>Forecasting |
| COSMO-SkyMed 4<br>ASI | L2010<br>E2017 | LEO SSO<br>620 km<br>97.1 mins<br>97.8 deg | Same as other COSMO Satellites | SAR 2000 | S: 10–100 km<br>R: 5–500m<br>C: 1.7%, 27% | Surveillance<br>Climate<br>Forecasting |
| CryoSat-2<br>CryoSat-2 (Earth Explorer Opportunity Mission)<br>ESA | L2010<br>E2013 | non-SSO<br>717 km<br>100 mins<br>92 deg | To determine fluctuations in the mass of the Earth’s major land and marine ice fields. | DORIS-NG, Laser Reflectors (ESA), SIRAL | S: 10–100 km<br>R: 5–500 m<br>C: 1.7%, 27% | Climate<br>Forecasting<br>Surveillance |

| **Mission Name Short Mission Name Full Mission Agencies** | **Launch Date (L) EOL Date (E)** | **Orbit Type Orbit Altitude Orbit Period Orbit Inclination** | **Applications** | **Instruments** | **Swath (S) Resolution (R) Coverage (C) 1-pass, daily %** | **Relevant Missions** |
|---|---|---|---|---|---|---|
| DMSP F-14<br>Defense Meteorological Satellite Program F-14<br>NOAA | L1997<br>E2012 | LEO SSO<br>833 km<br>101 mins<br>98.7 deg | The long-term meteorological program of the DoD - collect and disseminate worldwide atmospheric, oceanographic, solar-geophyscial, and cloud cover data. | OLS, SSB/X-2, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2 | OLS S: 3000 km<br>OLS R: 50–270 m<br>OLS C: 51%, 100%<br>SSM S: 1700 km<br>SSM R: 13–73 km<br>SSM C: 29%, 100% | Forecasting<br>Climate<br>Surveillance |
| DMSP F-15<br>Defense Meteorological Satellite Program F-15<br>NOAA | L1999<br>E2013 | LEO SSO<br>833 km<br>101 mins<br>98.9 deg | Same as other DMSP satellites (Primary operational satellite). | OLS, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2 | OLS S: 3000 km<br>OLS R: 50–270 m<br>OLS C: 51%, 100%<br>SSM S: 1700 km<br>SSM R: 13–73 km<br>SSM C: 29%, 100% | Forecasting<br>Climate<br>Surveillance |
| DMSP F-16<br>Defense Meteorological Satellite Program F-16<br>NOAA | L2003<br>E2012 | LEO SSO<br>833 km<br>101 mins<br>98.9 deg | Same as other DMSP satellites | OLS, SSI/ES-3, SSJ/5, SSM, SSM/IS, SSULI, SSUSI | OLS S: 3000 km<br>OLS R: 50–270 m<br>OLS C: 51%, 100%<br>SSM S: 1700 km<br>SSM R: 13–73 km<br>SSM C: 29%, 100% | Forecasting<br>Climate<br>Surveillance |
| DMSP F-17<br>Defense Meteorological Satellite Program F-17<br>NOAA | L2006<br>E2013 | LEO SSO<br>850 km<br>101 mins<br>98.7 deg | Same as other DMSP satellites | OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI | OLS S: 3000 km<br>OLS R: 50–270 m<br>OLS C: 51%, 100%<br>SSM S: 1700 km<br>SSM R: 13–73 km<br>SSM C: 29%, 100% | Forecasting<br>Climate<br>Surveillance |
| DMSP F-18<br>Defense Meteorological Satellite Program F-18<br>NOAA | L2009<br>E2014 | LEO SSO<br>850 km<br>101 mins<br>98.7 deg | Same as other DMSP satellites | OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI | OLS S: 3000 km<br>OLS R: 50–270 m<br>OLS C: 51%, 100%<br>SSM S: 1700 km<br>SSM R: 13–73 km<br>SSM C: 29%, 100% | Forecasting<br>Climate<br>Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| EO-1<br>Earth Observing-1<br>NASA | L2000<br>E? | LEO SSO<br>695 km<br>98.7 mins<br>98.21 deg | | ALI, Hyperion | ALI S: 36 km<br>ALI R: 30 m<br>ALI C: 0.6%, 9.8%<br>Hyp S: 7.5 km<br>Hyp R: 30 m<br>Hyp C: 0.13%, 2% | Climate |
| EROS-A<br>Earth Resources Observation Satellite<br>Israel Aircraft Industries (IAI) | L2006<br>E2020 | LEO SSO<br>480 km | High Resolution imaging | | R: 70 cm | Surveillance |
| FORMOSAT-2<br>National Space Organization (NSPO) | L2004<br>E? | | High Resolution imaging | | S: 24 km<br>R: 2–8 m<br>C: 0.4%, 7% | Surveillance<br>Climate |
| FY-1D<br>FY-1D Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | L2002<br>E2012 | LEO SSO<br>863 km<br>102.3 mins<br>98.8 deg | Meteorology, environmental monitoring. | MVISR (10 channels) | | Forecasting<br>Climate |
| FY-3A<br>FY-3A Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | L2008<br>E2012 | LEO SSO<br>830 km<br>101 mins<br>98.753 deg | Meteorology and environmental monitoring; data collection and redistribution. | ERM, IRAS, MERSI, MWAS, MWHS, MWRI, MWTS, SEM, SIM, TOU/SBUS, VIRR | | Forecasting<br>Climate |
| FY-3B<br>FY-3B Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | L2010<br>E2013 | LEO SSO<br>830 km<br>101 mins<br>98.753 deg | Meteorology and environmental monitoring; data collection and redistribution. (Experimental pre-cursor to FY-3C). | ERM, IRAS, MERSI, MWAS, MWHS, MWRI, MWTS, SEM, SIM, TOU/SBUS, VIRR | | Climate |
| GCOM-W1<br>Global Change Observation Mission-W1<br>JAXA | L2012<br>E2017 | LEO SSO<br>700 km<br>98 mins<br>98.2 deg | Understanding of water circulation mechanism. | AMSR-2 | | Climate<br>Forecasting |
| GeoEye-1<br>GeoEye Corp. | L2008<br>E? | LEO SSO<br>684 km<br>98 deg | High Resolution imaging | | R: 42 cm–1.7 m | Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| GOCE<br>Gravity Field and Steady-State Ocean Circulation Explorer<br>ESA | L2009<br>E2012 | LEO SSO<br>270 km<br>90 mins<br>96.7 deg | Research in steady-state ocean circulation, physics of Earth's interior and leveling systems (based on GPS). Will also provide unique data set required to formulate global and regional models of the Earth's gravity field and geoid. | EGG, GPS (ESA), Laser Reflectors (ESA), LRR, SSTI | | Climate |
| GOSAT<br>Greenhouse gases Observing SATellite<br>JAXA, MOE (Japan), NIES (Japan) | L2009<br>E2014 | LEO SSO<br>666 km<br>98.18 mins<br>98.06 deg | Observation of greenhouse gases. | TANSO-CAI, TANSO-FTS | CAI S: 1000 km<br>CAI R: 500 m<br>CAI C: 17%, 100%<br>FTS R: 10 km | Climate |
| HY-2A<br>Ocean dynamics satellite A<br>NSOAS, CAST | L2011<br>E2012 | LEO SSO<br>963 km<br>99.3 deg | Detecting ocean surface temperature, wind field, wave and topography. | ALT, RAD, SCAT | | Climate<br>Forecasting |
| IKONOS<br>GeoEye | L1999<br>E2012 | LEO SSO<br>681 km<br>98.33 min<br>98.10 deg | High-Resolution Imagery | | S: 11 km<br>R: 1–4 m<br>C: 0.19%, 3% | Surveillance<br>Climate |
| IMS-1<br>Indian Mini Satellite-1<br>ISRO | L2008<br>E2012 | LEO SSO<br>632 km<br>97 mins<br>97.92 deg | Micro-satellite for Third World countries for natural resources monitoring and management. | HySI (IMS-1), MxT | | Surveillance |
| Iridium<br>Iridium Communications Inc. | L1998-2002<br>E? | Non-SSO<br>485 km<br>86.4 deg | > 70 satellites in a constellation | | | Comm. |
| Jason-1<br>Ocean surface topography<br>NASA, CNES | L2001<br>E2013 | non SSO<br>1336 km<br>112.4 mins<br>66 deg | 3-year nominal mission life, currently in extended operations. Physical oceanography, geodesy/gravity, climate monitoring, marine meteorology. | DORIS-NG, JMR, LRA, POSEIDON-2 (SSALT-2), TRSR | | Climate |
| KOMPSAT-2<br>Korea Multi-Purpose Satellite -2<br>KARI, ASTRIUM Corp. | L2006<br>E2013 | LEO SSO<br>685 km<br>98.5 mins | Cartography, land use and planning, disaster monitoring. | MSC | | Surveillance |
| KOMPSAT-3<br>Korea Multi-Purpose Satellite -3<br>KARI, ASTRIUM, DLR | L2012<br>E2016 | LEO SSO<br>685 km<br>98.5 mins | Cartography, land use and planning, disaster monitoring. | AEISS | | Surveillance |
| Landsat-5<br>Landsat-5<br>USGS, NASA | L1984<br>E2012 | LEO SSO<br>705 km<br>98.9 mins<br>98.2 deg | Earth resources, land surface, environmental monitoring, agriculture and forestry, disaster monitoring and assessment, ice and snow cover. | MSS (Landsat), TM | R: 30 m | Climate<br>Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| Landsat-7<br>Landsat-7<br>USGS, NASA | L1999<br>E2017 | LEO SSO<br>705 km<br>98.9 mins<br>98.2 deg | 5-year nominal mission life, currently in extended operations. Same objectives as Landsat-5 | ETM+ | | Climate<br>Surveillance |
| Meteor-M N1<br>Meteor-M N1 Meteorological Satellite<br>ROSHYDROMET, ROSKOSMOS | L2009<br>E2014 | LEO SSO<br>820 km<br>102 mins<br>98.79 deg | Hydrometeorology, climatology, heliogeophysics, DCS. | DCS, GGAK-M, KMSS, MSU-MR, MTVZA, Severjanin | | Climate |
| Metop-A<br>Meteorological Operational Polar Satellite – A<br>EUMETSAT, ESA | L2006<br>E2013 | LEO SSO<br>840 km<br>107.1 mins<br>98.8 deg | Meteorology, climatology. | AMSU-A, ARGOS, ASCAT, AVHRR/3, GOME-2, GRAS, HIRS/4, IASI, MHS, S&R (NOAA), SEM (POES) | | Forecasting<br>Climate |
| MTI<br>Multi-Thermal Imager<br>DOE | L1999<br>E? | LEO SSO<br>555 km<br>97 deg | Climate, non-proliferation | Multispectral Imager VNIR-LWIR | S: 13 km<br>R: 5–20 m<br>C: 0.22%, 3.6% | Surveillance<br>Climate |
| NigeriaSat-2<br>NigeriaSat-2<br>NASRDA | L2011<br>E2018 | LEO SSO<br>700 km<br>97 mins<br>98 deg | Small satellite mission with technical and scientific objectives (environmental) monitoring. | NigeriaSat Medium and High Resolution | R: 5–30 m | Surveillance |
| NigeriaSat-X<br>NigeriaSat-X<br>NASRDA | L2011<br>E2018 | LEO SSO<br>700 km<br>97 mins<br>98 deg | Small satellite mission with technical and scientific objectives (capability demonstration). | NigeriaSat Medium Resolution | | Surveillance |
| NMP EO-1<br>New Millenium Program Earth Observing-1<br>NASA | L2000<br>E2013 | LEO SSO<br>690 km<br>99 mins<br>98.2 deg | 1.5-year nominal mission life, currently in extended operations. Land surface, earth resources. | ALI, Hyperion, LEISA AC | | Climate<br>Surveillance |
| NOAA-15<br>National Oceanic and Atmospheric Administration – 15 Polar-orbiting Operational Environmental Satellites (POES)<br>NOAA | L2098<br>E2012 | LEO SSO<br>813 km<br>101.4 mins<br>98.6 deg | Meteorology, agriculture and forestry, environmental monitoring, climatology, physical oceanography, volcanic eruption monitoring, ice and snow cover, total ozone studies, space environment, solar flux analysis, search and rescue. | AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA) | S: 2600 km<br>R: 1–4 km<br>C: 44%, 100% | Forecasting<br>Climate |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| NOAA-16<br>NOAA | L2000<br>E2012 | LEO SSO<br>870 km<br>102 mins<br>98.8 deg | Same as NOAA-X satellites. | AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES) | S: 2600 km<br>R: 1–4 km<br>C: 44%, 100% | Forecasting<br>Climate |
