Arctic Radiation-Cloud-Aerosol-Surface Interaction Experiment (ARCSIX)

Concept Paper for NASA Aircraft Investigation

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ARCSIX Overview

The Arctic Radiation-Cloud-Aerosol-Surface-Interaction Experiment (ARCSIX) is an airborne investigation planned to take place during early summer based from Northern Greenland and possibly Svalbard. It is driven by the need to:

1) Understand how coupling between radiative processes and sea ice surface properties influence summer sea ice melt;
2) Understand processes controlling the predominant Arctic cloud regimes and their properties; and
3) Improve our ability to monitor Arctic cloud, radiation, and sea ice processes from space.

In the Arctic, spaceborne retrievals of radiatively important parameters such as surface albedo, cloud and atmospheric properties have less skill than their counterparts in lower latitudes, and are rarely validated by suborbital observations. The resulting uncertainties in the surface and atmospheric energy budget and knowledge gaps in the cloud life cycle propagate into numerical weather predictions and reanalysis products. This makes the process-level understanding of the multi-scale interactions and feedback processes governing the evolution of sea ice surface properties and of locally and synoptically driven low-level Arctic clouds challenging if not impossible. It also curtails adequate predictive capabilities, of sea ice in particular, on seasonal to decadal scales.

The overarching goal of ARCSIX is to quantify the contributions of surface properties, clouds, aerosol particles, and precipitation to the Arctic summer surface radiation budget and sea ice melt during the early melt season (May through mid-July). It encompasses three main science questions and one objective:

- **Science Question 1 (Radiation):** What is the impact of the predominant summer Arctic cloud types on the radiative surface energy budget?
- **Science Question 2 (Cloud Life Cycle):** What processes control the evolution and maintenance of the predominant cloud regimes in the summertime Arctic?
- **Science Question 3 (Sea Ice):** How do the two-way interactions between surface properties and atmospheric forcings affect the sea ice evolution?
- **Remote Sensing and Modeling Objective:** Enhance our long-term space-based monitoring and predictive capabilities of Arctic sea ice, cloud and aerosols by validating and improving remote sensing algorithms and model parameterizations in the Arctic.

To accomplish ARCSIX science and objectives, two aircraft will fly in coordination. One will acquire in-situ aerosol particle, cloud, atmospheric and surface properties along with radiation below, above, and inside a cloud layer, while the other will serve as a bridge to satellite observations by surveying with heritage and novel remote sensing instruments from above. This will provide the required *near-simultaneous characterization* of radiative fluxes, surface and cloud properties to address Science Questions 1 and 3. *Statistical sampling* of cloud vertical structure, temperature and humidity profiles complemented by simultaneous remote sensing will address Science Question 2 and the Remote Sensing and Modeling Objective. To extrapolate the spatially and temporally limited field observations beyond ARCSIX itself, the ARCSIX airborne data will be integrated with satellite remote sensing observations and model simulations. Targeted sampling of distinct regimes defined by cloud type and the associated prevailing surface and meteorological conditions will enable more useful combinations of airborne and satellite remote sensing observations along with model simulations. This combination of observations and model simulations will push the performance of remote sensing algorithms towards more realism for a variety of conditions and culminate in a more realistic depiction of radiative processes, cloud life cycle and sea ice evolution in climate, regional forecast and process models.

1. Introduction

1.1. The New Arctic – uncharted territory for weather forecast, seasonal predictions, and climate projections

The Arctic is changing faster than any other region of the planet. September Arctic sea ice extent has declined by more than 40% since 1979 (Meier et al. 2017; Meredith et al., 2019) and sea ice thickness by ~70% since the early 1980s (Schweiger et al. 2011), *very likely* driven by human activities (Taylor et al. 2017; Meredith et al., 2019). The observed rapid declines in sea ice extent are an integral part of the processes leading to Arctic Amplification (e.g., Serreze and Barry 2011) and give rise to the well-understood sea ice albedo feedback; as sea ice retreats, the dark ocean is increasingly exposed, causing greater absorption of incident solar radiation and accelerating warming.

