*A sea ice, low cloud, and aerosol centric perspective on rapid Arctic climate change*

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**White Paper Description**: The Arctic is undergoing rapid climate change altering natural and human systems globally. A key science question is how will Arctic cloud and aerosol respond to and interact with Arctic sea ice loss. The rapid nature of Arctic climate change makes this question and the need for continued and improved satellite measurements extremely timely.

*Introduction*

The Arctic is undergoing rapid climate change altering natural and human systems globally. These changes are exemplified by the unprecedented decline in Arctic sea ice—September sea ice extent trend of -13% per decade—and increase in Arctic surface temperature—more than twice the global rate. The loss of Arctic sea ice, land ice, and snow cover is accelerating Arctic and global warming through enhanced absorption of solar energy. The shrinking mass of land ice and snow is contributing to rising seas impacting coastal communities around the world. More than just sea level rise, flooding oceans with freshwater and altering the atmospheric temperatures may be impacting oceanic and atmospheric circulation patterns. Further, thawing permafrost resulting form warmer Arctic temperatures is triggering the collapse of building, roads, and bridges.

Rapid Arctic warming is expected to have additional cascading effects with potentially severe consequences. Shorter winters suggest longer wildfire seasons across the boreal forests releasing additional carbon. Thawing permafrost could potentially release billions of tons of carbon and methane per year into the atmosphere over the next century. In light of these major concerns, a near-term focus on understanding the causes and impacts of rapid Arctic climate change is paramount. Clouds and aerosols are an important but highly uncertain component of the Arctic climate with the potential to amplify or dampen these rapid changes.

*What is a key science question?*

There are many scientific questions relating to rapid Arctic climate change with implications for human systems. **A key science question is how will Arctic clouds respond to the significant loss and expected sea ice-free Arctic summers in the coming decades and how will the Arctic respond to cloud changes?** This is an important science question because there is an indication that climate models simulate an unrealistically large cloud response to sea ice loss (e.g., Kay et al. 2010) producing a low bias in Arctic warming projections. The low bias results from the enhanced reflection of solar radiation by clouds offsetting a portion of the ice albedo feedback. Observational evidence suggests that low clouds weakly respond to sea ice loss in autumn, but not in summer (Kay and Gettelman 2009; Taylor et al. 2015). Despite this observational evidence, the physical mechanisms governing the interactions between sea ice and clouds and the interaction with the large-scale dynamics are not understood. Therefore, we cannot explain why clouds weakly respond to sea ice loss or physically represent such interaction in climate models.

The response of Arctic clouds to aerosol changes is a complicating factor when studying the cloud-sea ice relationship. Summertime sea ice loss would lead to large increases in aerosol and precursor gas emissions from the ocean. This increase may lead to increased cloud condensation nuclei (CCN) impacting cloud microphysics and lifetime; however, the end result is not clear given competing warming and cooling aerosol indirect effects. Additional impacts from anthropogenic aerosols associated with long range transport, increased ship traffic, black carbon deposits on snow further complicate studies of future Arctic conditions. Our poor understanding of these processes requires additional measurements and research to quantify the aerosol-cloud-sea ice Arctic climate feedbacks.

*Why is this challenge timely?*

It is timely to address this challenge from several perspectives. First, rapid Arctic climate change is influencing society now and observations are needed to inform adaptation and mitigation activities. Secondly, the Arctic is undergoing a potentially irreversible shift. We are on a “gradient” in the Arctic climate and this time period of rapid change may reveal interactions between the ocean, sea ice, and atmosphere that may never be observable again. Not studying this problem now would be a missed opportunity. A few climate models indicate that sea ice-free Arctic summers as early as the 2030s whereas most models suggest a higher probability of sea ice-free summers in the 2050s (Snape and Forster 2014). Therefore, the Arctic will not stay in this transition state between extensive, multi-year sea ice and much less extensive first-year sea ice without ice-free summers for long. Capturing the physics during this transition is an ephemeral opportunity that if seized can improve projections of the Arctic and global climate.

With regards to readiness, many observational capabilities to address Arctic sea ice-cloud-aerosol interactions are available but need to be extended (e.g., active remotely sensed cloud and aerosol information). An integrated and comprehensive observing strategy including satellite, ground, and airborne observing platforms is necessary for understanding aerosol-cloud-sea ice interaction; not all components can be constrained from space.