| NOAA-17<br>NOAA | L2002<br>E2014 | LEO SSO<br>833 km<br>101.4 mins<br>98.75 deg | Same as NOAA-X satellites. | AMSU-A, AMSU-B, ARGOS, AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES) | S: 2600 km<br>R: 1–4 km<br>C: 44%, 100% | Forecasting<br>Climate |
| NOAA-18<br>NOAA | L2005<br>E2015 | LEO SSO<br>870 km<br>102.1 mins<br>98.75 deg | Same as NOAA-X satellites. | AMSU-A, ARGOS, AVHRR/3, HIRS/4, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES) | S: 2600 km<br>R: 1–4 km<br>C: 44%, 100% | Forecasting<br>Climate |
| NOAA-19<br>NOAA | L2008<br>E2016 | LEO SSO<br>870 km<br>102.1 mins<br>98.75 deg | Same as NOAA-X satellites. | A-DCS4, ARGOS, AVHRR/3, HIRS/4, LRIT, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES) | S: 2600 km<br>R: 1–4 km<br>C: 44%, 100% | Forecasting<br>Climate |
| OCEANSAT-2<br>Ocean Satellite-2<br>ISRO | L2009<br>E2014 | LEO SSO<br>720 km<br>99.31 mins<br>98.28 deg | Ocean and atmosphere applications. | OCM, ROSA, Scatterometer (OCEANSAT) | | Climate<br>Forecasting |
| Odin<br>Odin<br>SNSB, TEKES, CNES, CSA | L2001<br>E2012 | LEO SSO<br>590 km<br>97.6 mins<br>97.8 deg | Atmospheric research, stratospheric ozone chemistry, mesospheric ozone science, summer mesospheric science. | OSIRIS, SMR | | Climate |
| OSTM (Jason-2)<br>Ocean Surface Topography Mission<br>NASA, NOAA, CNES, EUMETSAT | L2008<br>E2013 | Inclined, non-LEO SSO<br>1336 km<br>112.4 mins<br>66 deg | 3-year nominal mission life. Physical oceanography, geodesy/gravity, climate monitoring, marine meteorology. | AMR, DORIS-NG, GPSP, JMR, LRA, POSEIDON-3 | | Climate<br>Forecasting |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| PARASOL<br>Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a LIDAR<br>CNES | L2004<br>E2012 | LEO SSO<br>700 km<br>98.8 mins | Micro-satellite with the aim of XXXharacterization of the clouds and aerosols microphysical and radiative properties, needed to understand and model the radiative impact of clouds and aerosols. | POLDER-P | S: 550 km<br>R: 2.3 km<br>C: 9.3%, 50% | Climate<br>Forecasting |
| Pleiades 1<br><br>CNES | L2011<br>E2016 | LEO SSO<br>694 km | Cartography, land use, risk, agriculture and forestry, civil planning and mapping, digital terrain models, defence. | HiRI | S: 20 km<br>R: 50 cm–2 m<br>C: 0.34%, 5.5% | Climate<br>Surveillance |
| RADARSAT-1<br>RADARSAT-1<br>CSA | L1995<br>E2015 | LEO SSO<br>798 km<br>100.7 mins<br>98.594 deg | Environmental monitoring, physical oceanography, ice and snow, land surface. | SAR (RADARSAT) | | Climate<br>Surveillance |
| QuickBird<br>Digital Globe | L2001<br>E? | LEO SSO<br>450 km<br>93.4 min<br>98 deg | High-Resolution Imagery | VNIR | R: 60 cm–2.4 m | Surveillance<br>Climate |
| RADARSAT-2<br>RADARSAT-2<br>CSA, MDA | L2007<br>E2015 | LEO SSO<br>798 km<br>100.7 mins<br>98.6 deg | Environmental monitoring, physical oceanography, ice and snow, land surface. Note: Ownership of RADARSAT-2 has been transferred to MDA Corporation. CSA investment in the project is paid back with the data generated by the satellite since it entered operations. | SAR (RADARSAT-2) | S: 10–500 km<br>R: 3–50 m<br>C: 8%, 46% | Climate<br>Surveillance |
| RapidEye<br>RapidEye<br>DLR | L2008<br>E2015 | LEO SSO<br>622 km<br>98.7 deg | System of 5 satellites for cartography, land surface, digital terrain models, disaster management, environmental monitoring. | MSI | S: 77 km<br>R: 6.5 m<br>C: 1.3%, 20% | Surveillance<br>Climate |
| RASAT<br>RASAT Remote Sensing Satellite<br>TUBITAK | L2011<br>E2014 | LEO SSO<br>700 km<br>98.8 mins<br>98.21 deg | Cartography, land cover/land use, city planning, disaster mitigation/monitoring, environmental monitoring. | RASAT VIS Multispectral, RASAT VIS Panchromatic | | Surveillance |
| RESOURCESAT-1<br>Resource Satellite-1<br>ISRO | L2003<br>E2012 | LEO SSO<br>817 km<br>102 mins<br>98.72 deg | Natural resources management, agricultural applications, forestry, etc. | AwiFS, LISS-III (Resourcesat), LISS-IV | | Surveillance |
| RESOURCESAT-2<br>Resource Satellite-2<br>ISRO | L2011<br>E2016 | LEO SSO<br>817 km<br>102 mins<br>98.72 deg | Natural resources management, agricultural applications, forestry, etc. | AwiFS, LISS-III (Resourcesat), LISS-IV | | Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| Resurs DK 1<br>Resurs DK Environmental Satellite 1<br>ROSKOSMOS, ROSHYDROMET | L2006<br>E2012 | Inclined, non-LEO SSO<br>600 km<br>92 mins<br>70 deg | Land surface. | Arina, Geoton-L1, Pamela | | Surveillance |
| RISAT-1<br>Radar Imaging Satellite<br>ISRO | L2012<br>E2016 | LEO SSO<br>610 km<br>96.5 mins<br>97.844 deg | Land surface, agriculture and forestry, regional geology, land use studies, water resources, vegetation studies, coastal studies and soils – especially during cloud season. | SAR (RISAT) | | Surveillance |
| RISAT-2<br>Radar Imaging Satellite<br>ISRO | L2009<br>E2013 | LEO SSO<br>550 km<br>90 mins | For research and disaster management applications purpose. | SAR-X | | Surveillance |
| SAC-C<br><br>CONAE | L2000<br>E2013 | LEO SSO<br>705 km<br>98 mins<br>98.2 deg | Earth observation, studies the structure and dynamics of the Earth's surface, atmosphere, ionosphere and geomagnetic field. | DCS (SAC-C), GOLPE, HRTC, HSTC, ICARE, INES, IST, MMP, MMRS, WTE | | Surveillance<br>Climate |
| SAC-D/Aquarius<br>SAC-D/Aquarius<br>CONAE, NASA | L2011<br>E2017 | LEO SSO<br>657 km<br>98 mins<br>98 deg | Earth observation studies; measurement of ocean salinity; atmospheric and environmental parameters, emergency management. | Aquarius L-Band radiometer, Aquarius L-Band Scatterometer, CARMEN-1, DCS (SAC-D), HSC, Lagrange, MWR, NIRST, ROSA, SODAD/CARMEN-1, TDP | | Climate<br>Surveillance |
| SCISAT-1<br>SCISAT-I/ACE<br>CSA | L2003<br>E2015 | Inclined, non-LEO SSO<br>650 km<br>97.7 mins<br>74 deg | To improve our understanding of the depletion of the ozone layer, particularly over Canada and the Arctic. | ACE-FTS, MAESTRO | Solar Occultation | Climate |
| Sich-2<br><br>NSAU | L2011<br>E2015 | LEO SSO<br>668 km<br>98 mins<br>98 deg | Land observation. | MIRS, MSS (Sich) | | Surveillance |
| SMOS<br>Soil Moisture and Ocean Salinity (Earth Explorer Opportunity Mission)<br>ESA, CDTI, CNES | L2009<br>E2012 | LEO SSO<br>758 km<br>100.075 mins<br>98.44 deg | Overall objectives are to provide global observations of two crucial variables for modeling the weather and climate, soil moisture and ocean salinity. It will also monitor the vegetation water content, snow cover and ice structure. | MIRAS (SMOS) | S: 200 km<br>R: 35–50 km<br>C: 3.4%, 50% | Climate<br>Forecasting |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| SPOT-4<br>Satellite Pour l'Observation de la Terre – 4<br>CNES | L1998<br>E2013 | LEO SSO<br>832 km<br>101 mins<br>98.7 deg | Cartography, land surface, agriculture and forestry, civil planning and mapping, digital terrain models, environmental monitoring. | DORIS (SPOT),<br>HRVIR,<br>VEGETATION | S: 60 km<br>R: 10–20 m<br>C: 1%, 16% | Climate<br>Surveillance |
| SPOT-5<br>Satellite Pour l'Observation de la Terre – 5<br>CNES | L2002<br>E2014 | LEO SSO<br>832 km<br>101 mins<br>98.7 deg | Cartography, land surface, agriculture and forestry, civil planning and mapping, digital terrain models, environmental monitoring. | DORIS-NG (SPOT),<br>HRG, HRS,<br>VEGETATION | S: 60 km<br>R: 2.5–5 m<br>C: 1%, 16% | Climate<br>Surveillance |
| Suomi NPP National Polar-orbiting Partnership<br>NASA, NOAA | L2011<br>E2016 | LEO SSO<br>824 km<br>101 mins | 5-year nominal mission life. Operational polar weather and climate measurements. | ATMS, CERES, CrIS,<br>OMPS, VIIRS | | Climate<br>Forecasting<br>Surveillance |
| TacSat-4<br>NRL | L2011<br>E? | HEO Apogee<br>12,050 km | Polar communications | UHF | 4-hour orbit<br>2-hour comm. | Comm. |
| TanDEM-X, TerraSAR-X Add-on for Digital Elevation Measurements<br>DLR | L2010<br>E2015 | LEO SSO<br>514 km<br>94.85 mins<br>97.4 deg | Cartography, land surface, civil planning and mapping, digital terrain models, environmental monitoring. | X-Band SAR | | Surveillance |
| Terra<br>Terra (formerly EOS AM-1)<br>NASA, METI, CSA | L1999<br>E2013 | LEO SSO<br>705 km<br>99 mins<br>98.2 deg | 6-year nominal mission life, currently in extended operations. Atmospheric dynamics/water and energy cycles, atmospheric chemistry, physical and radiative properties of clouds, air-land exchanges of energy, carbon and water, vertical profiles of CO and methane volcanology. | ASTER, CERES,<br>MISR, MODIS,<br>MOPITT | ASTER S: 60 km<br>ASTER R: 15 m<br>C: 1%, 16% | Climate<br>Forecasting<br>Surveillance |
| TerraSAR-X<br>TerraSAR-X<br>DLR | L2007<br>E2013 | LEO SSO<br>514 km<br>94.85 mins<br>97.4 deg | Cartography, land surface, civil planning and mapping, digital terrain models, environmental monitoring. | GPSRO (Terra-SAR),<br>X-Band SAR | S: 10–150 km<br>R: 1–18 m<br>C: 2.5%, 40% | Climate<br>Surveillance |
| TES<br>Technology Experimental Satellite on Cartography<br>ISRO | L2001<br>E2012 | LEO SSO | For demonstrating many satellite technologies for future Cartosat satellites. | TES PAN | | Surveillance |
| THEOS<br>Thailand Earth Observation System<br>GISTDA | L2008<br>E2013 | LEO SSO<br>822 km<br>101 mins<br>98.7 deg | Earth resources, land surface and disaster monitoring, civil planning. | MS (GISTDA), PAN<br>(GISTDA) | R: 2 m | Surveillance<br>Climate |
| UK-DMC2<br>UK Disaster Monitoring Constellation 2<br>UKSA | L2009<br>E2014 | LEO SSO<br>670 km<br>98.5 mins<br>98.14 deg | Wide area, medium resolution optical imaging for mapping, crop monitoring, environmental resource and disaster management. | SLIM-6-22 | R: 20 m | Surveillance<br>Climate |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C)<br>1-pass, daily % | Relevant Missions |
|---|---|---|---|---|---|---|
| Worldview-1<br>Digital Globe | L2007<br>E2014 | LEO SSO<br>670 km<br>94.6 mins<br>97.2 deg | High-Resolution Imagery | | R: 50 cm–2 m | Surveillance<br>Climate |
| Worldview-2<br>Digital Globe | L2009<br>E2016 | LEO SSO<br>770 km<br>100 mins | High-Resolution Imagery | 8 spectral bands | S: 16.4 km<br>R: 46 cm–2 m<br>C: 0.3%, 4.5% | Climate<br>Surveillance |