Climate model projections indicate that the Arctic Ocean is likely to become ice-free by mid-century, and potentially as early as the 2030s (Jahn et al., 2016). As a consequence, Arctic sea ice is transitioning from a state dominated by thick, multi-year ice to one dominated by thinner, seasonal, first-year ice. The question is no longer whether, but when this transition will occur. As a consequence, a "New Arctic" with only seasonal sea ice will soon be the norm.

This "New Arctic" and the associated changes in sea ice, temperature, clouds, and circulation will significantly affect human endeavors within and outside of the Arctic. Given the projected increases in economic activity in the Arctic, the increased vulnerability of Arctic inhabitants and ecosystems, and the potential for geopolitical conflict over the region's natural resources, the value of sea ice predictions will only grow.

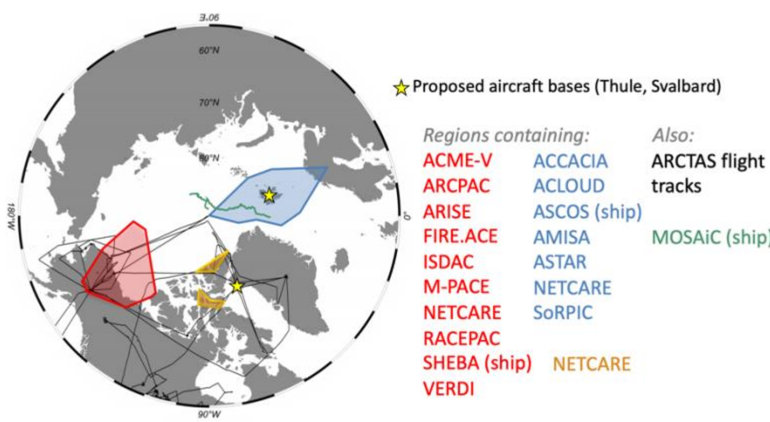

Figure 1: Location and tracks of select aircraft experiments in the Arctic, along with the trajectories of the ASCOS and MOSAiC ice breakers. Red: missions off the coast of Alaska; Green: Arctic Ocean; Blue: European/Russian Arctic; Brown: coastal Canada.

Understanding the causes and consequences of variability in the Arctic surface radiation budget (SRB) is essential because the investment of radiative energy into the system in the late spring and summer months strongly affects the sea ice extent in the Fall (Huang et al., 2019a). Yet, models generally do not reliably represent basic aspects of the unique regional aerosol, cloud, surface and radiative environment in the Arctic (e.g., Karlsson and Svensson, 2010; 2013; Cesana et al., 2012; English et al. 2015; Boeke and Taylor, 2016; Kay et al. 2016). Clouds in particular have been studied extensively because they act as primary modulators of the SRB, along with the surface reflectance, water vapor, and secondary factors such as the aerosol direct effect. Aircraft and surface-based observations over the past 20 years (**Fig. 1**) have led to significant advances in the understanding of cloud processes. For example, the longevity of mixed-phase stratiform clouds (Morrison et al., 2012) has been "de-mystified" to some degree through a number of case studies with large-eddy simulations (LES) based on prior airborne measurement campaigns (e.g., Fridlind and Ackerman, 2018). However, an evolving body of research is also calling for more statistics on a larger range of cloud types to answer new questions about processes such as glaciation, precipitation, coupling with surface properties and radiative effects.

1.2. Clouds – a major uncertainty for the future cryosphere

The radiative energy input into the Arctic surface depends strongly on the covariance between clouds and sea ice (Kay et al. 2008; Kay and Gettleman 2009; Kay and L'Ecuyer 2013; Hartmann and Ceppi 2014; Alkama et al. 2020). As Arctic sea ice varies, the cloud fraction and cloud properties are expected to respond, further affecting sea ice evolution and surface albedo. Moreover, this response may differ seasonally and exhibit a dependence on meteorological regimes, which are also shifting (e.g., Taylor et al. 2015: Morrison et al. 2018). In a seasonally sea ice-free Arctic, the role of clouds in modulating the SRB and setting the top-of-atmospheric albedo is much more important than when the bright sea ice surface is pervasive. **As primary modulators of the surface radiative budget, clouds are considered a major uncertainty for the future cryosphere.**

