Sea Ice Mass Budget of the Arctic: Bridging regional to global scales
Executive Summary

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Objectives of a SIMBA program

- Observe the state and evolution of SIMBA.
- Understand mechanisms and consequences of sea ice variability and change.
- Facilitate scientific communication and convey knowledge to the public.

Scientific Rationale for a SIMBA program

Arctic sea ice has undergone dramatic change over the recent decades of the satellite era. Ice extent has reduced by 3% per decade since 1970 (Cavalieri et al 1997), with the three lowest recorded ice extents occurring in this decade. Ice thickness has reduced in the central Arctic (Rothrock et al 1999) and the summer melt season length has increased (Belchansky et al. 2004) over the last 30 years. It is not clear if these recent changes in sea ice state can be attributed to anthropogenic climate change. There are indications that sea ice is involved in multi-decadal variability of the Arctic climate and oceanic circulation. The amplitude of variability of European sector sea ice extent over the last 400 years is large compared to present day inter-annual variability, and the mechanisms causing this variability are poorly understood. GCM CO_2 doubling simulations indicate that the Arctic ice pack will continue its reducing trend, eventually losing all perennial ice.

Sea ice is a critical component of the Arctic system that responds sensitively to changes in atmospheric circulation, incoming radiation, oceanic heat fluxes, and the hydrological cycle. Small perturbations in forcing or initial conditions of models result in large changes in simulated ice extent and thickness. As the sea ice system is sensitive to atmospheric and oceanic variability, and because sea ice is involved in several key climate feedbacks (ice-albedo feedback, cloud-radiation feedback etc), sea ice probably plays a substantial role in climate system variability. The high sensitivity of non-linear sea ice models make it difficult to simulate present and future ice state with reasonable accuracy. There is a great need for research that determines the mechanisms of observed change in the Arctic pack. Research that constrains parameterizations in key terms within the sea ice mass balance should lead to improvements in GCM modeling of sea ice processes, long-term prediction and short-term forecasting.

The Arctic sea ice pack changes observed over the last 30 years are compelling, and to understand these in the context of low frequency variability requires sea ice monitoring to be maintained decades into the future. An optimized SIMBA observing system should provide cost effective sea ice monitoring that will enable analysis of mechanisms causing change in the ice state, while providing information at scales relevant to the societal needs of forecasting and understanding the impacts of sea ice change. We also need to extend and preserve data sets back in time (at least through the 20th century and hopefully beyond to include the medieval warm period). This may require novel use of historical data sources and efforts to retrieve and interpret paleoclimate data.

Strategy and observing system design
The SIMBA objectives, and needs of the stakeholders may be met by:

- integrating observational and modeling efforts;
- further developing and maintaining an Arctic sea ice observing system;
- collection, preservation and use of historical and paleological data;
- targeted field and modeling campaigns, which utilize the observing systems and are designed to improve our understanding of SIMBA processes; and
- providing a forum for communication.

Discipline oriented working groups identified future research requirements and developed an observation strategy that acknowledges the different interests of Arctic residents and industry, climate research and sea ice natural science. A pan-Arctic sea ice observing program should consist of

1) a large scale sea ice mass budget (SIMBA) observing system;
2) linked, integrated coastal observatories; and
3) autonomous drifting stations (ice based observatories) and intense field campaigns to resolve and understand <100km scale processes and sea ice spatial variability.

Components of a SIMBA observing system

Ice thickness distribution	5 ULS, survey tracks (satellite, submarine, AUV, aircraft).
Snow depth distribution	surveys
Ice drift	IABP, DMSP passive microwave satellites
Ice concentration & extent	NASA satellites and DMSP passive microwave satellites
Ice export	ASOF: Fram Strait ULS, Canadian Archipelago

Status of current SIMBA monitoring and data gaps

- Ice thickness is routinely observed at the North Pole, two locations in the Beaufort Sea and the Fram Strait. Occasionally survey tracks are performed by submarine (less than every 4 years) or during field campaigns (erratic coverage). Satellite missions provide monthly or occasional pan-Arctic coverage, in the near future though there are large uncertainties associated with satellite measurements of ice thickness requiring further in-situ validation and development.
- The present snow depth climatology for the Arctic Ocean is of insufficient extent and probably does not represents current conditions.
- Gridded products of ice extent and concentration, and lagrangian measurements of drift and export are routinely provided with Defense Meteorological Satellite Program (DMSP) satellites, the International Arctic Buoy Program (IABP) and The Arctic Sub-arctic Ocean Fluxes (ASOF) Program. There are significant gaps in IABP coverage in the Siberian Arctic and seasonal ice covered seas.

Continuation of satellite monitoring, IABP and ice export monitoring are essential for maintaining a SIMBA observing system. There is a need for development of:

- autonomous platforms to provide ice thickness survey tracks;
- new methods to observe snow depth distribution; and
- buoys for seasonal ice.

