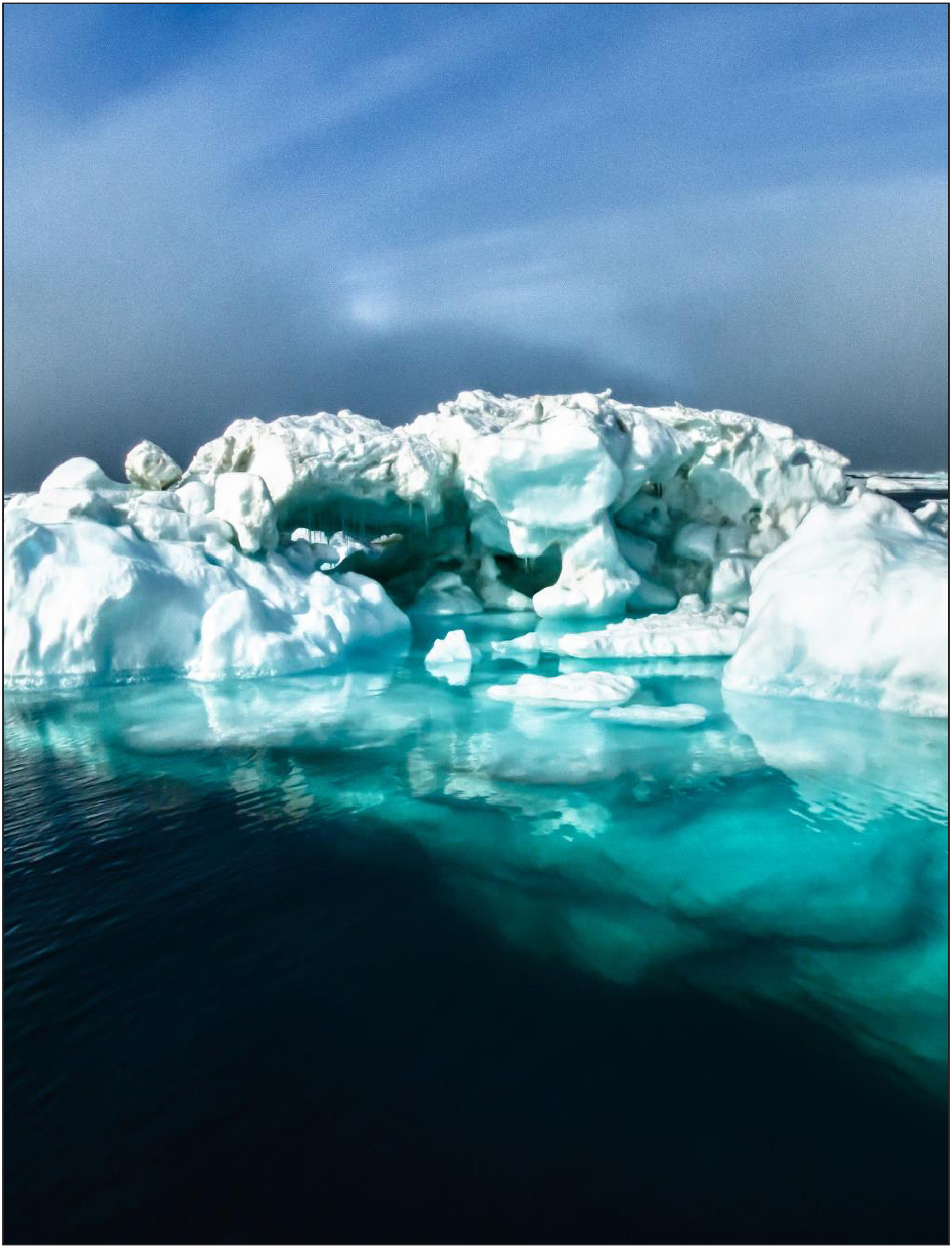
Predicting Arctic Weather and Climate and Related Impacts

Status and Requirements for Progress

Findings from the NOAA Science Challenge Workshop

May 13-15, 2014
NOAA Earth System Research Laboratory
Boulder, Colorado



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This workshop report is submitted to the NOAA Research Council on behalf of the workshop participants and the Workshop Organizing Committee

Randall Dole, on behalf of the Workshop Organizing Committee

September 2014

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Executive Summary

This report summarizes outcomes of the NOAA Science Challenge Workshop *Predicting Arctic Weather and Climate and Related Impacts: Status and Requirements for Progress*. The workshop was held at the NOAA Earth System Research Laboratory in Boulder, CO from May 13-15, 2014. Eighty scientists and science managers from across NOAA, other federal agencies, and academic institutions participated in the workshop. The participants included experts in Arctic science, forecasting and services on the weather, seasonal and climate scales from research, operations, academic and private sectors. There was substantial interagency engagement, with participation from Navy, NSF, the U.S. Arctic Research Commission, and the U.S. Interagency Arctic Research Policy Commission, as well as from the U.S. National Ice Center, the Canadian Ice Service, and Environment Canada.

The workshop focused on steps that NOAA could take together with partners to achieve significant advances in NOAA's Arctic weather and climate forecasts and services from the near-term out to approximately 2020. The participants were asked to: 1) inform NOAA on actions required to address present and anticipated future mission requirements for forecasts of Arctic weather and climate, including sea ice; and, 2) define actions needed to determine relationships between the Arctic and lower latitude weather and climate variability and their predictive implications. Participants were challenged to identify primary mission drivers for forecasting improvements, outstanding needs and gaps, priority opportunities, partnerships, and actions needed to achieve forecast and services advances.

Overarching recommendations from the workshop are to:

- **Focus intensive efforts on improving sea ice forecasts —** Sea ice forecasts are critically important for NOAA services and stakeholders. Sea ice is central to many Arctic hazards, and also strongly influences other Arctic weather and climate phenomena such as extreme Arctic storms and their coastal and marine impacts. Due to the tightly coupled nature of the Arctic system, improving sea ice forecasts requires improvements in observations, process understanding and modeling of the coupled atmosphere-ocean-ice system. NOAA needs to coordinate its efforts in these areas to achieve optimal advances. Strengthening partnerships with Navy and other federal agencies and through international bilateral and multilateral fora will help accelerate progress.
- **Participate vigorously in the WMO WWRP Polar Prediction Project (PPP), particularly in efforts related to the Year of Polar Prediction Project (YOPP) —** NOAA needs to develop an action plan now for coordination with and involvement in PPP/YOPP, planned for 2017-19. In

addition, an international field campaign, MOSAiC, has been proposed for 2018 to develop understanding of ice-atmosphere-ocean processes and interactions in the rapidly changing Arctic. MOSAiC is being coordinated with YOPP. This campaign is being designed to improve Arctic predictions, particularly of sea ice. NOAA would benefit from engaging strongly in MOSAiC to achieve understanding necessary to improve its sea ice forecasts.