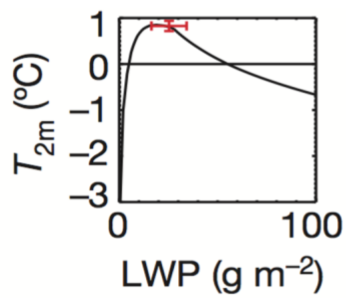

Figure 2: Low, thin liquid clouds raise air temperatures above freezing and accelerate melt. 2-meter temperature at Summit station as a function of the cloud liquid water path (LWP) around Summit, Greenland melt event (Bennartz et al., 2013).

Low-level liquid-containing clouds (hereafter referred to as low clouds) are ubiquitous across the Arctic (Cesana et al. 2012; Mioche and Jourdan 2018) and span a large range of optical thickness. They have a strong influence on the Arctic SRB (Shupe and Intrieri 2004; Kay and L'Ecuyer 2013; Boeke and Taylor 2016). In particular, optically-thin low liquid clouds with small liquid water path (LWP) values (Fig. 2) – played a key role in the wide-spread surface melting of the Greenland ice sheet in July 2012 (Bennartz et al. 2013). Clouds have an infrared (IR) warming effect for *any* LWP value, but also a "hot spot" in a limited LWP range (in the case of the Greenland melt event, around 30 g m^{-2}, **Fig. 2**). The maximum net warming effect at this value arises because the IR cloud emissivity increases *quickly* with LWP, warming the surface, whereas the shortwave cloud reflectance increases more *slowly*. The ratio between shortwave cooling and longwave warming and its dependence on LWP depends on the surface reflectance and solar zenith angle (Sedlar et al., 2011; Shupe and Intrieri 2004). This feature of low LWP clouds also operates over the Arctic sea ice, with an unknown effect on the surface radiative budget as these optically-thin low liquid clouds are frequently missed by passive remote sensing (Wendisch et al., 2019; Chen et al. 2020). Moreover, passive sensors cannot capture multi-layer clouds, which occur frequently over the Arctic but remain poorly documented (Matus and L'Ecuyer, 2017). While active sensors have provided valuable new insights on Arctic low clouds, they have "blind spots" inherent to the technique or due to orbital sampling. For example, CloudSat radar ground clutter prevents cloud detection below 1 km, while the CALIPSO lidar signal attenuates near an optical depth of three.

Another major uncertainty is the collective impact of summertime aerosols on Arctic cloud properties, and their impact on the regional SRB (Morrison et al., 2012; Kecorius et al., 2019). Arctic aerosols can noticeably change SRB-relevant cloud properties such as fraction, phase, droplet or crystal size, and precipitation efficiency (e.g., Coopman et al. 2018; Creamean et al. 2018; Maahn et al. 2017; Norgren et al. 2018; Solomon et al. 2018; Zamora et al. 2016, 2018). At low temperatures, Arctic clouds may be very sensitive to ice nucleating particle (INP) concentrations (Fridlind et al., 2012; Prenni et al., 2007). Under the clean conditions common in Arctic summer, small changes in cloud condensation nuclei (CCN) can also strongly influence cloud properties such as cloud droplet number and LWP (Leaitch et al., 2016; Mauritsen et al., 2011; Stevens et al., 2018; Tjernström et al., 2014). Combustion aerosol can also affect Arctic cloud fraction, phase, and precipitation, as observed during the winter and spring, when they are a dominant aerosol source type (e.g., Coopman et al. 2018; Norgren et al. 2018; Solomon et al. 2018; Zamora et al. 2017, 2018). Considering the present-day anthropogenic aerosol emissions in the Arctic from human activity (Willis et al. 2018), recent widespread retreat of Arctic glaciers and the associated changes in high-latitude dust (Tobo et al. 2019), and other environmental changes in the region, understanding the interactions between clouds, aerosols, and the SRB is another critical unanswered question.