## Table A-2. Future Satellites (Post-2012) on-orbit with Arctic Mission Capability

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| 3D Winds<br>Three Dimensional Tropospheric Winds from Space Based Lidar<br>NASA | Considered<br>L2030<br>E2033 | LEO SSO<br>400 km<br>97.03 deg | Phase-3 DS Mission, launch order unknown, 3-year nominal mission. Tropospheric winds for weather forecasting and pollution transport. | HDWL (3D Winds) | | Forecasting |
| ACE<br>Aerosol Clouds and Ecosystem Mission<br>NASA | Considered<br>L2020<br>E2023 | LEO SSO<br>650 km<br>98.2 deg | Phase-2 DS Mission, launch order unknown, 3-year nominal mission. Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry. | Cloud radar, HSRL, Multi-band UV/VIS Spectrometer, Next Gen APS | | Climate |
| ADM-Aeolus<br>Atmospheric Dynamics Mission (Earth Explorer Core Mission)<br>ESA | Approved<br>L2014<br>E2017 | LEO SSO<br>405 km<br>92.5 mins<br>97.01 deg | Will provide wind profile measurements for global 3D wind field products used for study of atmospheric dynamics, including global transport of energy, water, aerosols, and chemicals. | ALADIN | | Climate<br>Forecasting |
| AISSat-2<br>Automatic Identification System Satellite-2<br>NSC | Approved<br>L2012<br>E2015 | LEO SSO | Demonstrate and extend access to AIS (Automatic Identification System) signals beyond the land-based AIS system operated by the Norwegian Coastal Administration today. Observe ship traffic in the High North. | SDR | | Surveillance |
| ALOS-2<br>Advanced Land Observing Satellite-2<br>JAXA | Approved<br>L2013<br>E2017 | LEO SSO<br>628 km<br>100 mins<br>97.9 deg | Environmental monitoring, disaster monitoring, civil planning, agriculture and forestry, Earth resources, land surface. | L-Band SAR | | Surveillance<br>Climate |
| ALOS-3<br>Advanced Land Observing Satellite-3<br>JAXA | Planned<br>L2014<br>E2018 | LEO SSO | Cartography, digital terrain models, environmental monitoring, disaster monitoring, civil planning, agriculture and forestry, Earth resources, land surface. | HISUI, Optical Sensor | | Surveillance<br>Climate |
| AMAZONIA-1<br>Amazonia 1<br>INPE | Approved<br>L2014<br>E2017 | LEO SSO<br>752 km<br>99.9 mins<br>98.4 deg | Earth resources, environmental monitoring, land surface. | AWFI | | Climate |
| Arctica<br>Arctica<br>ROSHYDROMET | Approved<br>L2015<br>E2018 | HEO<br><br>718 mins | Meteorology, oceanography, including ice cover monitoring and disaster monitoring in the Arctic region. The payload and design of the satellites is similar to the ones in the Electro-L series. Molniya orbit. | DCS, GGAK-E, MSU-GS, S&R | | Forecasting<br>Climate |
| Arkon-2M<br>Arkon-2M<br>ROSKOSMOS | Planned<br>L2013<br>E2018 | LEO SSO<br>500 km | Earth observations and weather information. | Arkon-2M SAR | | Forecasting<br>Climate |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| ASCENDS<br>Active Sensing of CO2 Emissions over Nights, Days, and Seasons<br>NASA | Considered<br>L2020<br>E2023 | LEO SSO<br>450 km<br>97.3 mins | Phase-2 DS Mission, launch order unknown, 3-year nominal mission. Day/night, all-latitude, all-season CO2 column integrals for climate emissions. | CO2 LIDAR | | Climate |
| CARTOSAT-1A<br>Cartography Satellite -1A<br>ISRO | Considered<br>L2014<br>E2019 | LEO SSO | Ensure the continuity of high resolution imaging capability with multispectral capability, stereo imaging and hyperspectral imaging. | HYSI-SWIR, HYSI-VNIR, MX-VNIR, PAN-MX | | Surveillance<br>Climate |
| CARTOSAT-1B<br>Cartosat -1B<br>ISRO | Considered<br>L2017<br>E2022 | LEO SSO | Ensure the continuity of high resolution imaging capability with multispectral capability, stereo imaging and hyperspectral imaging. | HYSI -SWIR, HYSI-VNIR, MX-VNIR, PAN-MX | | Surveillance<br>Climate |
| CARTOSAT-2C<br>Cartography Satellite - 2C<br>ISRO | Considered<br>L2013<br>E2017 | LEO SSO<br>635 km<br>97.4 mins<br>97.87 deg | High precision large-scale cartographic mapping and thematic applications with MX data at 1:4000 scales. | HRMX | | Surveillance |
| CARTOSAT-2D<br>Cartography Satellite - 2D<br>ISRO | Considered<br>L2016<br>E2022 | LEO SSO<br>635 km<br>97.4 mins<br>97.87 deg | High precision large-scale cartographic mapping and thematic applications with MX data at 1:4000 scales. | HRMX | | Surveillance |
| CARTOSAT-3<br>Cartography Satellite - 3<br>ISRO | Planned<br>L2015<br>E2020 | LEO SSO | Suitable for cadastral and infrastructure mapping and analysis. | PAN | | Surveillance |
| CARTOSAT-3A<br>Cartography Satellite - 3A<br>ISRO | Considered<br>L2018<br>E2023 | LEO SSO | Suitable for cadastral and infrastructure mapping and analysis. | PAN | | Surveillance |
| CBERS-3<br>China Brazil Earth Resources Satellite - 3<br>INPE, CRESDA | Approved<br>L2012<br>E2015 | LEO SSO<br>778 km<br>100.3 mins<br>98.5 deg | Earth resources, environmental monitoring, land surface. | DCS, IRS, MUX, PAN, WFI-2 | | Surveillance<br>Climate |
| CBERS-4<br>China Brazil Earth Resources Satellite - 4<br>INPE, CRESDA | Approved<br>L2014<br>E2017 | LEO SSO<br>778 km<br>100.3 mins<br>98.5 deg | Earth resources, environmental monitoring, land surface. | DCS, IRS, MUX, PAN, WFI-2 | | Surveillance<br>Climate |
| CSG-1<br>COSMO-SkyMed Second Generation - 1<br>ASI | Approved<br>L2015<br>E2022 | LEO SSO<br>620 km<br>97.1 mins<br>97.8 deg | Environmental monitoring, surveillance and risk management applications, environmental resources management, maritime management, earth topographic mapping, law enforcement, informative / science applications. | SAR-2000 S.G. | | Surveillance |
| CSG-2<br>COSMO-SkyMed Second Generation - 2 | Approved<br>L2016<br>E2023 | LEO SSO<br>620 km<br>97.1 mins | Environmental monitoring, surveillance and risk management applications, environmental resources management, maritime management, earth topographic mapping, law enforcement, | SAR-2000 S.G. | | Surveillance |