Thickness distribution remains the least well sampled sea ice state variable. Coordination of ULS deployments and survey tracks, data inter-comparison campaigns, and modeling are needed to complete mass budget observations. It may be possible to use models to estimate the best locations given limited measurement resources, though these should be verified with campaigns measuring regional and temporal characteristics of the ice thickness distribution.

Further observing system components

Extra observations required for attribution of the mechanisms controlling SIMBA

Ice growth and melt	~15 ice mass balance bouys, Remote sensing and field campaigns.
Surface radiation budget	3-5 automated measurement sites on pack ice. Satellite data analysis (Visual/IR). Improved albedo parameterizations.
Oceanic heat flux to ice	Buoys or AUVs measuring near surfaceT/S (particularly near the Bering Strait and along Norway's coast). Monitoring of Atlantic and Pacific water pathways.
Wind Stress	Improved understanding of the surface roughness of sea ice. Near surface wind profiles (either from automated sounding stations or improved satellite retrievals). Improved atmospheric reanalysis for the Arctic.
Deformation	Field experiments to constrain ridging parameterization schemes. Observations of high frequency deformation (GPS buoy arrays, SAR).

All of these observation needs can be met with a combination of remote sensing, field campaigns and autonomous drifting stations. The drifting stations would be included in the IABP drifting buoy network, and will expand basic drifting buoy data collection to include ocean profiling, atmospheric profiling, surface radiation balance (to constrain satellite retrievals), surface energy balance (ice mass balance buoy), and high frequency deformation (GPS buoy array). Together with passive microwave, infra-red and visual radiometer satellite data, SAR, oceanic water mass monitoring and land-based observation centers, the drifting station/buoy network should resolve regional and temporal variations in surface energy balance and the momentum balance of sea ice.

Key processes, improving understanding of SIMBA modeling and prediction

SIMBA should provide information about the sea ice thickness distribution on scales relevant to ocean-atmosphere-sea ice-snowpack interactions (OASIS), biological processes and human activities. These scales are 1-2 orders of magnitude smaller than a large scale SIMBA network would provide. Sea ice is a heterogeneous material with dynamic processes ranging from 100m to 1000km, sub-hourly to seasonal scales. Thermodynamic processes are dominated by heterogeneity at the meter scale and seasonal transitions. Several processes are not realistically parameterized in sea ice surface energy balance and momentum balance models, and the characteristic sub-grid cell and/or satellite footprint heterogeneity is often poorly understood. Two of the key components of sea ice models are:

- albedo, and
- mechanical redistribution.

Process studies, using field campaigns and automated drifting stations, are required to determine the spatial and temporal variability of albedo and its dependence upon sea ice state variables. Up-scaling will lead to improved model parameterizations and development of remote sensing analysis methods for mapping sea ice surface characteristics. Improving mechanical redistribution models requires field campaigns for various ice types and times of year, incorporating campaigns to observe the high resolution ice thickness distribution. OASIS and biological field campaigns would benefit from high resolution observations or estimates of the thickness and snow distributions. Hence it makes sense to coordinate these campaigns with ice thickness surveys and autonomous drifting stations.

Components of a coastal sea ice observing system

The overarching science issues a pan-Arctic sea ice observing system must address are (1) understanding the change and variability of the Arctic ice pack and coastal sea ice, and (2) improving accuracy and usability of sea ice forecasts. Human activities in the coastal regions would benefit from precise forecasts of land fast ice, open water and ice type with better than 10km resolution. Observations should target the formation, extent and decay of land fast ice. A coastal observing system might include:

- Satellite monitoring of coastal ice;
- Coastal integrated measurement sites or systems combining semi-automated ice mass balance observations, coastal marine radar, web cams and perhaps community involvement in taking measurements;
- Data links to forecast centers and real time data availability.

Management

Optimized system design is crucial if a sea ice observing system is to be cost effective. This will involve reassessing measurement requirements as our knowledge of the processes controlling SIMBA evolves. Data from field campaigns coupled with results from modeling studies will aid determination of minimum observations resolving high resolution processes that are significant in SIMBA. Coordination of data collection will be aided by pre-existing facilities (IABP, BASC, NSIDC for example) with appropriate funding. A central management office would facilitate full coordination of SIMBA networks. Wherever possible, data would be made available in near real time and would be freely distributed.

Various groups would benefit from a SIMBA observing system and SIMBA related research: including global climate modeling, reanalysis programs, forecast centers, ice services and industry. As a SIMBA program would strive to understand the mechanisms and consequences of sea ice change and variability, SIMBA projects should incorporate links to these groups. For example, projects focusing on process studies that will lead to new parameterizations should include support to implement and test these in GCMs.

Outreach

A SIMBA program would maintain information on the state of the Arctic ice pack, and current understanding of the processes controlling the sea ice state and evolution. Synthesis of SIMBA observations will provide a time series of sea ice state variables and detailed information about seasonal and interannual variability on various scales. Analyses products and raw data would be freely distributed. The 3rd SIMBA objective requires an outreach program to convey understanding of sea ice change and variability to the scientific community and public. This will foster links within the research community and will ensure SIMBA programs are relevant to humanities needs.