- **Continue to develop an Arctic Testbed —** This NOAA testbed will integrate and synergize high-impact Alaskan and Arctic forecast improvement activities. Connections with federal and state partners, industry, external stakeholders and Canada should be pursued. The development, evaluation and validation of Arctic and user-focused metrics through the Arctic Testbed would provide substantial benefits efficiently and at relatively low cost.
- **Enhance observing system capabilities to meet the diverse and growing needs for Arctic environmental forecasts and related services —** Specific observing system priorities are problem-dependent, but several crosscutting actions are suggested. Taking better advantage of existing observations is critical, with improvements in data assimilation being one means to do this. Several satellites relevant for Arctic predictions will be launched over the next few years. NOAA needs to act to ensure the optimal use of these data. Improving the forecast models will also require full use of other observing sensors and techniques including airborne, surface and subsurface platforms.
- **Focus modeling efforts on the development and application of coupled atmosphere-ocean-ice-land models —** Research will be necessary to obtain the process-level understanding required to address current sources of model errors. Specific deficiencies were identified that cut across weather and climate predictions; e.g., Arctic clouds. While this workshop focused on hourly to seasonal predictions, many of the modeling challenges confronting weather and seasonal climate predictions are also common to models used in decadal climate predictions and climate change projections. Addressing these common challenges will convey broad benefits. NOAA needs to take advantage of the existing North American Multi-Model Ensemble (NMME), with a targeted focus on assessing model predictions in the Arctic region.
- **Advance understanding of Arctic-lower latitude linkages and their implications for weather and climate predictions —** New international research projects and ongoing assessments synthesizing present understanding of Arctic-midlatitude linkages provide opportunities for NOAA to conduct and coordinate research with partners to better understand the predictive implications of Arctic-lower latitude linkages. NOAA needs to coordinate and provide access to observational and model

data sets, including model experiments, that would support research to evaluate potential mechanisms for Arctic lower-latitude linkages and their predictive implications. To accelerate advances in NOAA's prediction services, NOAA would benefit from making versions of its operational models more easily and widely available for research purposes, similar to the NCAR Community Earth System Model paradigm. This would allow a much broader community than at present to address questions on Arctic-lower latitude linkages, as well as other key questions related to predictability and model sensitivity. Such a step would also provide new opportunities for diagnostic research and model development directly relevant to NOAA's operational models and forecast services.

Finally, this workshop focused on steps needed to improve predictions of the physical system, emphasizing the atmosphere, ocean and sea ice. NOAA would also benefit from additional focused science challenge workshops on the connections between physical, chemical and biological predictions, such as those relevant to fisheries and marine resource management, and on related social science challenges that would further support NOAA's mission.

1 Introduction

Recent changes in the Arctic have been among the most striking in the world, with profound consequences for inhabitants and ecosystems in the region. Changes within the Arctic do not occur in isolation. In particular, questions on possible links between Arctic warming, loss of sea ice and mid-latitude weather and climate extremes have emerged as subjects of intense scientific and public interest. The changes in the Arctic and possible connections with mid-latitude weather and climate variations have large and growing implications internationally, nationally, as well as for NOAA.

Within the context of a rapidly changing Arctic, NOAA's environmental prediction and stewardship missions are seeing increasing needs for Arctic services. Marine transportation, mineral, oil and gas extraction, state and federal partners, indigenous populations and marine resource management are all increasingly dependent on NOAA predictions and services. Meeting these needs will require that NOAA build from its rich history in Arctic research and services, and, in particular, its mandates for weather, climate and marine predictions that extend into the U.S. Arctic and beyond.

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In recognition of NOAA's mission in providing environmental intelligence to meet the needs of stakeholders, this NOAA Science Challenge workshop was convened to inform NOAA on actions that the agency could take together with partners to address present and anticipated new requirements for predictions of Arctic weather and climate and related impacts, including Arctic-lower latitude linkages and their implications for NOAA's forecasts and services. To complement the specific focus of this workshop on predictions of the physical system, NOAA would benefit from additional Arctic-focused science challenge workshops that explore interactions between physical, chemical, biological and social processes.

The recommended actions contained in this report address high priority goals identified for the nation in *An Interagency U.S. Implementation Plan for the National Strategy for the Arctic Region* (NSAR, 2014), and for *NOAA in NOAA's Arctic Strategy and Vision* (ASV, 2011) and *NOAA's Arctic Action Plan* (AAP, 2014). In particular, these actions will contribute to achieving four of the six Arctic strategic goals identified in NOAA's ASV and AAP: Forecast Sea Ice; Improve Weather and Water Forecasts and Warnings; Strengthen Foundational Science; and Enhance International and National Partnerships.

1.1 Workshop Focus

This workshop focused on the following prediction problems:

1. Predictions of Arctic weather and climate, including sea ice.

The changes in the Arctic, and possible connections with mid-latitude weather and climate variations, have large and growing implications internationally, nationally, as well as for NOAA.

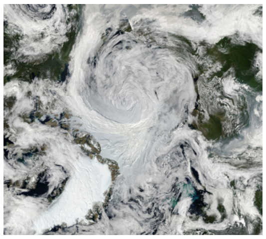
2. Predictions of mid-latitude weather and climate, focusing on the role of higher latitude processes such as variations in Arctic sea ice and the North Atlantic/Arctic Oscillation.

Sea ice predictions were included explicitly in both weather and climate predictions, and were implicit in discussions of Arctic-midlatitude linkages as well. This workshop emphasized predictions on hourly to seasonal time scales, while recognizing that physical processes in the Arctic affecting these time scales are often also crucial to more slowly evolving climate variations and changes. Because of this, actions aimed at improving models used for weather and seasonal climate predictions also contribute to improvements in models used for longer climate predictions and climate change projections. This workshop also emphasized actions that could be taken from now out to approximately 2020, corresponding to a typical time horizon of an implementation plan.

1.2 Participants and Support

Eighty scientists and science managers from across NOAA, other federal agencies, and academic institutions participated in the workshop (Appendix 1). The participants included experts in Arctic observations, processes, modeling and services from research, operational, and academic sectors. There was substantial interagency engagement, with representation from Navy, NSF, the U.S. Arctic Research Commission (USARC) and the Interagency Arctic Research Policy Commission (IARPC), as well as from the U.S. National Ice Center, the Canadian Ice Service, and Environment Canada. NOAA NWS, NESDIS, NOS and OAR representatives participated at the workshop, and all these lines as well as NMFS contributed to the workshop planning. The Assistant Administrators' Climate Board coordinated the workshop funding, with all of the above line organizations providing logistical and travel support. The University of Colorado/CIRES co-hosted the workshop and provided local support. Participants from other agencies, interagency programs, operational prediction centers and international research programs helped define potential roles and objectives for NOAA in relation to external partners, national and international research programs.

2 Overview and Breakout Group Recommendations



The Workshop was organized to maximize actionable recommendations. Subject matter experts provided initial overview presentations in plenary sessions on key drivers, science and services challenges and opportunities. Breakout groups then developed further analysis of the challenges and opportunities, as well as recommendations for actions required for progress. Appendix 2 provides the workshop agenda. Presentations from the workshop are available at www.esrl.noaa.gov/psd/events/2014/arctic-predictions-science/agenda.html

This rest of this section provides an overview of plenary presentations and breakout group recommendations, with the next section synthesizing this information into overarching recommendations.

2.1 Plenary Presentations

2.1.1 The Drivers: US and NOAA Requirements for Advancing Arctic Predictions

Introductory session presentations by David Titley and Mendal Scott Livezey focused on major factors driving present needs to improve Arctic weather and climate predictions now for the U.S. and particularly for the U.S. Navy, a key NOAA partner. David Kennedy provided a cross-NOAA perspective on NOAA imperatives, drivers and service needs, Ming Ji followed with a NWS Arctic operational forecast perspective on needs and actions, and Aimee Devaris concluded with a “boots on the ground” perspective from the NWS Alaska Region.

A common theme across these presentations was the importance of improving sea ice forecasts, a challenge made increasingly urgent by the rapid decline in Arctic sea ice and resulting implications for impacts. Predicting Arctic storms is another outstanding challenge, particularly in summer and fall when sea ice has retreated from the Alaskan coast, making coastal communities more vulnerable to storm surges and coastal erosion. Because many impacts depend on combined conditions of sea ice, weather, and water, predictions must be fully integrated into coastal and marine services. Stakeholders are very diverse and highly dependent on a broad spectrum of weather and climate products and information. Sectors with especially strong needs include marine shipping and transportation, coastal communities and subsistence hunting, fishing activity, national security, and search and rescue operations. Improved weather and climate forecasts are now becoming increasingly critical to better anticipate and reduce risks related to offshore energy extraction. For risk management, probabilistic forecasts are vital.

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On weather time scales, forecasts of Arctic clouds and intense summer and fall Arctic cyclones, as well as extended range storm outlooks, remain significant challenges.