1.3. Observational needs

Recent and ongoing observations in the Arctic (**Fig. 1**) address key questions about the interactions between the atmosphere, ocean and sea ice from the process to the climate scale. Although ground-based and airborne measurements provide the most complete "ground truth" data sets, particularly for cloud/aerosol properties and radiative/turbulent fluxes, only space-borne observations provide the spatial and temporal coverage to generalize case study-based findings. At the same time, monitoring long-term Arctic climate from space requires spatially and temporally representative airborne or ground-based measurements for uncertainty quantification and retrieval validation. Providing such airborne obserations was one of the motivations for the 2014 NASA Arctic Radiation – IceBridge Sea and Ice Experiment (ARISE, Smith et al., 2017), which targeted the Beaufort Sea during the sea ice minimum. Among other findings, it revealed significant biases in reanalysis products (Segal-Rozenhaimer et al., 2018; Dodson et al. 2020) and imagery-derived surface radiative fluxes under cloudy conditions (Chen et al., 2020). The field campaign results and research activities reinforce the notion of clouds as a major "wildcard" for the Arctic SRB, predictive models, and reanalysis products. This led to a community effort that defined the requirements for an Arctic cloud-radiation campaign (described in this white paper) to further our understanding of processes influencing the Arctic SRB and sea ice melt.

Four deliverables for such a campaign were identified:

- The statistically representative characterization of radiatively important lower-tropospheric cloud systems *regardless of observability from space*, in a manner that enables the identification of key cloud evolution processes (e.g., water vapor and aerosol sources, cloud formation, glaciation/phase partitioning, precipitation) as well as the quantitative representation of such processes in models on a range of scales;
- The characterization of surface reflectance and its spatial and temporal variability in response to precipitation and melting;

- Capture sea ice surface property and thickness evolution, including snow depth in spring to melt pond coverage and size distribution, and co-evolution with atmospheric conditions through recurring measurements of the same sea ice floes from pre-melt onset through the early melt season;
- Evaluation and innovation of remote sensing techniques for Arctic aerosol, cloud, and surface properties that enable the long-term observations.

These deliverables drive the ARCSIX design, including the preferred flight base location (Thule, Greenland, and possibly Svalbard), timing, the number of aircraft (two: a high-flying "remote sensing" aircraft and a low-flying "in-situ" aircraft).

1.4. Climatology

Clouds: Low liquid clouds (< 3.4 km) are common across the Arctic and exert a strong influence on the SRB (e.g., Curry et al., 1996; Shupe and Intrieri, 2004; Stramler et al., 2011; Cesana et al. 2012; Matus and L'Ecuyer 2016). Low liquid cloud fraction varies regionally (**Fig. 3**, middle row), exhibits a frequency that depends on the synoptic state (Stramler et al., 2011; Cesana et al., 2012), and is larger than ice clouds (e.g., Cesana and Chepfer, 2013). During the months of May to July, sea ice melt is beginning; cloud fraction can be as high as 90% (**Fig. 3**, top row), mostly due to liquid clouds forming in the lower free troposphere (z < 3.4 km, **Fig. 3**, bottom row). During this period, liquid clouds occur 50 to 80% of the time in the Fram Strait, North Greenland, and Beaufort Sea regions (**Fig. 3**; Cesana et al., 2012; Mioche et al. 2015; McIlhattan et al. 2017); clear-sky conditions prevail in all regions >10% of the time (**Table 1**). A substantial portion of these clouds form at sub-freezing temperatures, placing these clouds into the often-precipitating mixed-phase cloud regime. The fraction of liquid-containing clouds that are precipitating during May to July is ~10% (McIlhattan et al., 2017), although this percentage is highly uncertain.