| Mission Name Short Mission Name Full Mission Agencies | Mission Status Launch Date (L) EOL Date (E) | Orbit Type Orbit Altitude Orbit Period Orbit Inclination | Applications | Instruments | Swath (S) Resolution (R) Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| ASI | | 97.8 deg | informative / science applications. | | | |
| DMSP F-19<br>Defense Meteorological Satellite Program F-19<br>NOAA | Approved<br>L2012<br>E2017 | LEO SSO<br>833 km<br>101 mins<br>98.7 deg | The long-term meteorological program of the DoD - with the objective to collect and disseminate worldwide cloud cover data on a daily basis. | OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI | | Forecasting<br>Climate<br>Surveillance |
| DMSP F-20<br>Defense Meteorological Satellite Program F-20<br>NOAA | Approved<br>L2014<br>E2019 | LEO SSO<br>850 km<br>101 mins<br>98.7 deg | The long-term meteorological program of the DoD - with the objective to collect and disseminate worldwide cloud cover data on a daily basis. | OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI | | Forecasting<br>Climate<br>Surveillance |
| DSCOVR<br>Deep Space Climate Observatory<br>NOAA, NASA | Approved<br>L2014<br>E2016 | TBD | Measure a combination of solar phenomena and earth climate measurements. Provides 15 min warning for solar storms (CME) events. | EPIC, NISTAR | | Comm.<br>Climate |
| EarthCARE<br>EarthCARE<br>ESA, JAXA | Approved<br>L2015<br>E2018 | LEO SSO<br>393 km<br><br>97 deg | To Improve the understanding of atmospheric cloud-aerosol interactions and of the Earth's radiative balance towards enhancing climate and numerical weather prediction models. The 2 active and 2 passive instruments of EarthCARE make unique data product synergies possible. | ATLID, BBR, CPR, MSI | | Forecasting<br>Climate |
| EnMAP<br>Environmental Mapping & Analysis Program<br>DLR | Approved<br>L2015<br>E2020 | LEO SSO<br>650 km<br>97.5 mins | Hyperspectral imaging, land surface, geological and environmental investigation. | HSI | | Surveillance<br>Climate |
| Environsat-1<br>Environmental Satellite - 1<br>ISRO | Considered<br>L2013<br>E2017 | | Monitoring of greenhouse gases, aerosols and other atmospheric trace gases which are responsible for global warming. | HRSS-1, HRVS-1A/-1B | | Climate |
| Environsat-2<br>Environmental Satellite - 2<br>ISRO | Considered<br>L2016<br>E2020 | | Monitoring of greenhouse gases, aerosols and other atmospheric trace gases which are responsible for global warming. | HRSS-1, HRVS-1A/-1B | | Climate |
| EPS-SG-a<br>EUMETSAT Polar System, second generation<br>EUMETSAT, NOAA, DLR, EC, CNES, ESA | Planned<br>L2019<br>E2027 | LEO SSO | Meteorology, climatology. EPS-SG-a carries the Sentinel-5 mission. 3 satellites (TBC). | 3MI, ATMS, IASI-NG, METimage, RO | | Climate |
| EPS-SG-b<br>EUMETSAT Polar System, second generation<br>EUMETSAT, EC, ESA | Planned<br>L2020<br>E2028 | LEO SSO | Meteorology, climatology. 2 satellites (TBC). | MWI-Cloud, MWI-Precip, RO, SCA | | Climate |

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|---|---|---|---|---|---|---|
| FY-3C<br>FY-3C Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | Approved<br>L2012<br>E2015 | LEO SSO<br>830 km<br>101 mins<br>98.753 deg | Meteorology and environmental monitoring; data collection and redistribution. (Operational follow-on to FY-3B). | ERM, IMWAS, IRAS, MERSI, MIRAS, MWHS-2, MWRI, MWTS-2, SES, SIM, SIM-2, TOU/SBUS, VIRR | | Forecasting<br>Climate |
| FY-3D<br>FY-3D Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | Approved<br>L2014<br>E2017 | LEO SSO<br>830 km<br>101 mins<br>98.753 deg | Meteorology and environmental monitoring; data collection and redistribution. | ASI, GAMI, GNOS, IMWAS, MERSI-2, MIRAS, MWHS-2, MWRI, MWTS-2, SES | | Forecasting<br>Climate |
| FY-3E<br>FY-3E Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | Planned<br>L2017<br>E2020 | LEO SSO<br>830 km<br>101 mins<br>98.753 deg | Meteorology and environmental monitoring; data collection and redistribution. | ASI, ERM-2, GNOS, IMWAS, MERSI-2, MIRAS, MWHS-2, MWTS-2, OMS, SES, SIM, SIM-2, WindRAD | | Forecasting<br>Climate |
| FY-3F<br>FY-3F Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | Planned<br>L2019<br>E2022 | LEO SSO<br>830 km<br>101 mins<br>98.753 deg | Meteorology and environmental monitoring; data collection and redistribution. | ASI, GAMI, GNOS, IMWAS, MERSI-2, MIRAS, MVIRS, MWHS-2, MWRI, MWTS-2, SES | | Forecasting<br>Climate |
| FY-3G<br>FY-3G Polar-orbiting Meteorological Satellite<br>NSMC-CMA, NRSCC | Considered<br>L2021<br>E2024 | LEO SSO | Meteorology and environmental monitoring; data collection and redistribution. | ASI, ERM-2, GNOS, IMWAS, MERSI-2, MIRAS, MVIRS, MWHS-2, MWTS-2, OMS, SIM-2, WindRAD | | Forecasting<br>Climate |
| GACM<br>Global Atmospheric Composition Mission<br>NASA | Considered<br>L2030<br>E2033 | LEO SSO | Phase-3 DS Mission, launch order unknown, 3-year nominal mission. Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction. | IR Spectrometer, Microwave limb sounder, UV Spectrometer | | Climate |
| GCOM-C1<br>Global Change Observation Mission-C1<br>JAXA | Approved<br>L2013<br>E2018 | LEO SSO<br>800 km<br>98 mins<br>98.6 deg | Understanding of climate change mechanism. | SGLI | | Climate |
| GCOM-C2<br>Global Change Observation Mission-C2<br>JAXA | Planned<br>L2017<br>E2022 | LEO SSO<br>800 km<br>98 mins<br>98.6 deg | Understanding of climate change mechanism. | SGLI | | Climate |
| GCOM-C3<br>Global Change Observation Mission-C3<br>JAXA | Planned<br>L2021<br>E2026 | LEO SSO<br>800 km<br>98 mins<br>98.6 deg | Understanding of climate change mechanism. | SGLI | | Climate |

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|---|---|---|---|---|---|---|
| GCOM-W2<br>Global Climate Observation Mission-W2<br>JAXA | Planned<br>L2016<br>E2021 | LEO SSO<br>700 km<br>98 mins<br>98.2 deg | Understanding of water circulation mechanism. | AMSR-2 | | Climate |
| GCOM-W3<br>Global Change Observation Mission-W3<br>JAXA | Planned<br>L2020<br>E2025 | LEO SSO<br>700 km<br>98 mins<br>98.2 deg | Understanding of water circulation mechanism. | AMSR-2 | | Climate |
| GOSAT Follow-On<br>Greenhouse gases Observing SATellite<br>JAXA, MOE (Japan), NIES (Japan) | Planned<br>L2016<br>E2021 | | Observation of greenhouse gases. | FTS | | Climate |
| GPM Core<br>Global Precipitation Measurement Mission Core spacecraft<br>NASA, JAXA | Approved<br>L2014<br>E2017 | non-LEO SSO<br>407 km<br>95 mins<br>65 deg | 3-year nominal mission life, 5-year goal. Study of global precipitation, evaporation, and cycling of water are changing. The mission comprises a primary spacecraft with active and passive microwave instruments, and a number of constellation spacecraft with passive microwave instruments. | DPR, GMI | | Climate |
| HJ-1C: Disaster and Environment Monitoring and Forecast Small Satellite Constellation C<br>CRESDA, CAST, NRSCC | Approved<br>L2012<br>E2014 | LEO SSO<br>499 km<br><br>97.3 deg | Disaster and environment monitoring and forecasting. | S-Band SAR | | Surveillance |
| HY-2B<br>Ocean dynamics satellite B<br>NSOAS, CAST | Planned<br>L2012<br>E2015 | LEO SSO<br>963 km<br>99.3 deg | Detecting ocean surface temperature, wind field, wave and topography. | ALT, RAD, SCAT | | Climate |
| HY-2C<br>Ocean dynamics satellite C<br>NSOAS, CAST | Planned<br>L2015<br>E2018 | LEO SSO<br>963 km<br>99.3 deg | Detecting ocean surface temperature, wind field, wave and topography. | ALT, RAD, SCAT | | Climate |
| HY-2D<br>Ocean dynamics satellite D<br>NSOAS, CAST | Planned<br>L2019<br>E2022 | LEO SSO<br>963 km<br>99.3 deg | Detecting ocean surface temperature, wind field, wave and topography. | ALT, RAD, SCAT | | Climate |
| HY-3A<br>HY-3A<br>NSOAS, CAST | Planned<br>L2015<br>E2020 | LEO SSO | Ocean monitoring, environmental protection, coastal zone survey, etc. | WSAR | | Climate<br>Surveillance |
| HY-3B<br>HY-3B<br>NSOAS, CAST | Planned<br>L2017<br>E2022 | LEO SSO | Ocean monitoring, environmental protection, coastal zone survey, etc. | WSAR | | Climate<br>Surveillance |
| HY-3C<br>HY-3C<br>NSOAS, CAST | Planned<br>L2022<br>E2027 | LEO SSO | Ocean monitoring, environmental protection, coastal zone survey, etc. | WSAR | | Climate<br>Surveillance |