2.1.2 Scientific Foundations for Improving Predictions

The second session focused on scientific foundations for improving predictions. John Walsh described challenges for improving Arctic weather and climate predictions, Judah Cohen presented evidence on possible Arctic-lower latitude linkages, and Marika Holland discussed factors related to sea ice predictability. On weather time scales, forecasts of Arctic clouds and intense summer and fall Arctic cyclones affecting Alaska, as well as extended range storm outlooks, remain significant challenges. Major challenges for seasonal forecasts are predictions of impact variables, with seasonal variations in sea ice, Alaskan wildfires, and times of river breakup being of particular interest. Links between sea ice and snow cover variability, tropospheric-stratospheric variability and the Arctic Oscillation have been identified over the past decade, but understanding of causal mechanisms is limited. Improvements in seasonal climate predictions are possible through advances in modeling of atmosphere-ice-snow coupling and troposphere-stratosphere interactions. Idealized studies of sea ice predictability suggest potential predictability of up to 1-2 years, depending on season. This contrasts with the much more limited skill currently being achieved in operational models. Results suggest that sources for extended predictability depend on season. Overall, the presentations reinforce the need for predictability research and model sensitivity studies to identify where improvements in observations and models are likely to yield greatest benefits.

Major seasonal forecast challenges include predictions of impact variables such as sea ice, wildfire, and river ice breakup.

2.1.3 Operational Predictions: Status, Challenges, and Requirements for Progress

It is critically important to develop fully coupled atmosphere-ocean-ice-land models that capture fine scale details in observations and models in the Arctic, and take maximum advantage of available data through coupled model data assimilation.

Presentations by Robert Grumbine of NOAA, Richard Allard of Navy, Caryn Panowicz and Benjamin Zib of the U.S. National Ice Center, and Hal Ritchie of Environment Canada summarized the current status and plans for operational predictions. Presentations indicated common service needs and challenges across the operational centers. Ice edge location is extremely important for general transit and search and rescue operations, with forecasts requiring high spatial resolution in and around the marginal ice zone in both observations and models. There are major biases and drifts in NOAA sea ice predictions, leading to rapid loss of predictability. There is a strong need to develop common forecast skill metrics for sea ice. Overall conclusions reinforce the importance of developing fully coupled atmosphere-ocean-ice-land models, capturing fine scale details in observations and models in the Arctic, and taking maximum advantage of available data through coupled model data assimilation. There is also a strong need to develop sea ice and other metrics for model verification and evaluation.

2.1.4 International and National Partnership Opportunities

The final session considered international and national partnership opportunities. Chris Fairall described two major new international opportunities: the

World Weather Research Programme Polar Prediction Project (PPP), which includes the Year of Polar Prediction (YOPP), and a planned field campaign Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC).

PPP is a decadal international research project to improve weather and environmental prediction services for polar regions on hourly to seasonal time scales. PPP flagship themes are: 1) Sea Ice prediction; 2) Polar-lower latitude linkages; 3) Polar observations and 4) the Year of Polar Prediction (YOPP). YOPP is planned for mid-2017 to mid-2019. It will have intensive observing periods, dedicated model experiments, research in the use and value of forecasts, intensive verification efforts, and a summer school. Information on PPP and YOPP plans is available at polarprediction.net.

MOSAiC is a field experiment being coordinated with PPP/YOPP, and is planned to occur in 2018. MOSAiC is intended to provide a process-level understanding of the new central Arctic climate system, which contains dramatically less and thinner ice than during the Surface Heat Budget in the Arctic (SHEBA) experiments that occurred 20 years earlier. A manned, trans-polar drifting observatory has been proposed as a central hub for intensive observations of atmosphere, ocean and sea ice over the course of at least a year. MOSAiC is being designed to collect information through a full annual cycle necessary to improve models used in weather, climate, and sea ice predictions. More information on MOSAiC can also be obtained at polarprediction.net.

John Farrell described interagency processes and mechanisms. USARC and the Interagency Arctic Research Policy Committee (IARPC) are coordinated through the White House (OSTP and OMB). USARC's duties include developing a national Arctic research policy and facilitating Arctic research cooperation with IARPC. Several research themes identified in the U.S. Arctic Research Plan are highly relevant to this workshop. There are IARPC interagency Implementation Teams in areas directly related to this workshop. Recommended NOAA actions are to: 1) Continue and enhance participation in IARPC collaboration teams; 2) Develop better understanding of users of Arctic weather and climate predictions; 3) Keep abreast of other developments like the National Ocean Council and Arctic Council; and 4) Constructively address the "polar vortex" issue because the links between the Arctic and mid-latitudes are important.

Dan Eleuterio of ONR gave an overview of the National Earth System Prediction Capability (ESPC) Project. ESPC is an interagency collaboration involving Navy, Air Force, NOAA, DOE, NASA and NSF. The project seeks to improve global prediction of weather, ocean and sea ice conditions at weather to short-term climate variability time scales. Achieving this capability requires development of seamless Earth System models. Eleuterio also described related efforts supported under the ONR Arctic Research Program, which has as its major thrusts observing technologies, physical understanding and development of fully integrated Arctic System Models. These thrusts align well with NOAA interests, providing a strong basis for collaboration to accelerate observations and forecast improvements.

Julienne Stroeve described another interagency-supported project, the Sea Ice Prediction Network (SIPN). SIPN aims are to: coordinate and evaluate seasonal sea ice predictions; integrate, assess and guide observations; synthesize predictions and observations; and disseminate predictions and engage key stakeholders. A critical need for SIPN is to interact with the modeling community to obtain guidance from predictive models on the best observing strategies, that is, what observations are needed and where they are most needed to improve predictive skill. More information on the SIPN is available at www.arcus.org/sipn.

Barbara Brown of NCAR concluded the session with a presentation on forecast evaluation and user-focused verification. Forecast verification is essential for monitoring performance and measuring progress. New model metrics will be needed for Arctic predictions, such as for sea ice, as well as metrics that are relevant to users. The Arctic Testbed provides an opportunity to bring together metric development and conduct user-focused verifications that may be especially critical in the Arctic region.

2.2 Breakout Groups

Breakout groups were organized on three classes of prediction problems: Arctic Short-term Weather and Hazards Predictions; Arctic Climate Predictions; and Arctic-Lower Latitude Linkages. There were two groups each for weather and climate predictions, which helped to keep groups sufficiently small to be interactive while allowing for diverse perspectives. Each of the five breakout groups had three co-leads, one from NOAA services, one from NOAA research, and one from outside NOAA, to ensure that the various perspectives were all represented. The groups operated completely independently and approached their analyses in very different ways. All groups were asked to begin their discussion from a services perspective, and then address foundational requirements (observations, process understanding, models) and strategies (partnerships, services development, metrics) necessary to achieve improvements. Each group produced a highly summarized set of bullets, with format and approaches differing considerably. The raw output of the groups is provided at www.esrl.noaa.gov/psd/events/2014/arctic-predictions-science/agenda.html. The group reports should be consulted for detailed recommendations on specific challenges.

The groups were also asked to summarize the three highest priority needs for actions that they had identified. The following tables provide a subset of priorities from groups for each of the three classes of problems.