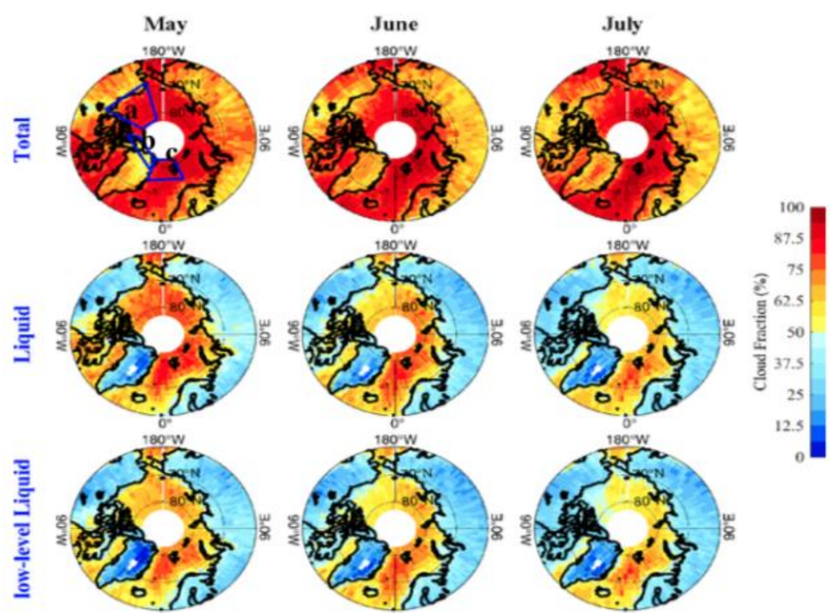

Figure 3: Monthly climatology (2006-2016) of total, liquid-containing and low-level (< 3.4 km) liquid-containing cloud fraction (%, from top to bottom) during May, June and July (from left to right) over the Arctic. This figure shows that the cloud fraction over the ice-free Arctic Ocean is mostly contributed by liquid-containing clouds. The potential study regions are marked in blue in the top left plot: a: Beaufort Sea, b: North of Greenland, and c: North Atlantic/Fram Strait. Data were obtained from the CALIPSO-GOCCP dataset, version 3.1.2, for the time-period 2006-2016.

The Arctic net surface CRE exhibits a seasonal dependence, warming the surface most of the year and cooling the surface during summer (Kay and L'Ecuyer 2013; Boeke and Taylor 2016). Matus and L'Ecuyer (2016) indicate that liquid-containing and mixed-phase clouds (with a -5 to -10 W m^{-2} net CRE) cool the surface during summer. May through July represent a period of rapid change in the net surface CRE from a net warming in May to a net cooling in July based on CERES data (Boeke and Taylor 2016); a feature that climate models struggle to accurately represent, simulating too rapid a transition and too strong a cloud cooling effect.

Table 1: CALIPSO-based climatology (June, 2006-2016) of cloud regimes in three candidate regions.

Region	N	% Clear	Shallow	Mid-/multi-level	Deep/cirrus
North of Greenland	47	26	36	17	21
North Atlantic/Fram Strait	43	7	26	58	9
Beaufort Sea	37	11	46	35	8

Sea ice surface albedo: Sea ice properties and surface reflectance over the Arctic Ocean during the early melt season are continuously evolving (Perovich et al., 2002). It is driven by the occurrence and depth of snow (fresh or old), blowing and melting snow, surface roughness/topography, bare ice, melt ponds (Malinka et al., 2018), draining of melt ponds, leads, new ice formation in leads, rain on snow, dust deposition, and even algae blooms (as reported during Operation IceBridge flights). As a result of these factors, the sea ice surface albedo and reflectance declines through early summer (Perovich et al. 2002). Sedlar et al. (2011) and many others demonstrate that the SW cooling effect of clouds is significantly reduced over brighter surfaces. The surface albedo changes from May through July due to sea ice melt, indicating that the change in the CRE during the early melt season is influenced by a change in the surface albedo in addition to cloud property changes (Kay and L'Ecuyer 2013; Sledd and L'Ecuyer 2019; Alkama et al 2020).