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|---|---|---|---|---|---|---|
| HyspIRI<br>Hyperspectral Infrared Imager<br>NASA | Considered<br>L2020<br>E2023 | LEO SSO<br>626 km<br><br>98 deg | Phase-2 DS Mission, launch order unknown, 3-year nominal mission. Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health. | Multi-spectral thermal infrared imager, Visible imaging spectrometer | | Climate |
| ICESat-II<br>Ice, Cloud, and Land Elevation Satellite II<br>NASA | Planned<br>L2016<br>E2018 | non-LEO SSO<br>600 km<br>97 mins<br>94 deg | Early 2015 launch expected (after SMAP). Continue the assessment of polar ice changes and measure vegetation canopy heights, allowing estimates of biomass and carbon in aboveground vegetation in conjunction with related missions, and allow measurements of solid earth properties. | ATLAS | | Climate |
| Ingenio<br>Ingenio<br>CDTI, ESA | Approved<br>L2014<br>E2021 | LEO SSO<br>685 km<br>98 mins<br>98 deg | Cartography, land use, urban management, water management, agriculture and environmental monitoring, risk management and security. | PAN+MS (RGB+NIR), UVAS | | Surveillance<br>Climate |
| Jason-3<br>Jason-3<br>NASA, NOAA, CNES, EUMETSAT | Approved<br>L2014<br>E2017 | non-LEO SSO<br>1336 km<br>112.4 mins<br>66 deg | 3-year nominal mission life, currently in extended operations. Physical oceanography, geodesy/gravity, climate monitoring, marine meteorology. | AMR, POSEIDON-3B | | Climate |
| JPSS-1<br>Joint Polar Satellite System - 1<br>NOAA, EUMETSAT, NASA | Approved<br>L2017<br>E2023 | LEO SSO<br>824 km<br>101 mins<br>98.75 deg | Meteorological, climatic, terrestrial, oceanographic, and solar-geophysical applications; global and regional environmental monitoring, search and rescue, data collection. | ATMS, CERES, CrIS, OMPS, VIIRS | | Forecasting<br>Climate |
| JPSS-2<br>Joint Polar Satellite System - 2<br>NOAA, EUMETSAT, NASA | Approved<br>L2023<br>E2029 | LEO SSO<br>833 km<br>101 mins<br>98.75 deg | Meteorological, climatic, terrestrial, oceanographic, and solar-geophysical applications; global and regional environmental monitoring, search and rescue, data collection. Note that free-flyer options are being considered for the A-DCS4 and SARSAT instruments, though these are considered part of the JPSS system. | A-DCS4, ATMS, CrIS, ERBS, OMPS, SARSAT, TSIS, VIIRS | | Forecasting<br>Climate |
| Kanopus-V N1<br>Kanopus-V Environmental Satellite N1<br>ROSKOSMOS, ROSHYDROMET | Approved<br>L2012<br>E2019 | LEO SSO<br>600 km<br>98 mins<br>98 deg | Land surface, disaster monitoring. | MSS, MSU-200, PSS | | Surveillance |
| Kanopus-V N2<br>Kanopus-V Environmental Satellite N2<br>ROSKOSMOS, ROSHYDROMET | Considered<br>L2013<br>E2018 | LEO SSO<br>600 km<br><br>98 deg | Land surface, disaster monitoring. | MSS, MSU-200, PSS | | Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| KOMPSAT-3A<br>Korea Multi-Purpose Satellite -3A<br>KARI, ASTRIUM, DLR | Approved<br>L2014<br>E2018 | LEO SSO<br>528 km<br>98.5 mins | Cartography, land use and planning, disaster monitoring. | AEISS-A | | Surveillance<br>Climate |
| KOMPSAT-5<br>Korea Multi-Purpose Satellite -5<br>KARI, TAS-i | Approved<br>L2012<br>E2016 | LEO SSO<br>550 km<br>98.5 mins | Cartography, land use and planning, disaster monitoring. | COSI | | Surveillance<br>Climate |
| LDCM<br>Landsat Data Continuity Mission<br>NASA, USGS | Approved<br>L2013<br>E2018 | LEO SSO<br>705 km<br>99 mins<br>98.2 deg | 5-year nominal mission life. Earth resources, land surface, environmental monitoring, agriculture and forestry, disaster monitoring and assessment, ice and snow cover. | OLI, TIRS | | Climate<br>Surveillance |
| LIST<br>Lidar Surface Topography<br>NASA | Considered<br>L2030<br>E2033 | LEO SSO | Phase-3 DS Mission, launch order unknown, 3-year nominal mission. Land surface topography for landslide hazards and water runoff. | Laser altimeter | | Surveillance |
| MERLIN<br>Methane Remote Sensing Lidar Mission<br>DLR, CNES | Planned<br>L2016<br>E2019 | LEO SSO<br>500 km<br>90 mins | Global atmospheric methane concentration. | IPDA LIDAR | | Climate |
| Meteor-3M N2<br>ROSHYDROMET, ROSKOSMOS | Approved<br>L2012<br>E2016 | LEO SSO<br>1024 km<br>105.3 mins<br>99.6 deg | Hydrometeorology, climatology, land surface, physical oceanography, heliogeophysics and space environment, data collection, sounding of the atmosphere, agriculture. | BRK, DCS, IKFS-2, KMSS, MSGI-MKA, MSU-MR, MTVZA, SAR | | Climate |
| Meteor-M N2<br>Meteor-M Meteorological Satellite N2<br>ROSHYDROMET, ROSKOSMOS | Approved<br>L2012<br>E2017 | LEO SSO<br>835 km<br>102 mins<br>98.7 deg | Hydrometeorology, climatology, heliogeophysics, DCS. | DCS, GGAK-M, IKFS-2, KMSS, MSU-MR, MTVZA, Severjanin | | Climate |
| Meteor-M N3<br>Meteor-M Oceanographical Satellite N3<br>ROSHYDROMET, ROSKOSMOS | Approved<br>L2015<br>E2020 | LEO SSO<br>835 km<br>102 mins<br>98.7 deg | Oceanography, hydrometeorology, climatology. | CZS, DCS, OCS, Radiometer, SAR, Scatterometer | | Climate |
| Meteor-MP N1<br>Meteor-MP Meteorological Satellite N1<br>ROSHYDROMET, ROSKOSMOS | Planned<br>L2014<br>E2019 | LEO SSO | Hydrometeorology, climatology, heliogeophysics, DCS. | Advanced DCS, Advanced GGAK-M, Advanced IKFS-2, Advanced KMSS, Advanced MSU-MR, Advanced MTVZA, Advanced Radiomet, Advanced SAR, Advanced | | Climate |

| Mission Name Short Mission Name Full Mission Agencies | Mission Status Launch Date (L) EOL Date (E) | Orbit Type Orbit Altitude Orbit Period Orbit Inclination | Applications | Instruments | Swath (S) Resolution (R) Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| | | | | Scatterometer, TGSP | | |
| Meteor-MP N2<br>Meteor-MP Meteorological Satellite N2<br>ROSHYDROMET, ROSKOSMOS | Planned<br>L2015<br>E2020 | LEO SSO | Hydrometeorology, climatology, heliogeophysics, DCS. | Same list as Meteor-MP N1. | | Climate |
| Meteor-MP N3<br>Meteor-MP Meteorological Satellite N3<br>ROSHYDROMET, ROSKOSMOS | Planned<br>L2016<br>E2021 | LEO SSO | Hydrometeorology, climatology, heliogeophysics, DCS. | Same list as Meteor-MP N1. | | Climate |
| Metop-B<br>Meteorological Operational Polar Satellite - B<br>EUMETSAT, ESA | Approved<br>L2012<br>E2017 | LEO SSO<br>840 km<br>101.7 mins<br>98.8 deg | Meteorology, climatology. | AMSU-A, ARGOS, ASCAT, AVHRR/3, GOME-2, GRAS, HIRS/4, IASI, MHS, S&R (NOAA), SEM (POES) | | Forecasting<br>Climate |
| Metop-C: Meteorological Operational Polar Satellite - C<br>EUMETSAT, ESA | Approved<br>L2016<br>E2021 | LEO SSO<br>840 km<br>101.7 mins<br>98.8 deg | Meteorology, climatology. | A-DCS4, AMSU-A, ARGOS, ASCAT, AVHRR/3, GOME-2, GRAS, IASI, MHS, SEM (POES) | | Forecasting<br>Climate |
| MIOSAT<br>Piccola MIssione Ottica basata su microSATellite<br>ASI | Approved<br>L2014<br>E2016 | LEO SSO<br>615 km<br>97 mins<br>97.9 deg | Land surface, agriculture and forestry, regional geology, land use studies, water resources, vegetation studies, coastal studies and soils and main atmospheric gases detection. | ALISEO, Mach-Zehnder Micro-interferometer, PAN CAM | | Climate |
| OCEANSAT-3<br>Ocean Satellite-3<br>ISRO | Considered<br>L2014<br>E2019 | LEO SSO<br>720 km<br>99.31 mins<br>98.28 deg | Ocean and atmosphere applications. | OCM (Oceansat-3/3A), TIR (Oceansat-3/3A) | | Climate |
| OCEANSAT-3A<br>Ocean Satellite-3A<br>ISRO | Considered<br>L2018<br>E2023 | LEO SSO<br>720 km<br>99.31 mins<br>98.28 deg | Ocean and atmosphere applications. | OCM (Oceansat-3/3A), TIR (Oceansat-3/3A) | | Climate |
| OCO-2<br>Orbiting Carbon Observatory-2 | Approved<br>L2014<br>E2017 | LEO SSO<br>705 km<br>98.8 mins | High resolution carbon dioxide measurements to characterize sources and sinks on regional scales and quantify their variability over the seasonal cycle. | Spectrometer | | Climate |

