Observing the Arctic Ocean Sea Ice Cover: 2017-2027

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1 Key Challenges

Arctic sea ice extent and thickness are declining, and the expectation that current trends will continue portends a future with larger expanses of open ocean, longer durations of ice free conditions, and a more accessible Arctic. However, our limited understanding of the coupled interactions among the sea ice, ocean, atmosphere, and land hinders our ability to predict the rate and magnitude of future change. The need to understand, adapt to and take advantage of a changing sea ice cover places new demands on the research community and observational systems. Societal needs require that we:

- Continue development of focused research and integrated observational networks to better understand the changing arctic. This includes improved subseasonal-to-seasonal forecasts and refined projections of future climate patterns and how they will develop as a result of the interacting physical, biological, and human systems.
- Develop tools for scaling predictions of arctic-wide ice conditions down to the local-to-regional level at which most decision-makers operate. Local information is needed to understand how decisions will influence the dynamics of the natural and social-ecological systems that they manage.

Key Questions:

- How predictable are different aspects of the Arctic sea ice cover, and what is needed to improve predictability at the local and regional scale to facilitate planning, mitigation, and adaptation? Improvements in model physics and specification of initial state. While there are intrinsic limitations on Arctic sea ice predictability, some appear to reside in the initial ice/ocean state and in the longer-term trend; the initial states (e.g. thickness, snow depth, etc.) affect the potential trajectories in the evolution of ice coverage.
- What are the critical linkages between the Arctic system and the larger Arctic and global systems? Although efforts are under way to better understand the role of Arctic sea ice in this broader context, progress has been limited by the lack of coordinated observations of sea ice and associated forcing parameters (atmosphere and ocean) at appropriate time and space scales.

Addressing these questions depends on a robust program of well-planned and coordinated observations. Improving short- and long-term forecasts will require better models, with fully coupled ice-ocean-atmosphere processes that assimilate advanced observations and generate time-varying sea-ice concentration, thickness, and ice-edge location at high temporal and spatial resolution. Continuous or frequently repeated data collection will be needed, including broad surveys of ice conditions over the annual cycle to initialize forecasts. Furthermore, data should be returned in near real-time to support forecasting at shorter time scales and to verify sensor performance.

2 Key Sea Ice Parameters

We advocate the continued and coordinated monitoring of four crucial sea ice parameters in 2017-2027. They are: *sea ice concentration, thickness and motion, and snow depth*.

Ice concentration. These retrievals are from passive microwave measurements acquired by the series of space-based radiometers, that started with NASA's Nimbus-7 SMMR in 1979, has been maintained by successive SSM/Is launched by the Defense Meteorological Satellite Program (DMSP) and by the Japan Aerospace Exploration Agency's (JAXA's) GCOM-W AMSR2. The DMSP program will be ending and JAXA's plan to launch another space-based radiometer at this time is in question. Without these assets, the time series for monitoring the sea ice cover, used in a broad range of applications (from operational to scientific research), may come to an end - this includes the multi-decadal record of ice extent that has served to document the dramatic decline in the Arctic Ocean sea ice coverage. This is of significant concern if there were no commitments to continue these measurements.

Time-variable sea ice thickness, motion and snow depth observations are essential for describing the evolution of the ice cover. While thermodynamic processes are responsible for mass changes at the upper and lower surfaces of the ice, it is mechanical processes due to non-uniform ice motion that cause the formation of the thinnest (leads) and thickest ice (pressure ridges) in the thickness distribution. On longer time scales, the thickness distribution represents a time-integral of interactions between the thermodynamic and dynamic responses of the ice cover to external forcing. There is hence a requirement of coupled observations of ice thickness and motion for documenting changes, understanding processes, and for use in predictions and projections as well as validation of ice conditions at various time scales. Snow on sea ice is important because it regulates the transfer of heat through the pack ice. Further, meltwater from winter snow, together with surface roughness, determines melt pond coverage and albedo of the summer ice surface.