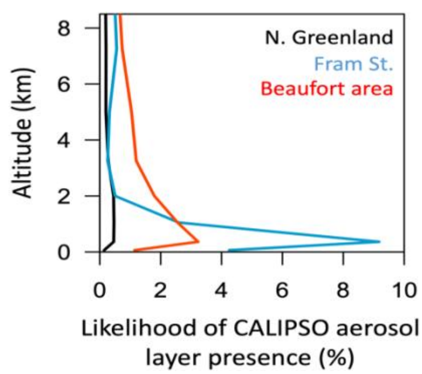

Figure 4: The likelihood of CALIPSO-detectable aerosol layer presence at different altitude levels in each region between May-July. Estimates are based on the area-averaged percent of the time in which a high-confidence CALIPSO aerosol layer was detected in cloud-free conditions (2006-2017). These data show the generally clean conditions in all three regions, and the fact that we are more likely to capture aerosol events over the Fram Strait than over the North Greenland and Beaufort regions, particularly at the lower altitudes.

Aerosols: During May-July, all three regions in **Fig. 3** are generally dominated by clean background aerosol conditions (**Fig. 4**). Long-range transport events can bring high concentrations of smoke, dust, and pollution into the summertime Arctic (e.g., Soja et al. 2008). Local aerosol sources from exposed soil, mining, and industry can also be important, impacting CCN and cloud properties (Schmale et al., 2017; Creamean et al., 2018; Maahn et al., 2017). Overall, the amount of externally-sourced aerosol is low due to the relatively high rainfall in the subarctic and reduced long-range transport from lower altitudes (Engvall et al., 2008; Stohl, 2006). Local aerosol sources from the open ocean and melt ponds are expected to dominate during summer.

Arctic Ocean regions in summer are typified by a high relative fraction of aerosols with diameters <100 nm, likely related to marine biogenic secondary organic aerosol formation (Croft et al., 2016; Koike et al., 2019) with the potential to grow to CCN sizes (Willis et al., 2018). Small particle concentrations are highly variable, ranging from 10^1-10^4 cm^{-3} (Collins et al., 2017). As a result, the summertime low liquid clouds expected during ARCSIX often contain low droplet concentrations (i.e., < 100 cm^{-3}) (e.g., Hobbs and Rangno (1998)). Field campaign-derived CCN concentrations typically range between 1-100 cm^{-3} at supersaturations between 0.3-0.8%, but concentrations below 10 cm^{-3} are fairly common, particularly poleward of 80°N (Bigg and Leck, 2001; Lannefors et al., 1983; Leaitch et al., 2016; Leck et al., 2002; Leck and Svensson, 2015; Mauritsen et al., 2011; Stevens et al., 2018). Under weak inputs of long-range transports, the ocean also serves as a potentially important source of INPs (Burrows et al., 2013; Wilson et al., 2015; DeMott et al. 2016; Bigg 1996). Glacial dust—a new Arctic aerosol source—from locations near the Fram Strait (Groot Zwaaftink et al., 2016; Tobo et al., 2019) is thought to be a particularly effective INP source (Tobo et al., 2019).

1.5. Observations—Limitations and Opportunities

In the Arctic, the contrast between clouds and underlying bright surface is weak, which makes the detection of clouds challenging, particularly when using passive imagery to detect optically or geometrically thin liquid-containing low clouds. Precise knowledge of their total and relative frequency of occurrence and their microphysical properties is crucial to estimating polar cloud feedbacks (e.g., Gettelman and Sherwood, 2016) and ice sheet (e.g., Bennartz et al., 2013) and sea ice melt (Stramler et al., 2011). With respect to sea ice, ICESat-2 has provided an unprecedented ability to monitor sea ice thickness, however large uncertainties remain in summer measurements due to the prevalence of melt ponds (Kwok et al. 2019). For aerosols, the bright surface, generally low aerosol optical depth (AOD) and low sun angle also make retrievals with broad-swath, passive and even multi-angle imagers difficult or impossible, often leading to a reliance on poorly validated aerosol transport models (Duncan et al., 2020). Arctic precipitation also remains greatly underestimated (Mclhattan et al., 2017) contributing to uncertainties in the cloud life cycle and surface radiative properties.