| Mission Name Short Mission Name Full Mission Agencies | Mission Status Launch Date (L) EOL Date (E) | Orbit Type Orbit Altitude Orbit Period Orbit Inclination | Applications | Instruments | Swath (S) Resolution (R) Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| NASA | | 98.2 deg | | | | |
| PACE: Preliminary Aerosol, Cloud, Ecosystem NASA | Considered L2019 E2021 | LEO SSO 650 km 98.2 deg | Phase-2 DS Mission, launch order unknown, 3-year nominal mission. Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry. | Next Gen APS (ACE), OES | | Climate |
| PAZ PAZ CDTI | Approved L2013 E2018 | LEO SSO 514 km 95 mins 97.44 deg | Security, land use, urban management, environmental monitoring, risk management. | Paz SAR-X | | Surveillance Climate |
| PCW-1 Polar Communications and Weather-1 CSA | Planned L2018 E2028 | HEO 718 mins 63.4 deg | Continuous meteorological observation and communications service to the Arctic. | PCW PHEMOS - Atmospheric, PCW PHEMOS - Solar-Terrestrial, PCWMP | | Comm. Forecasting Climate |
| PCW-2 Polar Communications and Weather-2 CSA | Planned L2018 E2028 | HEO 718 mins 63.4 deg | Continuous meteorological observation and communications service to the Arctic. | PCW PHEMOS - Atmospheric, PCW PHEMOS - Solar-Terrestrial, PCWMP | | Comm. Forecasting Climate |
| Pleiades 2 CNES | Approved L2013 E2018 | LEO SSO 694 km | Cartography, land use, risk, agriculture and forestry, civil planning and mapping, digital terrain models, defense. | HiRI | | Surveillance |
| PRISMA PRecursore IperSpettrale della Missione Applicativa ASI | Approved L2014 E2019 | LEO SSO 615 km 97 mins 97.9 deg | Land surface, agriculture and forestry, regional geology, land use studies, water resources, vegetation studies, coastal studies and soils. | HYC, PAN CAMERA | | Climate |
| RADARSAT C-1 RADARSAT CONSTELLATION-1 CSA | Approved L2016 E2023 | LEO SSO 600 km 96.4 mins 97.7 deg | Ecosystem monitoring, maritime surveillance, disaster management. | AIS, SAR | | Surveillance Climate |
| RADARSAT C-2 RADARSAT CONSTELLATION-2 CSA | Approved L2017 E2025 | LEO SSO 600 km 96.4 mins 97.7 deg | Ecosystem monitoring, maritime surveillance, disaster management. | AIS, SAR | | Surveillance Climate |
| RADARSAT C-3 RADARSAT CONSTELLATION-3 CSA | Approved L2017 E2025 | LEO SSO 600 km 96.4 mins 97.7 deg | Ecosystem monitoring, maritime surveillance, disaster management. | AIS, SAR | | Surveillance Climate |
| RESOURCESAT-2A Resource Satellite-2A ISRO | Considered L2013 E2018 | LEO SSO 817 km 102 mins 98.72 deg | Natural resources management, agricultural applications, forestry, etc. | AWiFS, LISS-III, LISS-IV | | Climate |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| RESOURCESAT-3<br>Resource Satellite-3<br>ISRO | Considered<br>L2015<br>E2020 | LEO SSO<br>817 km<br>102 mins<br>98.72 deg | Natural resources management, agricultural applications, forestry, etc. | ATCOR, WS LISS III | | Climate |
| RESOURCESAT-3A<br>Resource Satellite-3A<br>ISRO | Considered<br>L2018<br>E2023 | LEO SSO<br>817 km<br>102 mins<br>98.72 deg | Natural resources management, agricultural applications, forestry, etc. | ATCOR, WS LISS III | | Climate |
| Resurs P N1<br>Resurs P Environmental Satellite N1<br>ROSKOSMOS, ROSHYDROMET | Approved<br>L2012<br>E2017 | | Land surface. | Arina, Geoton-L1, Pamela | | Climate |
| Resurs P N2<br>Resurs P Environmental Satellite N2<br>ROSKOSMOS, ROSHYDROMET | Planned<br>L2013<br>E2018 | | Land surface. | Arina, Geoton-L1, Pamela | | Climate |
| RISAT-1A<br>Radar Imaging Satellite<br>ISRO | Considered<br>L2015<br>E2019 | LEO SSO<br>610 km<br>96.5 mins<br>97.844 deg | Land surface, agriculture and forestry, regional geology, land use studies, water resources, vegetation studies, coastal studies and soils - especially during cloud season. | SAR | | Surveillance<br>Climate |
| RISAT-3<br>Radar Imaging Satellite<br>ISRO | Considered<br>L2016<br>E2021 | LEO SSO<br>96.5 mins<br>97.844 deg | Land surface, agriculture and forestry, regional geology, land use studies, water resources, vegetation studies, coastal studies and soils - especially during cloud season. | SAR-L | | Surveillance<br>Climate |
| SAC-E/SABIA_MAR-A<br><br>CONAE | Approved<br>L2016<br>E2021 | LEO SSO | Global ocean color medium resolution, urban lights, polar auroras, centralized data collection. | DCS (SABIA_MAR), HSC, MUS-M | | Surveillance<br>Climate |
| SAC-E/SABIA_MAR-B<br><br>CONAE | Approved<br>L2017<br>E2022 | LEO SSO | Coastal zones ocean color low resolution. | DCS (SABIA_MAR), HSC, MUS-L | | Climate |
| SAGE-III<br>Stratospheric Aerosol and Gas Experiment<br>NASA | Planned<br>L2014<br>E2017 | non-LEO SSO<br>425 km<br><br>51 deg | Refurbishment of the SAGE-III instrument and of a hexapod pointing platform, and accommodation studies. This mission flies on the ISS. | SAGE-III | | Climate |
| SAOCOM 1A<br><br>CONAE, ASI | Approved<br>L2014<br>E2019 | LEO SSO<br>620 km<br>97.2 mins<br>97.89 deg | Earth observation and emergency management with an L-band SAR. | SAR-L | | Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| SAOCOM 1B<br><br>CONAE, ASI | Approved<br>L2015<br>E2020 | LEO SSO<br>620 km<br>97.2 mins<br>97.89 deg | Earth observation and emergency management with an L-band SAR. | SAR-L | | Surveillance |
| SAOCOM-2A<br><br>CONAE | Planned<br>L2019<br>E2024 | LEO SSO<br>620 km<br>98 deg | Earth observation and emergency management with an L-band SAR. | SAR-L | | Surveillance |
| SAOCOM-2B<br><br>CONAE | Planned<br>L2020<br>E2025 | LEO SSO<br>620 km<br>98 deg | Earth observation and emergency management with an L-band SAR. | SAR-L | | Surveillance |
| SARAL<br>Satellite with ARgos and ALtiKa<br>CNES, ISRO | Approved<br>L2012<br>E2014 | LEO SSO<br>799 km<br>100.59 mins<br>98.55 deg | This will provide precise, repetitive global measurements of sea surface height, significant wave heights and wind speed. | AltiKa, ARGOS | | Climate |
| SARE-1B<br>SARE-1<br>CONAE | Planned<br>L2014<br>E2017 | | Segmented architecture development. | SAR components testing | | Surveillance |
| Scatterometer Satellite-1<br>Scatsat-1<br>ISRO | Considered<br>L2013<br>E2017 | TBD | Ocean and atmosphere applications, wind speed over oceans, temperature. | Scatterometer (OCEANSAT), TSU | | Climate |
| SCLP: Snow and Cold Land Processes<br>NASA | Considered<br>L2030<br>E2033 | LEO SSO | Phase-3 DS Mission, launch order unknown, 3-year nominal mission. Snow accumulation for fresh water availability. | K band radiometers, Ku and X-band radars | | Climate |
| Sentinel-1 A<br>Sentinel-1 A<br>ESA, EC | Approved<br>L2013<br>E2020 | LEO SSO<br>693 km<br>98.74 mins<br>98.19 deg | Providing continuity of C-band SAR data for operational applications notably in the following areas: monitoring of sea ice zones and the arctic environment, surveillance of marine environment, monitoring of land surface motion risks and mapping in support of humanitarian aid in crisis situations. | C-Band SAR | | Surveillance<br>Climate |
| Sentinel-1 B<br>Sentinel-1 B<br>ESA, EC | Approved<br>L2015<br>E2022 | LEO SSO<br>693 km<br>98.74 mins<br>98.19 deg | Same as Sentinel-1 A. | C-Band SAR | | Surveillance<br>Climate |
| Sentinel-1 C<br>Sentinel-1 C<br>ESA, EC | Considered<br>L2019<br>E2026 | LEO SSO<br>693 km<br>98.74 mins<br>98.19 deg | Same as Sentinel-1 A. | C-Band SAR | | Surveillance<br>Climate |
| Sentinel-2 A<br>Sentinel-2 A<br>ESA, EC | Approved<br>L2013<br>E2021 | LEO SSO<br>786 km<br>100.7 mins<br>98.62 deg | Supporting land monitoring related services, including: generation of generic land cover maps, risk mapping and fast images for disaster relief, generation of leaf coverage leaf chlorophyll content and leaf water content. | MSI | | Surveillance<br>Climate |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| Sentinel-2 B<br>Sentinel-2 B<br>ESA, EC | Approved<br>L2015<br>E2022 | LEO SSO<br>786 km<br>100.7 mins<br>98.62 deg | Same as Sentinel-2 A. | MSI | | Surveillance<br>Climate |
| Sentinel-2 C<br>Sentinel-2 C<br>ESA, EC | Considered<br>L2020<br>E2027 | LEO SSO<br>786 km<br>100.7 mins<br>98.62 deg | Same as Sentinel-2 A. | MSI | | Surveillance<br>Climate |
| Sentinel-3 A<br>Sentinel-3 A<br>ESA, EUMETSAT, EC | Approved<br>L2013<br>E2021 | LEO SSO<br>814 km<br>100 mins<br>98.65 deg | Supporting global land and ocean monitoring services, in particular: sea/land color data and surface temperature; sea surface and land ice topography; coastal zones, inland water and sea ice topography; vegetation products. | OLCI, SLSTR, SRAL | | Climate |
| Sentinel-3 B<br>Sentinel-3 B<br>ESA, EUMETSAT, EC | Approved<br>L2014<br>E2022 | LEO SSO<br>814 km<br>100 mins<br>98.65 deg | Same as Sentinel-3 A. | OLCI, SLSTR, SRAL | | Climate |
| Sentinel-3 C<br>Sentinel-3 C<br>ESA, EUMETSAT, EC | Considered<br>L2020<br>E2027 | LEO SSO<br>814 km<br>100 mins<br>98.65 deg | Same as Sentinel-3 A. | OLCI, SLSTR, SRAL | | Climate |
| Sentinel-5<br>Sentinel-5<br>ESA | Planned<br>L2019<br>E2026 | LEO SSO | In early stages of mission definition. Other payloads will be added. The Sentinel-5 mission is carried on EPS-SG-a. | IRS, METimage, UVNS | | Climate |
| Sentinel-5 precursor<br>Sentinel-5 precursor<br>ESA, NSO | Approved<br>L2014<br>E2020 | LEO SSO<br>824 km<br>17 mins<br>98.742 deg | Supporting global atmospheric composition and air quality monitoring services. It will bridge the gap between Envisat and Sentinel-5. | UVNS | | Climate |
| SMAP<br>Soil Moisture Active Passive<br>NASA | Planned<br>L2014<br>E2017 | LEO SSO<br>685 km<br><br>98 deg | Late 2014 launch expected, 3-year nominal mission life. Global soil moisture mapping. | L-band Radar, L-band Radiometer | | Climate |
| SWOT<br>Surface Water Ocean Topography<br>NASA, CNES | Considered<br>L2019<br>E2022 | non-LEO SSO<br>970 km<br><br>78 deg | Phase-2 DS Mission, launch order unknown, 3-year nominal mission. Ocean, lake, and river water levels for ocean and inland water dynamics. | CO Sensor (ASCENDS), Ka-band Radar INterferometer (KaRIN) | | Climate |
| TSX-NG<br>TerraSAR Next Generation<br>DLR | Planned<br>L2016<br>E2023 | LEO SSO | Commercial follow-on mission to TerraSAR-X operated by Infoterra. Cartography, land surface, civil planning and mapping, digital terrain models, environmental monitoring. | X-Band SAR | | Surveillance |