2.2.1 Recommendations: Arctic Short-term Weather/Hazards Predictions

Need	Solution	Metrics	Partners/POC
Better ice information for numerical weather prediction (NWP)	Improved initialized ice concentration data for RAP weather forecasts	RAP running with full ice concentration data experimentally at GSD 2015; operationally at NCEP 2016	NIC, GSD, NCEP, CIS
Better atmospheric information for Arctic NWP	Incorporate more cloud and moisture observations to improve model initializations including satellite, commercial aircraft data	Experimental improved cloud initialization using polar orbiters in RAP 2016; assessment report published 2017 (NWS-AR & GSD)	FAA, NESDIS, OAR, NCEP, MSC, NWS-AR, GSD
Improved sea ice model and coupled model forecasts to predict snow and ice	Coupled air-ocean-ice-wave-land model that takes maximum advantage of observations. Run coupled slab ocean-atmosphere-ice model now to assess sensitivity of weather forecasts to coupling	Satellite and buoy data assimilated into models Satellite retrievals validated Improved spatial and temporal cover of in situ and remote observations Sensitivity results published	NCEP, ONR, PPP, MSC, GSD, NASA, ESRL, academic community
Improved coastal storm forecasts for surge, flood, and inundation	Migrate, adapt models developed for the CONUS, increase tide/water level gauges, update DEMs	Published assessment of applicability of models to Arctic Improvements incorporated into models	NOS, NHC, UND, AOML, MSC, NCEP
Improved short-range forecasts of sea ice characteristics, freeze-up, break-out, edge, flash freezes, bergs, etc.	Generate fast ice, ice edge, and MIZ masks. Add fast-ice buoys, seismic arrays Improve bathymetry Assimilate enhanced data into models. Run RAP ensemble in Alaska	Masks developed DEMs updated Fast ice observations increased Observations assimilated into sea ice models Fast ice incorporated in sea ice models	NOS, OMAO, NIC, MSC, UAF, UW-IABP, UCSD/IRIS, academic community
Higher resolution marine/aviation forecasts for ceiling, icing issues for aircraft, ships, & structures	Better representation of the marginal ice zone (MIZ) in sea ice models; cloud microphysics; in-line Chemistry model included in HRRR; targeted process study field studies	Improved parameterizations for stable BL, sea spray, cloud microphysics incorporated into NOAA models for predictions.	FAA, MSC, NCEP, ESRL, NCAR, DOE, ONR, USCG, academic community
Observations in critical regions, e.g., around the marginal ice zone	Outreach to end users to receive and send data and information, e.g., community-based weather and sea ice observations	Increase in observations incorporated into forecasts and warnings and assimilated into forecast models	NWS-AR, Regional Team, native communities, fishing fleets, oil/gas companies, etc.

2.2.2 Recommendations: Arctic Climate Predictions

Needs	Solution	Metrics	Partners/POC
Assessment of Arctic climate predictability	Model sensitivity studies for the Arctic. OSSEs for observing system design.	Peer-reviewed publications.	OAR, NCEP, other agency and academic community
Improved monthly to seasonal sea ice predictions	Better use of upper ocean and ice thickness information for ice freeze forecasts, ice thickness for summer forecasts	Model performance for forecasting freeze-up on seasonal scale. Skill improvements in summer sea ice forecasts.	NIC, GSD, NCEP, CIS SIPN, academic community
Estimates of uncertainty in multi-model performance for the Arctic	Assess NMME performance in Arctic.	Publication of assessment.	OAR, NASA, NCEP, NCAR, academic community
Better use of observations	Use observations from ships of opportunity; develop instruments for ice-covered waters	Observations assimilated into NOAA prediction models	OAR, NASA, NCEP, ONR, NCAR, and academic partners
Improved process understanding for model improvement	NOAA participation in YOPP and field studies to obtain process-level observations and research	Peer-reviewed publications. Transition to operations of improved parameterizations.	OAR, NCEP, NCAR, ONR, academic community
Improved understanding of Arctic cloud impacts	Initiate a Climate Process Team focused on mixed phase clouds	Peer-reviewed publications. Transition to operations of improved parameterizations	OAR,NCEP, other agency and academic community
Increased access and use of data	Coordinate NOAA observation and data management groups contributing to the Arctic Observing Network and PPP. Include ecology, biology and physical data on characteristics of the Arctic Ocean	Increase in data used and accessible to end users Contributions to GEO Arctic-BON	NCDC, cross-NOAA groups
Partnerships to increase data availability	Continue the process of establishing MOUs with commercial partners	MOUs established. Data acquired.	NOAA, NWS Alaska Region, commercial partners

2.2.3 Recommendations: Arctic-Lower Latitude Linkages

Needs	Solution	Metrics	Partners/POC
Assessment of the viability of proposed mechanisms for Arctic-lower latitude linkages.	Research to perform rigorous hypothesis testing. Sensitivity studies to assess whether specific deficiencies limit current models from reproducing proposed linkage mechanisms.	Peer-reviewed publications.	NWS, OAR PMEL, ESRL/PSD, GFDL academic and external research community
Assessment of the predictive implications of Arctic-lower latitude linkages	Research on predictive implications of linkages	Peer-reviewed publications. Assessment initiated on the predictive implications of linkages, focusing on Alaska and surrounding regions and the contiguous US. Assessment completed.	NWS, ESRL/PSD, other NOAA and academic and external research community
Increased availability of model and observational data to accelerate research on Arctic-lower latitude linkages	Implement a “Linkages Diagnosis” Portal, providing access to model output, reanalysis data, archived forecasts, web links to in-situ data and tools for exploring relationships. Initiate access to data from ESRL model experiments.	Portal implemented. Number of external users employing portal or model experiments for linkages research.	OAR, ESRL/PSD, NWS
Increased use of NOAA operational prediction models in research settings.	Develop and make accessible versions of NOAA operational prediction models for research purposes, similar to NCAR CESM approach.	Increase in number of users employing NOAA operational models for research.	NWS, OAR, external community

3 Overarching Recommendations

The overarching recommendations synthesize information obtained from presentations, breakout groups, and plenary discussions. They emphasize crosscutting actions that, if taken, are expected to lead to forecast and services advances in several areas.

3.1 Focus intensive efforts on improving sea ice forecasts

Participants emphasized the critical need for NOAA to develop its sea ice capabilities and services.

Improved sea ice forecasts would benefit the Alaskan economy and communities, natural resources and ecosystems management, transportation, and marine safety.

Participants emphasized the critical need for NOAA to develop its sea ice forecast capabilities and services. At this time, the NWS provides sea ice information and forecasts from weather through climate timescales to support decision-making related to life and safety for stakeholders in the public (e.g., US Coast Guard) and private sectors. NOAA now produces daily sea ice analyses in various formats and scales to meet operational, tactical, and planning needs, in addition to short-term, monthly and seasonal sea ice forecasts, primarily to support Alaska's coastal communities and marine transportation. Improved sea ice forecasts would benefit the Alaskan economy and communities, natural resources and ecosystems management, transportation, and marine safety. Improvements in sea ice forecasts and services for weather and climate require a coordinated approach that includes advances in and commitment to sustaining ice, ocean, atmosphere, and wave **observations**; field studies that focus on gaining **process understanding to improve modeling** of the coupled atmosphere-ocean-ice-wave system, including the Arctic's large river inflow areas; development of **an operational coupled atmosphere-ocean-wave-sea ice forecast model** and ensemble numerical guidance; and the development and delivery of useful and usable **products to stakeholders**, including enhanced short range Alaska Region sea ice forecasts and seasonal outlooks for melting and freezing times. In order to achieve these goals, many specific actions were identified by breakout groups.

Some recommendations are:

- Sustain current Arctic measurements and commit to new, needed observations that support ice, ocean, atmosphere, and wave measurements in support of analysis, forecasting, verification, and evaluations of coupled model output.
- Participate vigorously in the WWRP/PPP on activities related to sea ice prediction, including observational and model experiments and evaluation during YOPP.
- Participate in MOSAiC.

- Establish foundational components of a Regional Operations Center and Arctic Testbed to strengthen NOAA's ability to be responsive to emerging service requirements in the Arctic and leverage new science and technology capabilities.
- Develop improved sea ice prediction metrics, possibly through the Arctic Testbed, and in collaboration with other agencies and centers.
- Contribute to and take maximum advantage of ongoing coordinated efforts on sea ice predictions, such as the SIPN.
- Develop and expand product suites with new and more frequent ice services.
- Integrate new satellite-derived sea ice information into National Ice Center operations, such as ice thickness, ice concentration, and size of leads in ice.
- Improve snow depth, snow cover, ice cover, and ice thickness analysis for operational model initialization or assimilation.
- Conduct coordinated calibration and validation of satellite measurements of the cryosphere through in-situ and airborne missions in collaboration with national and international partners.
- Foster and coordinate partnerships related to sea ice predictions, services, and applications across NOAA, including NWS/NCEP; NWS Alaska Region; OAR Labs and Programs, GFDL, GLERL, ESRL, PMEL, CPO; NMFS; and the U.S. National Ice Center; with other federal agencies via mechanisms such as the Interagency Arctic Research Policy Committee, United States Global Change Research Program, and National ESPC; entities within the State of Alaska; and with international bodies such as the Arctic Council and WCRP/CLIVAR and WMO/PPP.