*Why are space-based observations fundamental to addressing this question? Are existing and planned U.S. and international programs sufficient to enable substantial progress?*

Unraveling the interactions between Arctic sea ice, clouds, and aerosols requires synergism between atmosphere, ocean, and sea ice observations and modeling. Space-based observations are very important to this problem because satellites are the only platform available to provide the required spatial information and consistent, long-term record of the critical variables.

There are a wide of range of observed quantities needed to constrain sea ice-cloud interaction. Key quantities for measurement include temperature and humidity throughout the cloud field at high vertical resolution, especially below cloud base. High vertical resolution is necessary to determine the connection between the cloud layer and the surface and cloud top inversion characteristics. Cloud and aerosol information is necessary including cloud microphysical measurements (phase partitioning, total water content, hydrometeor size distribution), cloud dynamical/turbulence measurements (e.g., vertical motion), and aerosol and CCN measurements (e.g., size distribution, composition, IN vs. CCN, ‘Arctic Haze’). Surface characteristics must also be defined including sea ice state (sea ice extent, concentration, and thickness), ocean state (temperature and mixed layer depth), and surface turbulent fluxes (latent and sensible heat fluxes). Knowledge of large-scale meteorological state is also critical for constraining the aerosol-cloud-sea ice relationships, which is generally obtained from poorly constrained meteorological reanalysis.

Current satellite information enables progress on this problem but is insufficient to solve it. Microwave radiometer retrieved sea ice information (extent and concentration) and active remotely sensed (e.g., CALIPSO/CloudSat) cloud and aerosol properties are being used to investigate cloud-sea ice interactions at interannual and cloud process timescales. However, standard backscatter lidars lack the calibration required to detect the tenuous but vertically extensive background aerosol—e.g., ‘Arctic Haze’. Passive remote sensing cloud information and atmospheric reanalysis, which assimilates satellite data, are not reliable enough to make substantial progress on this problem. Further, current satellite instruments cannot provide lower tropospheric temperature and humidity profiles (below ~3 km) of sufficient accuracy and vertical resolution (better than ~100m near the surface and inversion). Lastly, surface latent and sensible heat fluxes at the required accuracy levels to constrain the cloud response are not available.

We are skeptical that existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress. As implied above, active satellite-based remote sensing instruments are providing high quality observations of Arctic clouds and aerosols. After EarthCARE no plans appear to exist for a mission capable of extending the vertical cloud and aerosol distribution record, as the status of ACE seems uncertain. A long-term and continuous active remote sensing record of Arctic/global clouds and aerosols (e.g., CALIPSO/CloudSAT synergy) is needed to track changes in cloud properties, cloud vertical distributions, and aerosol to inform cloud process and climate model studies. However, the need to ask interdisciplinary science questions that incorporate ocean ecosystems and aerosols into the cloud-sea ice interaction problem is on the horizon and requires more accurate measurements of Arctic aerosol and complementary measurements of ocean productivity (e.g., plankton distributions) that can be provided by the high spectral resolution lidar technique.

*How to link space-based observations with other observations to increase the value of data for addressing key science question and societal needs?*

Satellite-based instruments are not able to resolve the cloud-sea ice interaction problem alone. As stated previously, an integrated and comprehensive observing strategy including satellite, ground, and airborne observing platforms is required. Satellite capabilities to address the sea ice-cloud interaction problem can be enhanced with carefully designed airborne campaigns and surface observing stations on land, sea, or ice. Value can be added to satellite observations by simultaneously observing the necessary components of the ocean-atmosphere-sea ice system during extensive airborne field campaigns over different Arctic regions sampling diverse large-scale environments and sea ice conditions.

*Involved Science communities*

The science communities directly involved in the question of sea ice-cloud interactions includes atmosphere, sea ice, and ocean communities. However, the broader context of rapid Arctic climate change also includes the ecological and land ice. Rapid Arctic climate change is an important question within all Earth Science as the impacts from these changes will influence global atmospheric and oceanic circulation patterns and the science questions of concern in other regions.

*Anticipated scientific and societal benefits*

Anticipated science value of studying aerosol-cloud-sea ice relationships is better knowledge of the processes that drive rapid Arctic climate change. This information will be useful for constraining climate model physics and projections. Constraining climate projections will be useful to society, enabling a better assessment of Arctic climate change impacts on the global system including sea level rise, ecosystems, and extreme weather. In many respects, resolving Arctic climate change uncertainty will enable progress on many other climate science problems including sea level rise, atmosphere and ocean circulation change, and global temperature change.

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