| Mission Name Short<br>Mission Name Full<br>Mission Agencies | Mission Status<br>Launch Date (L)<br>EOL Date (E) | Orbit Type<br>Orbit Altitude<br>Orbit Period<br>Orbit Inclination | Applications | Instruments | Swath (S)<br>Resolution (R)<br>Coverage (C) | Relevant Missions |
|---|---|---|---|---|---|---|
| VENUS<br>Vegetation and Environment monitoring on a New Micro-Satellite<br>CNES, ISA | Approved<br>L2013<br>E2016 | LEO SSO<br>720 km<br><br>98.27 deg | Vegetation, agriculture monitoring, water management. | VSC | | Climate |

# Appendix B. UAS Specifications, Example Systems

This appendix is a companion reference for Section 5 of this report.

## Manta UAS
Block B4

Get big results with our biggest capacity payload UAS.

The Manta – an unmanned aircraft system (UAS) – offers an unprecedented number of mission profiles in its small, lightweight category.

Choose from a large number of missions due to the large size of its payload. Take advantage of its small size and mobility. Enjoy its low cost and ease of use. Select from two options of fuel tank design.

Customizable to your configuration; take a few moments and discover how the Manta can provide the information you want.

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REAL PERFORMANCE. REAL ADVANTAGE.

# Manta UAS
## Block B4

### SPECIFICATIONS

| | |
|---|---|
| Air Vehicle Wet Weight — Standard Payload | 20.4 kg (45 lb) |
| Air Vehicle Maximum Take-off Weight | 27.7 kg (61 lb) |
| Mission Endurance | Up to 8 Hours |
| Fuel Type | 100:1 Gasoline (87 Octane MOGAS) / Oil Pre-Mix |
| Mission Airspeed | 83-120 kph (45-65 knots) |
| Dash Airspeed | 139 kph (75 knots) |
| Stall Airspeed | 70 kph (38 knots) |
| Navigation | DGPS / GPS / INS |
| Service Ceiling | 4,870 m (16,000 ft) Density Altitude |
| Launch | Rolling Take-off or Pusher Prop Launcher |
| Recovery | Wheeled Gear |
| Payload (EO) | Configured to Customer's Requirements |
| Payload (IR) | Configured to Customer's Requirements |
| Command and Control Radio (C2) | Military or ISM Band Radio Modem Narrow and Wideband Operation Modes Available |
| Command and Control Radio Range | 37 km (20 nm), LOS |
| Video Transmitter | User Selectable 2W/5W Output, S-Band FM Video TX with Optional 19.2 Kbps Data Carrier |
| Video Transmission Frequency Range | S-Band or L-Band Standard (Other Frequencies are Optional) |
| Video System Range | 15-37 km (8-20 nm), LOS |
| Payload Capacity | 6.8 kg (15 lb) |
| Onboard Power | (2) Lithium Polymer Battery |
| Onboard Power Capacity | 14.4 V, 15 or 30 AH |
| Fuel Capacity | 8.0 L (2.1 gal) |
| Engine | 2-Stroke/2-Cylinder Reciprocating Gasoline Engine in Reverse Rotation |
| Ignition | Electronic, Capacitive Discharge |
| Propulsion | 20x10 3-Blade Pusher Propeller |
| Starting Method | Hand-Held Electric Starter (12V) |
| Shipping Size | 1.24 m x 1.3 m x 0.61 m (49 in x 52 in x 24 in) |
| Wingspan | 2.6 m (105 in) |
| Fuselage Length | 1.9 m (76 in) |
| Tail Height | 0.6 m (24.5 in) |

**FOR MORE INFORMATION CONTACT:**

BAE Systems
Unmanned Aircraft Programs
3292 East Hemisphere Loop
Tucson, AZ 85706 USA
Telephone 520-573-6300
Fax 520-573-0257
www.baesystems.com



OSR Approved for Public Release 09-S-2549 dated July 30, 2009

# AEROSONDE® MARK 4.7: REDEFINING EXPEDITIONARY

TEXTRON Systems

## Small footprint, transportable and deployable

The Aerosonde Mark 4.7 redefines expeditionary in unmanned aircraft systems (UAS). Its light weight, small logistics footprint, unique launch/recovery system and low cost make it a great choice for customers desiring a long-endurance, intelligence, surveillance and reconnaissance (ISR) solution.

# LONG-ENDURANCE ISR

*AAI's Aerosonde Mark 4.7, with our integrated launch and recovery system, is ideal for maritime operations.*

AAI Corporation's Aerosonde Mark 4.7 is part of the company's modular fleet of Aerosonde Mark 4 UAS. With increased capacity over previous Mark 4 aircraft and a low acoustic signature, the Mark 4.7 is ideal for covert maritime operations.

The Mark 4.7 maintains the high endurance of preceding aircraft in the series, yet has the added advantage of a unique launch and recovery system ideally suited for confined-area and maritime operations, with no ship alterations required.

With its combined electro-optic (EO), infrared (IR) and laser pointer (LP) payload, the Mark 4.7 is a complete maritime target acquisition solution. Features include:

- Automated launch and recovery capability
- Car-top or rail launch flexibility
- Multiple energy reduction landing system
- Imagery data link
- Day/night motion imagery payload
- Laser pointer capability

The Mark 4.7 is compatible with AAI's Expeditionary Ground Control Station (EGCS) for fast, easy setup and launch. All Aerosonde aircraft also are being incorporated into AAI's interoperability network of common ground control technologies, including the NATO standardization agreement (STANAG) 4586-compliant One System® Ground Control Station and One System Remote Video Terminal.

## Specifications

### Airframe

- Endurance: 10 or more hours with EO/IR/LP payload
- Wing span: 11.8 feet (ft.) or 3.6 meters (m)
- Maximum gross takeoff weight:
  - 38.6 pounds (17.5 kilograms) with J-type engine
  - 55 pounds (25 kilograms) with K-twin engine
- Cruise speed: 50-60 knots
- Dash speed: 62-80 knots at sea level
- Ceiling: 15,000 ft. or 4,500 m density altitude
- Launch and recovery:
  - Auto launch
  - Auto belly or net recovery

### Payload Capacity

- 12 inches (in.) length x 9.5 in. width x 9.5 in. height, or approximately 1,000 $in.^3$
- Weight 7.5-10 pounds
- 75-190 watts available

### Power Plant

- Engine: J-type, four-stroke, 24 cubic centimeters electronic fuel injection (EFI)
- Engine upgrade: K-twin, dual cylinder, four-stroke, EFI
- Fuel: 93 premium octane or 100 low-lead aviation gas

### A typical system includes:

- Three Mark 4.7 aircraft
- One trailer-mounted combined launch/recovery system
- Three EO/IR/LP payloads
- EGCS, the newest hardware configuration of AAI's STANAG 4586-compliant One System Ground Control Station family
- Associated ground equipment
- Award-winning, long-term logistical support

### Avionics

- Primary data link: 300 megahertz (MHz) ultra-high frequency, or UHF (Mil band)
- Secondary data link: 300/1,300 MHz (Mil band)
- Imagery data link: C-band (4.4-4.99 gigahertz)
- Payload: Cloudcap Technology payload – TASE T2 day/night payload with laser pointer
- Transponder: Mode 3 identification friend or foe, or IFF
- Precision GPS
- Visible navigation lights
- IR anti-collision lights
- Battery back-up
- Three-axis magnetometer
- Optional laser altimeter
- Avionics power: 18 volts direct current, or VDC
- Payload power: 15 VDC

**For additional information, please contact**
AAI Corporation, 124 Industry Lane
Hunt Valley, MD 21030
800-655-2616
RSC_AAIReg@aai.textron.com

aaicorp.com
aerosonde.com

# Appendix C. Past Science Operations in the Arctic

The following table and accompanying photo are reproduced from the paper titled *Enabling Science Use of Unmanned Aircraft Systems for Arctic Environmental Monitoring* (Crowe et al. 2012) referenced in Section 5.