The WMO Polar Prediction Project and the WCRP Polar Climate Predictability Initiative offer unique opportunities to leverage major international collaborative activities and resources to help NOAA advance its polar predictions.

3.2 Participate Vigorously in the WMO WWRP Polar Prediction Project (PPP), Particularly Related to the Year of Polar Prediction Project (YOPP)

The WMO Polar Prediction Project (hours-to-seasonal) and the WCRP Polar Climate Predictability Initiative (seasonal-to-decadal) offer unique opportunities to leverage major international collaborative activities and resources to help NOAA improve its polar predictions. PPP is intended as a 10-year research effort to guide development of operational polar predictions. Flagship themes in the PPP research goals include improving sea ice prediction information and services; improving knowledge of linkages between polar and lower latitudes; and optimization and improved availability of polar observations. These themes map perfectly to those identified in the NOAA Science Challenge Workshop.

PPP's goal is to achieve end-to-end improvements in polar prediction services from observations to societal applications on hourly to seasonal time scales. PPP engages and helps coordinate national modeling and process-oriented research into a larger, more integrated and comprehensive international effort to accelerate development of environmental predictions in polar regions. The major PPP coordinated effort will be the Year of Polar Prediction (YOPP) – a massive modeling and observational data archiving effort that will provide the underpinning for much of the model research. Details about PPP (goals, Science Steering Group, Science and Implementation plans, YOPP plans) can be found at www.polarprediction.net/about-ppp.html. PPP will also coordinate several international process studies for YOPP. For example, the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) is a multi-year drifting Arctic ice station with atmospheric, oceanic, and ice observations planned for the 2017-2019. MOSAiC is a modernized version of the Surface Heat Budget of the Arctic (SHEBA) project conducted for one year in the late 1990s. SHEBA is the most comprehensive and most cited Arctic field program conducted to date. MOSAiC is being aligned as a significant component of the overall YOPP and as the primary Arctic sea-ice process study of the YOPP.

The case for NOAA's engagement in PPP/YOPP was called out by all five breakout groups.

The case for NOAA's engagement in PPP/YOPP is so compelling that it was called out by all five breakout groups. Benefits to NOAA are apparent from NCEP's short-term plans for sea-ice forecasting to plans to engage in the NMME and ESPC. The societal applications research will directly benefit the NWS Alaska regional office, where the complexities of bringing forecast products to highly varied user groups are well known. Research on observational technology, data assimilation, satellite retrievals, and observing systems all fall within NOAA's mandate for environmental observations.

Some specific recommendations are that:

- NOAA needs to engage strongly in YOPP. It should consider hosting a data/model archive. There are clear roles for NWS, NESDIS, and OAR.
- NOAA would benefit from engaging strongly in MOSAiC. This includes providing NOAA's unique process observational assets (research vessel, research aircraft, UAS) and augmenting NOAA's contribution to the U.S. Interagency Arctic Buoy Program with strong participation by NOAA's environmental research laboratories.
- NOAA needs to develop plans for an enhanced Arctic Testbed that can respond effectively to activities in and results from YOPP.
- NOAA should consider a comprehensive Arctic research and development initiative built around PPP.

3.3 Continue to Develop an Arctic Testbed

Testbeds, such as the Joint Hurricane Testbed (Miami, FL) and the Hazardous Weather Testbed (Norman, OK) have been highly effective in meeting unique or pressing science and service challenges for the NWS. NWS Alaska Region leadership has developed plans for a significant enhancement to operational capabilities in Alaska to address the emerging requirements of the Arctic: An Arctic Testbed.

Historically, the complexity of forecast operations and the inherent challenges in Alaska have not been addressed well by the Research and Development programs, and projects that support the CONUS regions of the NWS. The Arctic Testbed is an appropriate setting to address mitigation science and technology gaps as well as major forecast challenges:

A NOAA Arctic Testbed will provide a crucial nexus for ensuring NOAA's developers understand Alaska's needs, improve NOAA's responsiveness to its Arctic-related science and service priorities among the NWS and OAR , and better leverage other research initiatives and data sources external to NOAA.

- Scarcity of in situ observations (e.g., wave, ocean, and ice buoys, weather observation platforms, river gauge) in the Arctic.
- Related to these observational gaps, numerical weather, water, ocean and wave prediction model performance concerns in the Arctic region as compared to the rest of the US.
- The lack of maturity of tactical and medium range sea ice modeling capabilities.
- Weather, water, ocean and wave, and sea ice forecasting gaps in the Arctic as well as coupled forecast challenges.

In addition to the science and technology gaps, there are unique service challenges in the Arctic. Emerging requirements from marine transportation, mineral and oil/gas extraction, state and federal partners, and indigenous populations necessitate an evolution in service delivery. The NWS Alaska Region will utilize the testbed to develop useful products and delivery mechanisms to communicate current and forecast weather as well as sea ice and climate information with associated marine and coastal impacts including surge, inundation, and Arctic storms to enhance decision making among Arctic customers and stakeholders.

In the past, innovation and evaluation of new techniques and products in the NWS Alaska Region were performed within the operational environment. This practice tended to stress operational resources, often led to inadequate testing and evaluation as well as the delivery of immature technologies and products. The Arctic Testbed will address these deficiencies as well as address national, NOAA and NWS goals in the Arctic.

Specific recommended actions are for the NOAA Arctic Test Bed to:

- Provide input to the Arctic Report Card

- Partner with, and leverage ongoing NESDIS Satellite Proving Ground activities as well as other NOAA Testbeds and Proving Grounds
- Formalize collaboration and coordination with other federal agencies with similar goals (e.g., BOEM, USACE, USGS, DOE, USCG , FAA) as well as other NOAA line offices
- Provide direct and meaningful partnership with stakeholders such as the Alaska native communities and tribal councils
- Provide input to science-based decision-making and adaptive planning guided by ongoing research and monitoring
- Work with partners to develop, evaluate and validate prediction and user-focused metrics of particular importance to Alaska and the Arctic region.

A NOAA Arctic Testbed will provide a crucial nexus for ensuring NOAA's developers understand Alaska's needs, improve NOAA's responsiveness to its Arctic-related science and service priorities among the NWS and OAR (CPO and ESRL), and better leverage other research initiatives and data sources external to NOAA which are particular to the polar region (e.g., WWRP Polar Prediction Project).

NOAA has strong interests in observations for monitoring current conditions and long-term trends, and supporting improvements in process understanding and operational forecasts.

3.4 Enhance Observing System Capabilities to Meet the Diverse and Growing Needs for Arctic Environmental Forecasts and Related Services

The polar regions are among the most sparsely observed parts of the globe by conventional observing systems such as surface meteorological stations, radiosonde stations, and aircraft reports. The polar oceans are also sparsely observed by the Argo array of automated profiling floats, implying problems in coupled forecasting. The polar regions are barely sampled by geostationary satellites, although they generally have a denser sampling by polar-orbiting satellites. Using satellite-based observations of the polar surface is still challenging, partly due to the ever-changing and highly heterogeneous snow/ice covering along with the presence of cloud cover. The relative remoteness and harsh environmental conditions of the Arctic will continue to pose challenges to our observing capabilities. Improvements in technology and power systems will help us address some of the observing barriers, although access to required funding will likely pose an additional constraint.