Ice thickness distribution. To date, both the ICESat-1 and CryoSat-2 (CS-2) missions have provided ice thickness estimates from retrieved sea ice freeboard. Although CS-2 has passed its nominal mission life, ESA plans to continue operations. ICESat-2 will be launched in 2017 for a 3-year mission and measurement of sea ice freeboard as one of its science requirements. ESA's Sentinel-3 (launch in late 2015) will carry an altimeter similar to CS-2 but the sun-synchronous orbit inclination will offer coverage of only 70% of the Arctic Ocean. Furthermore, radar altimeter-based retrievals currently also cannot reliably provide ice thickness during the summer months. Beyond 2021, there are currently no plans for another altimeter suitable for fully mapping Arctic sea ice thickness. This is an important consideration.

Ice motion. Sea-ice motion can be retrieved from time-sequential satellite imagery. The quality of these measurements depends more on the geometric fidelity and image resolution than on a thorough physical understanding of the ice signatures. Although motion estimates have been derived from a variety of sensors, only Synthetic Aperture Radar (SAR) imagery provides high enough resolution to capture small-scale ice deformation. NISAR (launch data: 2020) will provide 3-day ice motion for a large part of the Arctic Ocean. Beyond NISAR, a follow-on SAR mission or an ESA SAR mission may be needed.

Coordinated observations: motion and thickness. Satellite retrievals of sea ice thickness and motion are typically acquired independently with little consideration of the close links between thermodynamic and dynamic processes that control ice conditions, which must be treated realistically to improve predictive models. While near-simultaneous observations of these parameters challenge current satellite technologies, the science need is high and merits special attention.

Snow depth. Approaches to extract snow depth from passive microwave measurements exist but there are significant limitations. The capability of measuring snow depth has been demonstrated with airborne radar on Operation IceBridge but a spaceborne approach has yet to be demonstrated. NASA's GPM mission can measure snowfall and thus may enable estimates of snow depth but its inclination limits coverage to 65°N. Snow depth is arguably one of the most important polar variables for which no long-term and Arctic-wide measurement concept has been developed.

3 Other considerations

We discuss other considerations in the design of observational systems that would benefit other needed observations of the Arctic sea ice.

Coordination/Validation. Given limited resources, coordination of national and international assets (field programs, airborne campaigns) is important for validation and assessment of satellite retrievals. The development of sub-orbital platforms (UAVs) is crucial for validation of on-orbit assets. A sustained network of coordinated in-situ observations will be necessary to complement space-based observations. In-situ measurements for validation as well as to provide information on variables not readily observed from space are needed. In particular, observations of heat storage and distribution in the upper ocean as well as buoys capable of measuring individual components of the ice mass balance are critical to complement space based observations of thickness and deformation.

High inclination orbits and other satellite missions. Where feasible and appropriate, satellite missions that can support Arctic research should consider higher inclination orbits to provide better high latitude coverage. A good example of a multiple-use instrument was the scatterometer on QuikSCAT, which provided maps of multiyear coverage during its mission.

Observations of clouds and precipitation over the Arctic: a critical gap. To understand past variability and improve forecasts require accurate information about all components of the sea ice mass and energy balance. While this white paper addresses surface remote sensing, cloud cover has first-order impacts on the surface energy balance that affect, and are affected by, the sea ice cover. Critical processes, particularly cloud formation and their connection to sea ice and aerosols, need to be better characterized to improve our understanding of the surface energy balance and how cloud conditions will change in a changing Arctic climate. To date, the temporal and spatial variability of the most basic cloud variables is highly uncertain and the impact of changing surface characteristics (sea ice, melt ponds) is not well constrained. Measurements of cloud profiles from CloudSat/Calipso over the Arctic suffer retrieval problems due to ground interference and attenuation by thicker clouds. Further, precipitation affects surface albedo, ice growth and melt, but satellite measurements of precipitation are currently not from polar orbits and hence do not provide the necessary coverage.

4 Antarctic sea ice

The Antarctic sea ice extent has been slowly increasing and this trend and its variability are poorly understood. Changes in the patterns of sea ice in the Southern Ocean strongly affect atmospheric and oceanic circulations as well as carbon dioxide uptake, and the Antarctic biota and ecosystems; therefore, improved monitoring and modeling of sea ice will be as important in the next decade. The measurements and assets advocated for the Arctic, are similar to those needed for the Antarctic, if available concurrently would facilitate significant advances in Antarctic system science.

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