**Table 8.1.** Science applications, platforms and locations throughout the Arctic where unmanned aircraft have been flown.

| Year | Location / permissions | Science issue / Aircraft | Contact |
|---|---|---|---|
| 1999-2004 | Alaska, USA<br>Local FAA approval | Sea ice characterization / ***Aerosondes*** | Jim Maslanik, Univ. Colorado |
| 2007 | Greenland<br>Greenlandic and Danish CAA | Glacial melt ponds / ***Manta*** | John Adler, NOAA; Betsy Weatherhead, Univ. Colorado |
| 2007 | Icelandic CAA | FLOHOF campaign/***KALI & SUMO*** | Joachim Reuder, Univ. Bergen |
| 2008 | Longyearbyen, Svalbard<br>Norwegian CAA Danger Area & Notam BLOS ops | Polar Lows / ***Cryowing*** | Rune Storvold, Norut |
| 2008 | Part ship-based part Longyearbyen, Svalbard<br>Norwegian CAA | Polar Lows / ***SUMO*** | Joachim Reuder, Univ. Bergen |
| 2008 | Ny-Ålesund, Svalbard<br>Norwegian CAA Danger Area & Notam BLOS ops | Glacier dynamics / ***Cryowing*** | Rune Storvold, Norut |
| 2008 | Ny-Ålesund, Svalbard<br>Norwegian CAA Danger Area & Notam BLOS ops | Polar meteorology/ ***Cryowing*** | Rune Storvold, Norut |
| 2009 | Bering Sea<br>US FAA / safety case allowed 3-5 miles | Ice seal populations / ***Scan Eagle*** | Robyn Angliss, NOAA |
| 2009 | Longyearbyen, Svalbard<br>Norwegian CAA Danger Area & Notam BLOS ops | Boundary layer meteorology / ***SUMO*** | Joachim Reuder, Univ. Bergen |
| 2009 and 2011 | Ny-Ålesund, Svalbard<br>Norwegian CAA Danger Area & Notam BLOS ops | Ice albedo feedback / pollution / ***Cryowing*** | Rune Storvold, Norut; John Burkhart, NILU |
| 2010 | US Arctic<br>US FAA – flew above commercial airspace | Atmospheric chemistry / ***Global Hawk*** | Dave Fahey, NOAA; Paul Newman, NASA |
| 2010 | Summit Camp, Greenland<br>Danish CAA Danger Area & Notam BLOS ops | Ice albedo feedback / pollution / ***Cryowing*** | Rune Storvold, Norut; John Burkhart, NILU |
| 2011 | Ny-Ålesund, Svalbard<br>Norwegian CAA Danger Area & Notam BLOS ops | Ice albedo feedback / pollution / ***Cryowing, Manta, Eleron*** | Rune Storvold, Norut; Tim Bates, NOAA; Sergey Lesenkov, AARI |

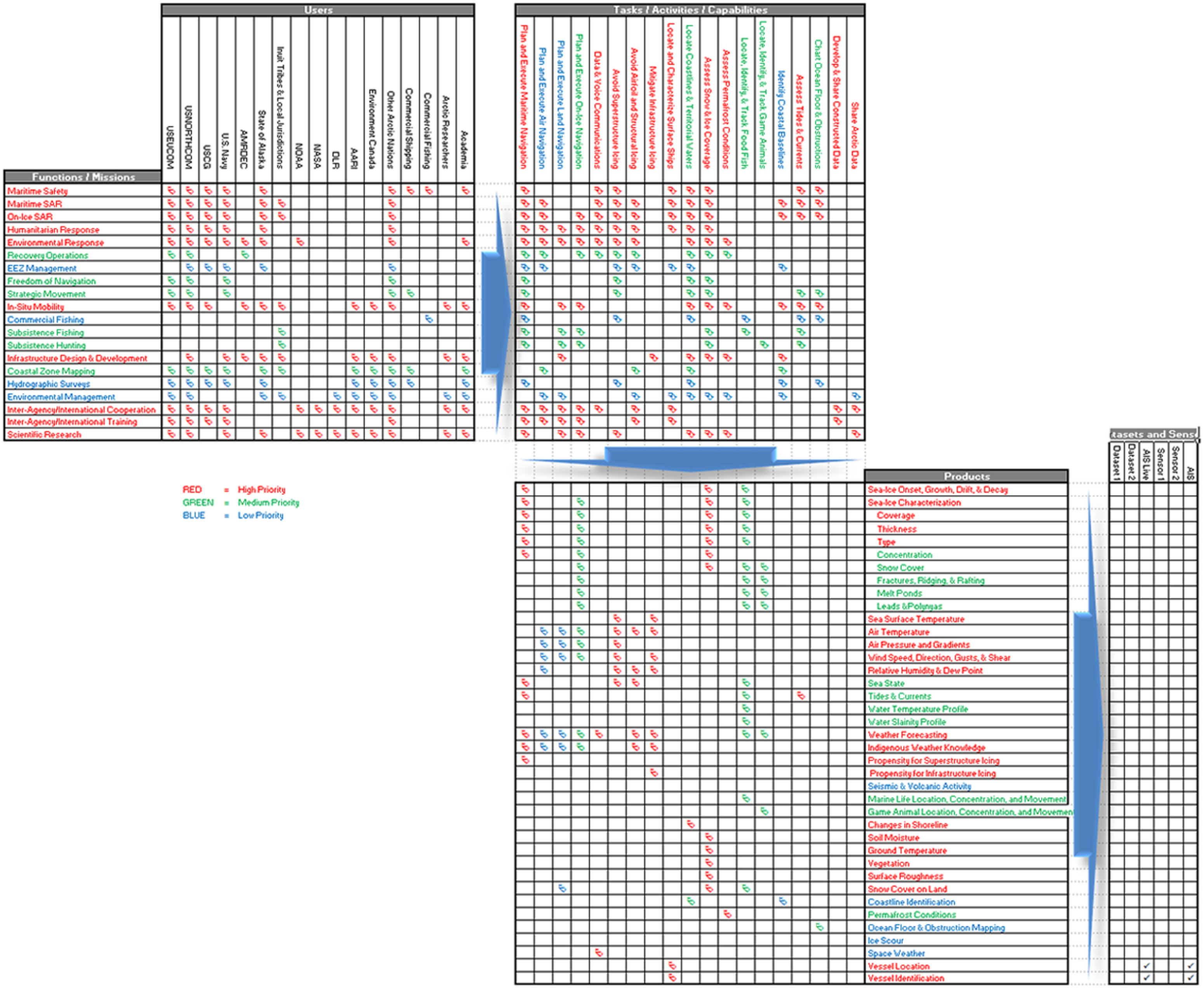
CICCI flight crews in Ny-Alesund, Svalbard in 2011. From left: *Cryowing* Norut (Norway), *Manta* NOAA (USA) and *Eleron-10* AARI (Russia). Photo: Kjell Sture Johansen, Norut.

# Appendix D. Arctic Functional Responsibilities and Geophysical Data Products

The matrix in this appendix is an analysis related to the Arctic Collaborative Environment (ACE) that links mission requirements to data product needs and ranks these by color. Red indicates high priority; green indicates medium priority; blue indicates low priority. The methodology employed in the matrix is implemented via the ACE site on the Internet.[25]

This analysis provides a means to map Department of Defense–related mission requirements to prioritized data products. The Products table lists high-priority atmospheric measurements, the majority of which are basic thermodynamic measurements, such as air temperature and water vapor content. The results of this study are useful in gauging the possible cross-agency benefits of Arctic geophysical measurement programs or campaigns, which is one important goal of interagency programs including the Interagency Arctic Research Policy Committee (IARPC).

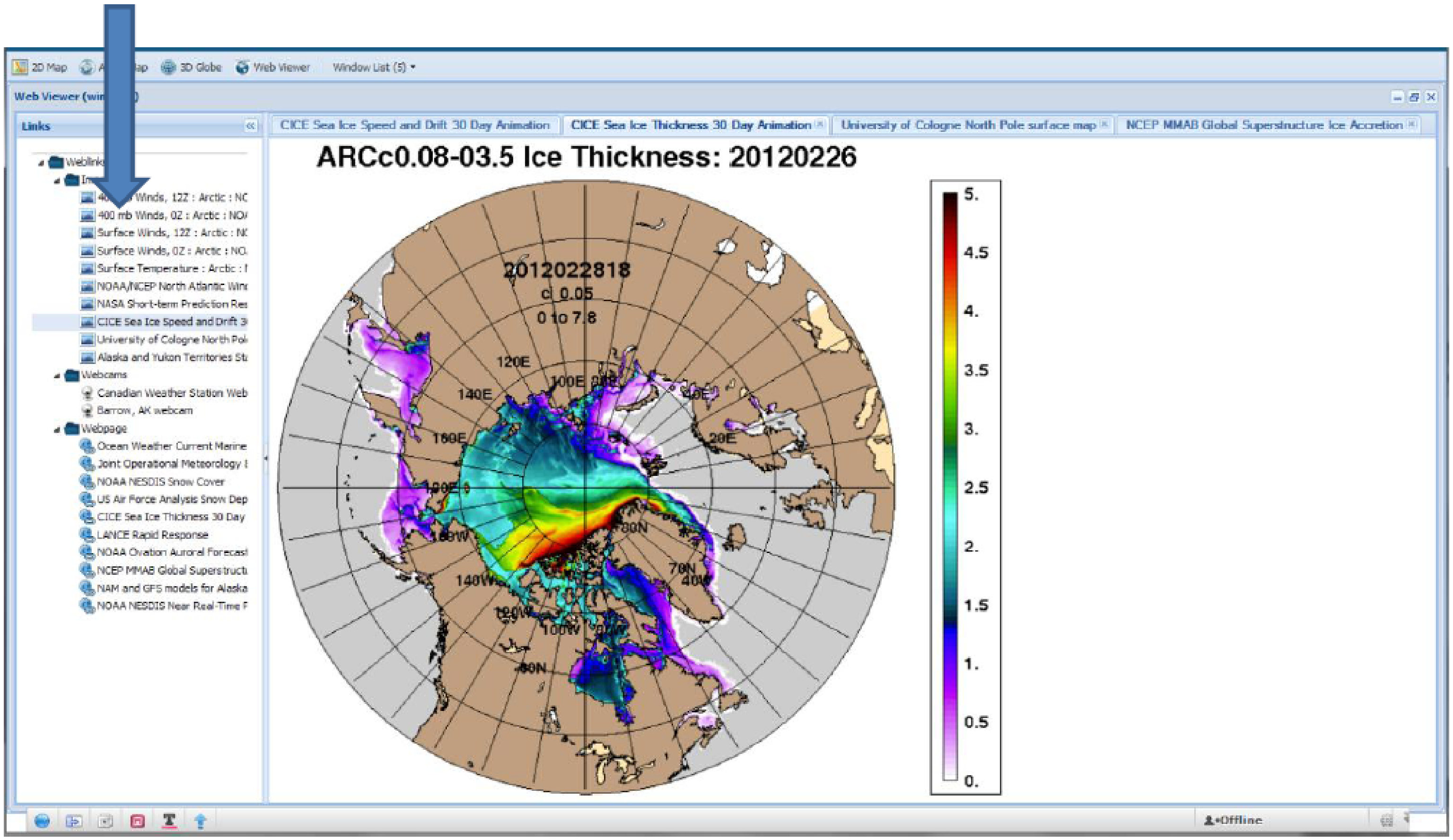
[25] ACE is available at https://ace.arsc.edu/ (accessed on August 7, 2014).




RED = High Priority
GREEN = Medium Priority
BLUE = Low Priority

An example of a product accessible from an ACE web page is shown below.[26]

Sea Ice Thickness (and three other tabs, each with separate data sets)

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26 The above image was copied from the presentation "Arctic Collaborative Environment," dated August 1, 2012, Washington, DC: Arctic Collaborative Environment (ACE) JCTD, Rapid Fielding Directorate.

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