The workshop participants emphasized that NOAA has strong interests in observations for monitoring current conditions and long-term trends, and supporting improvements in process understanding and operational forecasts. Specific observing system priorities are problem-dependent, but a number of common actions were suggested. Given the sparseness of current observations, taking better advantage of existing observations was emphasized. One means to do this is through development of improved data assimilation capabilities. Development of an Arctic system analysis capability would enable diverse observations to be integrated into a state-of-the-art model to reduce uncertainties in present conditions and establish an improved baseline for validating weather and climate models. Development of a corresponding reanalysis capability would enable improved estimates to be made of how the Arctic system is changing over time.

Several satellites relevant for Arctic predictions will be launched over the next few years. NOAA needs to take actions to ensure optimal use of these new data streams. Participants identified numerous partnership opportunities for NOAA to improve Arctic observations. Key amongst these was a strong recommendation that NOAA participate in the WWRP Polar Prediction Project, and specifically the Year of Polar Prediction (YOPP) planned from mid-2017 to mid-2019. YOPP provides a major opportunity for NOAA to augment, test and evaluate its observational capabilities within an intensive international collaborative effort focused on improving polar observations, predictions and services. Participants recommended that NOAA participate in a field campaign, MOSAiC, scheduled for FY18. This campaign is focused on understanding ice-atmosphere-ocean processes and interactions in the rapidly changing Arctic with an ultimate goal of improving Arctic predictions, particularly of sea ice.

Some specific recommendations are that NOAA:

- Promote development of a sustained Arctic Observing System.
- Develop a plan to prioritize Arctic observations and a plan for sustained marine observations for the Bering and U.S. Arctic waters that is integrated across NOAA.
- Establish MOUs with interagency, international, and commercial interests to develop exchange mechanisms and promote timely sharing of observations.
- Expand capabilities of the U.S. Interagency Arctic Buoy Program to observe atmospheric, sea ice, and oceanic parameters.
- Expand outreach to end users so they can provide as well as receive observational data/information, e.g., observations on ice, around the marginal ice zone, and in coastal regions.
- Complete build out and enhancement of the Alaska Climate Reference Network (CRN) including increasing density, measurement capacity and cold weather hardening; expand outside US territories.
- Contribute to development and deployment of in situ new observing technologies appropriate for the Arctic (UAS, Arctic ARGO, etc.).

- Develop a pipeline for interagency access (e.g. NASA) to albedo (MODIS), sea ice thickness (ICESAT 2), soil moisture (SMAP) and coordination on satellite observations.
- Develop a plan to use YOPP observations to improve satellite retrievals.
- Request that NASA and NOAA block significant time during critical periods (i.e., sea ice transition) of Global Hawk and P3/G4 usage for Arctic surveys.
- Develop cross-line coordination to work closely with IARPC/CLIVAR/NOPP to identify resources and/or ongoing activities as a contribution to support the WWRP Polar Prediction Project (PPP) Year of Polar Prediction (YOPP).
- Establish a U.S. – Russia- Canada intensive rawinsonde campaign during YOPP.
- Support observational activities and process research for MOSAiC.
- Develop a robust archive of data analyses and products (input data, output data and products, observations).
- Support Arctic data rescue for weather and climate reanalysis and reforecasts.
- Develop observations strategy for coupled data assimilation in planned fully coupled model structures (ESPC, NMME).
- Establish transitions for research to operations for observation sustainability (Arctic Testbed).
- Update bathymetry digital elevation maps (DEMs) and increase tide/water level observations for predicting coastal surges and impacts.

NOAA needs to place emphasis in future modeling efforts primarily on the development and application of fully coupled atmosphere-ocean-ice-land models.

3.5 Focus Modeling Efforts on the Development and Application of Coupled Atmosphere-Ocean-Ice-Land Models

Arctic weather and climate predictions present severe challenges for current generation models, leading to lower skill in forecasts compared with the contiguous U.S. In contrast to midlatitudes, where weather forecasts out to a week or longer are largely dependent on atmospheric initial conditions, the Arctic is a highly coupled system in which atmosphere, ocean, and sea ice states must be considered together even for short-term weather and hazards forecasts. Freshwater inflows from rivers into the Arctic also substantially affect sea ice distributions. To achieve its mission, NOAA needs to place emphasis in future modeling efforts primarily on the development and application of fully coupled atmosphere-ocean-ice-land models that include land hydrology, and perhaps ultimately also biophysical and ecological processes. This development will require sustained, long-term efforts. Over the next several years, simpler uncoupled or weakly coupled weather and sea ice prediction models will still be needed. Much can be learned from careful diagnoses of the strengths and limitations of these simpler models that can inform future coupled model developments.

Observations in the Arctic are relatively much more limited than at lower latitudes, and are a major source of forecast errors. The sparseness of observations also hinders attempts to validate models and verify accuracy of their predictions. Making maximum use of available observations is therefore especially critical in the Arctic. A key challenge for NOAA will be to develop data assimilation methods for coupled models that can take advantage of all available observations, including from satellites and airborne, surface and subsurface sensors. Satellites launched over the next few years will provide a wealth of new observations. NOAA needs to prepare now to access and assimilate these new data.

Making maximum use of available observations is especially critical in the Arctic. A key challenge for NOAA will be to develop data assimilation methods for coupled models that can take advantage of all available observations, including from satellites and airborne, surface and subsurface sensors.

Another major modeling challenge is to represent key features and processes in the Arctic, such as Arctic clouds and sea ice, melt ponds and leads. An important question is whether current model parameterizations developed for lower latitudes are suitable for the Arctic, or rather provide a significant source for model errors. Process studies, as during PPP and MOSAiC, will provide important opportunities to evaluate current parameterizations and develop and test new parameterizations that can be incorporated within next-generation NOAA coupled models. As key features such as leads, melt ponds and locations of marginal ice zones occur on fine spatial scales, increasing model resolution will be required. In the near term, NOAA can take advantage of the existing North American Multi-Model Ensemble (NMME), with a targeted focus on the Arctic to establish a baseline for ensemble prediction skill leading into YOPP. In the longer term, NOAA needs to consider an Ensemble Prediction System that would be tailored to the unique characteristics of the Arctic. This could be developed in coordination with other national and international modeling activities in YOPP.

Some specific recommendations are:

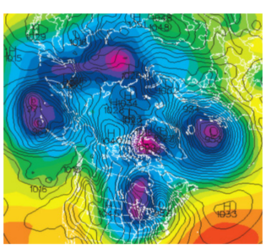
- Develop new experimental multi-model predictions in the Arctic using the NMME system.
- Document Arctic prediction skill of the NMME.
- Implement multi-model prediction capabilities for the Arctic region building on NMME to aid in the development of an operational prediction capability for Arctic sea ice extent across multiple timescales.
- Coordinate GFDL, ESRL and NCEP modeling efforts and CPO programs to improve week-two to interannual predictions in the Arctic and to improve understanding of past decadal changes and trends.

- Prepare for assimilation of new satellite data that will become available over the next few years (e.g., GOESS-R, ICESAT 2, Sentinel series, JPSS series, COSMIC-2).
- Develop and implement advanced assimilation techniques for Arctic analyses, reanalyses and reforecasts. These products will improve estimates of current and past Arctic conditions to be used for monitoring, forecasts, and model evaluations.
- Participate in ESPC, IARPC and other collaborative activities to develop coupled Earth system prediction models for the Arctic.
- Collaborate with Navy, Environment Canada and other US and international partners to develop the next generation of coupled atmosphere-ocean-ice-land models that will incorporate advances in observations and process understanding for the Arctic.

3.6 Advance Understanding of Arctic Lower Latitude Linkages and Their Implications for Weather and Climate Predictions

Linkages between the rapidly changing Arctic and weather and climate conditions at lower latitudes have significant implications for NOAA's prediction mission across the U.S. and globally.

Linkages between the rapidly changing Arctic and weather and climate conditions at lower latitudes have significant implications for NOAA's prediction mission across the U.S. and globally. The Arctic is experiencing a system-wide response to global changes in climate across its atmosphere, marine, and terrestrial components, including changes in seasonality and extremes. Over the last decade, Arctic temperatures have increased at least three times the rate of mid-latitude temperatures. This rapid Arctic warming is projected to continue, but understanding of its effects on the large-scale atmospheric circulation, while growing, remains inadequate. Multiple interacting feedbacks between clouds, heat storage, surface forcing, atmospheric dynamics and other system components can all contribute to Arctic amplification. These non-linear interactions are not well captured in climate models, limiting their value for understanding and predicting Arctic-lower latitude linkages. This topic provides a core science challenge and opportunity for NOAA, because the linkages between the Arctic and lower latitudes have the potential to significantly impact weather and climate conditions both within the Arctic and over the contiguous U.S. and surrounding oceans.

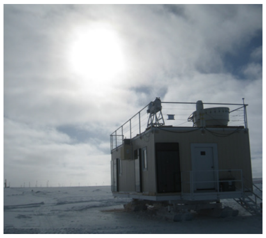


Sorting out a causal role for Arctic forcing on mid-latitude flow is difficult. The current observational record is too short to provide rigorous evidence of causality. Studies based on observations, theory, and model simulations have yielded inconsistent results, fostering controversy and skepticism. Further, the Arctic is an open system: changes in the Arctic both affect, and are affected by, conditions in lower latitudes. Large-scale weather patterns (jet stream meanders, blocking, polarity of the Arctic Oscillation, teleconnections, shifts in planetary wave numbers, etc.) and synoptic storms are prominent features characterizing the daily-to-decadal timescales of the subarctic atmosphere. Over the last decade, there have been large and coherent variations in intensity, frequency, and locations of many of these features. The degree to which these shifts are related to Arctic changes (Arctic amplification, snow and sea ice cover, etc.) and may be affected systematically in the future is unclear. It is only through a comprehensive analysis of the interplay between components that we will understand the wide-ranging changes and their implications for NOAA's weather and climate predictions and services.

Specific recommendations are that NOAA:

- Participate in ongoing international research and assessment reports synthesizing the present state of knowledge of Arctic/mid-latitude linkages. This involves partners in the international community (WMO/PPP/PPCI, IASC, and AMAP), the Polar Research Board, the university community, and the interagency Earth System Prediction Capability project.
- Conduct and coordinate research with partners to assess predictive implications of Arctic-lower latitude linkages on weather-to-seasonal time scales, leading to a synthesis report that focuses on Alaska and surrounding regions and the contiguous U.S.
- Implement a "Linkages Diagnosis Portal" to provide access to model output, reanalysis data, archived forecasts, web links to in-situ data and tools for exploring relationships.
- Make versions of NOAA operational prediction models accessible for research purposes, similar to the NCAR CESM approach.
- Address model deficiencies that affect Arctic Amplification and linkages, such as cloud radiative forcing and the need for higher spatial model resolution to adequately predict high latitude blocking and other high-impact phenomena.
- Lead or co-lead the North American focus in the PPP/Year of Polar Prediction (YOPP).
- Convey the state of knowledge about Arctic changes and potential linkages to broader audiences (public, stakeholders, policy community) by information and outreach efforts that include products such as NOAA fact sheets and the Arctic Report Card.

4 Conclusions



Within the context of a rapidly changing Arctic, the science challenge of predicting Arctic weather and climate has large and growing implications for NOAA's mission. The relevance and interest in this topic across NOAA was clearly evident at this workshop. Four line organizations participated in the workshop, with OAR, NWS, NESDIS, NOS, NMFS, the NOAA Research Council, Arctic Task Force, and AA Climate Board all contributing to the workshop's planning and support.

The external community also showed great interest and provided outstanding contributions to the workshop. Of the eighty participants, half were from outside NOAA, from university cooperative institutes, other universities and research centers, other federal agencies, and national and international operational prediction centers. The diverse research, operational and service backgrounds provided a rich set of perspectives for identifying actions needed to address key science issues in an end-to-end fashion. The breadth of scientific and organizational expertise required to address the difficult science challenges also reinforces the need to build partnerships across a spectrum from academia to services to achieve most rapid progress.

The breadth of scientific and organizational expertise required to address the difficult science challenges also reinforces the need to build partnerships across a spectrum from academia to services to achieve most rapid progress.

This NOAA Science Challenge Workshop was the first of its kind to go to this level of specificity in identifying actions needed by NOAA to support US and NOAA Arctic strategic goals related to predicting Arctic weather and climate and related impacts. This workshop focused on actions that could be taken between now and approximately 2020, a time frame consistent with implementation planning. While there was no expectation that an implementation plan would be developed at the workshop itself, the recommended actions can inform NOAA's development and subsequent implementation of such a plan.

In this report, recommended actions have been summarized in two ways: first, to address three classes of prediction problems confronting NOAA services: 1) Arctic weather and hazards forecasts; 2) Arctic climate forecasts; and 3) Arctic-midlatitude linkages, and second, to identify crosscutting actions that would contribute to forecast and services improvements in multiple areas. Some actions have significant resource needs and may take several years to accomplish; however, others require no or limited new resources and could be implemented in the near-term. A few examples are:

- Develop an action plan for NOAA's engagement in the Year of Polar Prediction.
- Identify and coordinate NOAA groups that will participate in the Polar Prediction Project.

An end-to-end approach that coordinates Arctic observations, process understanding, model development and services together, as at this workshop, will help to ensure that progress on this science challenge is achieved most rapidly and efficiently.

- Develop and leverage partnerships:
  - » Continue the process of establishing MOUs with commercial partners to enhance critical observations.
  - » Explore citizen and community-based approaches to increasing and sharing available observations.
- Initiate plans for an Arctic Forecast Improvement Program.
- Assess skill of current model prediction systems for the Arctic (NMME).
- Initiate access to data from ESRL model experiments.
- Develop metrics to better assess forecast skill and observational uncertainties.

In addition, NOAA would benefit from coordinating and integrating its planning across the agency. An end-to-end approach that coordinates Arctic observations, process understanding, model development and services together, as at this workshop, will help to ensure that progress on this science challenge is achieved most rapidly and efficiently.

While much of value has come from this workshop, inevitably there were limitations that should be recognized. Due to both time and logistical constraints, this workshop focused on steps needed to improve predictions of the physical system, emphasizing the atmosphere, ocean and sea ice. It did not address other critical prediction problems for the Arctic, in particular biological predictions for NOAA fisheries and marine resources management. In addition, although aspects of societal impacts were discussed in presentations at the workshop, key issues like communications, needs and uses of products for decision-making and societal value of services did not receive the attention that they deserve. To address these limitations, NOAA would benefit from holding additional focused science challenge workshops to strengthen connections between physical, chemical and biological predictions, such as those relevant to fisheries and marine resource management, and to address related social science challenges to further support NOAA's mission.

From the outset, this workshop had as its overarching purpose to inform NOAA on actions needed to address present and anticipated future mission requirements for predictions of Arctic weather and climate and related impacts. By that measure, the workshop can be considered as a success. However, from the perspective of the participants, the more fundamental measure of success will be the extent to which the recommended actions are incorporated into NOAA's plans and, ultimately, into actions that will benefit society.

Acknowledgements

We thank all of the participants for their contributions to the workshop and NOAA's planning process and, especially, to those participants who served as breakout group co-chairs and rapporteurs, as well as to the many staff from NOAA ESRL and CU CIRES for their help during the course of the workshop. Our thanks also to NOAA OAR, NWS, NESDIS, NOS and NMFS for their funding support, which was arranged through the AA Climate Board and made this workshop possible.

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Graphic Designer: Barb DeLuisi, NOAA/ESRL/PSD

Appendix 1: Workshop Agenda

Tuesday, May 13

8:30 am	Welcome to NOAA ESRL – Sandy MacDonald (NOAA ESRL, Director)
8:35 am	Workshop Overview and Objectives - Randy Dole (NOAA)

1. The Drivers: US and NOAA Requirements for Advancing Arctic Predictions - Dole, Chair

8:50 am	National Needs for Improved Arctic Weather & Climate Predictions – David Titley (PSU, Center for Solutions to Weather and Climate Risk)
9:05 am	A Navy perspective on Current and Future Needs for Arctic Operational Predictions - RADM Jon White (US Navy)
9:20 am	NOAA Imperatives, Drivers and Service Needs – David Kennedy (NOAA)
9:35 am	NOAA NWS Arctic Operational Forecasting Perspectives – Ming Ji (NWS/NCEP)
9:50 am	Arctic Information and Regional Service Needs– Aimee Devaris (NWS Regional Director– Alaska Region)

2. Scientific Foundations for Improving Predictions - Bromwich, Chair

10:30 am	Arctic Science for Improving Predictions – John Walsh (University of Alaska, Fairbanks, CIFAR)
10:50 am	Arctic-Lower Latitude Linkages: Implications for weather and climate predictions – Judah Cohen (AER)
11:10 am	Arctic Sea Ice Predictability – Marika Holland (NCAR)
11:30 am	Open discussion, with presenters of the first two sessions as panelists

3. Operational Predictions: Status, Challenges & Opportunities for Progress - Devaris, Chair

1:00 pm	NOAA – Robert Grumbine (NOAA NCEP)
1:15 pm	Navy – Rick Allard (NRL)
1:30 pm	National Ice Center & North American Ice Service –Caryn Panowicz and Behnjamin Zib (NIC)
1:45 pm	Environment Canada – Hal Ritchie (EC)
2:00 pm	Open discussion, with presenters as panelists

Breakout Group Discussions – Key Challenges and Opportunities

3:00 pm Breakout group guidance (Dole)

3:15 pm Breakout groups convene in breakout rooms

- Consider end-to-end capabilities. Take advantage of cross-disciplinary expertise.
- What are the critical gaps limiting progress?
- Are there specific high priority problems where near-term progress is feasible?
- Are there common challenges that cut across several problems that, if addressed, would allow progress on multiple problems?

5:00 pm Reconvene in plenary – Summary, next steps (Dole)

Wednesday, May 14

8:30 am Day 1 Recap, Day 2 Objectives (Dole)

8:40 am Day 1 Breakout Summaries

Brief summaries (~5-10 minutes, 1-2 slides) from each breakout group followed by plenary discussion of key challenges and opportunities

4. International and National Partnership Opportunities - Renee Tatusko, Chair

10:15 am WWRP Polar Prediction Project, YOPP, MOSAiC – Chris Fairall (NOAA)

10:30 am Interagency Processes & Mechanisms IARPC and USARC John Farrell (USARC)

10:45 am Earth System Prediction Capability – Dan Eleuterio (ONR)

11:00 am Sea Ice Prediction Network - Julienne Stroeve (NSIDC)

11:15 am Forecast Evaluation and User-Focused Verification – Barb Brown (NCAR)

11:30 am Open discussion, with presenters as panelists

Breakout group discussions Day 2 - Requirements for Progress

1:00 pm Breakout group guidance (Dole)

1:15 pm Breakout groups convene in breakout rooms

- What are actions recommended for NOAA to improve predictions of Arctic weather and climate and Arctic-lower latitude linkages over the next 5-6 years?
- How can NOAA work together with partners to address these challenges?

3:30 pm Breakout groups reconvene – Draft key recommendations

Thursday, May 15

5. Recommendations for NOAA Actions - Plenary session

8:30 am	Day 2 Recap, Day 3 Objectives (Dole)
8:40 am	Breakout group summaries – Opportunities, actions, partnerships
10:45 am	Open discussion
11:30 am	Initial summary of findings and NOAA response, next steps
12:15 pm	Closed-session for Program Committee and Program Managers

Appendix 2: Workshop Participants and Affiliations

Name		***Affiliation***
Waleed	Abdalati	CIRES, University of Colorado/NOAA
Michael	Alexander	NOAA/OAR/ESRL
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Edward	Blanchard-Wrigglesworth	University of Washington
David	Bromwich	Ohio State University
Barbara	Brown	NCAR
James	Butler	NOAA/OAR/ESRL
Jessie	Carman	NOAA/CPO
Joseph	Casas	NASA MSFC
Steven	Cavallo	University of Oklahoma
Pablo	Clemente-Colón	NOAA/NESDIS/NIC
Judah	Cohen	AER
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Aimee	Devaris	NOAA/NWS/Alaska Region
Randy	Dole	NOAA/OAR/ ESRL
David	Easterling	NOAA/NCDC
Geoffry	Eberle	US Navy
Marc	Eckardt	US Navy
Michael	Ek	NOAA/NWS/NCEP/EMC
Daniel	Eleuterio	DOD/ONR/ESPC
Chris	Fairall	NOAA/OAR/ESRL
John	Farrell	US Arctic Research Commission
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Florence	Fetterer	NSIDC
Steven	Goodman	NOAA/NESDIS
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Participants continued...

Name		Affiliation
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Amy	Holman	NOAA/NOS
Janet	Intrieri	NOAA/OAR/ESRL
David	Jackson	Canadian Ice Service
Ming	Ji	NOAA/NWS/NCEP
Paul	Kushner	University of Toronto
David	Legler	NOAA/OAR/CPO
Michelle	L'Heureux	NOAA/NWS/NCEP/CPC
Mendal Scott	Livezey	Oceanographer of the Navy
Sandy	Lucas	NOAA/OAR/CPO
Gudrun	Magnusdottir	University of California Irvine
Alexander	McDonald	NOAA/OAR/ESRL
Rym	Msadek	NOAA/OAR/GFDL
William	Neff	CIRES, University of Colorado/NOAA
Matt	Newman	CIRES, University of Colorado/NOAA
James	Overland	NOAA/OAR/PMEL
Caryn	Panowicz	U.S. National Ice Center
James	Partain	NOAA/NESDIS
Judith	Perlwitz	CIRES, University of Colorado/NOAA
Gene	Petrescu	NOAA/NWS/Alaska Region
Ignatius	Rigor	UW - Polar Science Center
Hal	Ritchie	Environment Canada
Mel	Shapiro	NCAR
Matthew	Shupe	CIRES, University of Colorado/NOAA
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Sandy	Starkweather	CIRES, University of Colorado/NOAA
Julienne	Stroeve	NSIDC
Shan	Sun	CIRES, University of Colorado/NOAA
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Rick	Thoman	NOAA/NWS
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Participants continued...

Name		Affiliation
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Wanqiu	Wang	NOAA/NWS/NCEP/CPC
Robin	Webb	NOAA/OAR/ESRL
Wayne	Weeks	NOAA/NWS
Xingren	Wu	NOAA/NWS/NCEP
Benjamin	Zib	U.S. National Ice Center

Appendix 3: List of Acronyms

AER	Atmospheric and Environmental Research
AO	Arctic Oscillation
AOML	Atlantic Oceanic and Meteorological Laboratory
AR	Alaska Region
AWIPS	Advanced Weather Interactive Processing System
CFS.v2	Climate Forecast System Version 2
CIS	Canadian Ice Service
CIRES	Cooperative Institute for Research in Environmental Sciences
CPC	Climate Prediction Center
CPO	Climate Program Office
EC	Environment Canada
ERSL	Earth System Research Laboratory
ESPC	Earth System Prediction Capability
IARPC	Interagency Arctic Research Policy Committee
MOU	Memorandum of Understanding
MSC	Met Service Canada
NCEP	National Centers for Environmental Prediction
NHC	National Hydrological Center
NIC	National Ice Center
NMME	North American Multi-Model Ensemble
NOS	National Ocean Service
NRL	Naval Research Laboratory
NSAR	National Strategy for the Arctic
NSF	National Science Foundation

Acronyms continued...

NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
ONR	Office of Naval Research
PMEL	Pacific Marine Environmental Laboratory
PIOMAS	Pan Arctic Ice Ocean Modeling and Assimilation
SIPN	Sea Ice Prediction Network
UND	University of Notre Dame
USARC	United States Arctic Research Commission
WMO	World Meteorological Organization
YOPP	Year of Polar Prediction