With the launch of CALIPSO and CloudSat in 2006, it became much easier to observe the presence and properties of liquid-containing clouds and aerosols (e.g., Cesana et al. 2012). ICESat-2 lidar measurements also provide complementary cloud fraction and vertical profile measurements (Palm et al. 2010). Radiative flux products derived from merged active and passive remote sensing such as 2B-FLXHR-LIDAR (Henderson et al., 2013) and C3M (Kato et al. 2010; 2011) capitalize on the joint information in complementary techniques (thick cloud detection and light precipitation from radar, thin cloud and aerosol detection from lidar; cloud optical properties from radar and passive imagery) and improve our estimates of Arctic SRB. However, these active-sensor products have not been extensively validated with airborne or surface-based measurements in the Arctic. As a result, satellite retrievals of cloud-, aerosol- and thermodynamic-related quantities (amount, phase, water content, optical depth, temperature, wind) exhibit non-negligible uncertainties (e.g., Cesana et al. 2016; Chepfer et al. 2013; Lebsock and Su 2014; Mclhattan et al. 2017; Stubenrauch et al. 2013) that limit our understanding of weather and climate processes, and translate into poorly constrained climate models (Cesana et al. 2012, 2015; Cesana and Waliser 2016; Klein et al. 2009, 2013; Mclhattan et al. 2017). This, in turn, limits our confidence in climate projections.

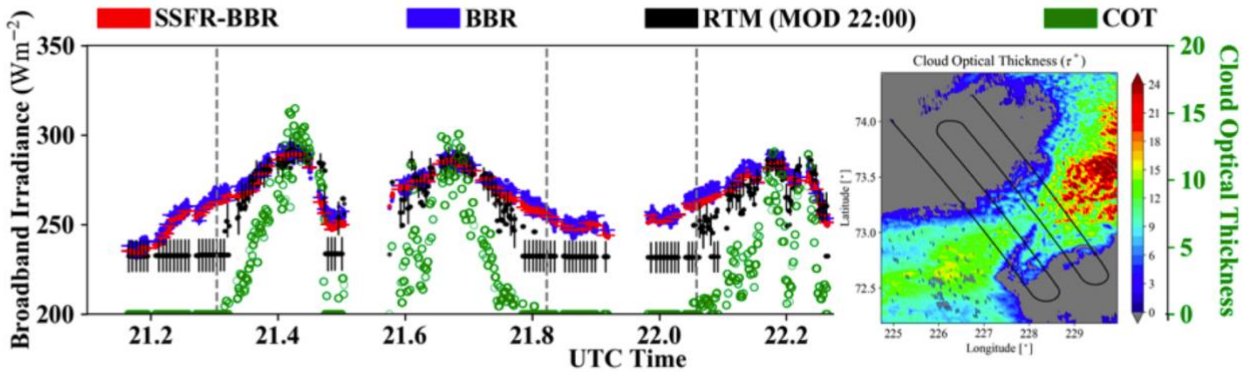

Figure 5: Pixel-by-pixel inter-comparison of broadband upwelling solar irradiance above clouds overlying snow/ice with collocated imager-derived values (via MODIS cloud optical thickness, COT). The irradiance was sampled by the Broadband Radiometer (BBR) and the Solar Spectral Flux Radiometer (SSFR) during the ARISE campaign.

Aircraft validation of radiative fluxes derived from imagery during ARISE suggests that clouds below an optical thickness of 2 went undetected (**Fig. 5**; from Chen et al., 2020) – about a third of the clouds in this case study. Wendisch et al. (2019) show similar results for a campaign near Svalbard. If such thin clouds are a common occurrence over sea ice (as expected), their net warming effect (at least in the shoulder seasons) could be significantly underestimated, while new research suggests that during the summer months their impact on surface temperature is minimal (Maillard et al., 2020).

Figure 6 (from Segal-Rozenhaimer et al., 2018) illustrates the utility of airborne measurements for validating atmospheric temperature profiles from reanalysis products for two surface regimes – open ocean and sea ice. The discrepancies near the surface (~3K) are significant, limiting our ability to understand the relationship between clouds and their thermodynamic environment as well as quantifying cloud radiative effects. Uncertainty in temperature and humidity profile data represents a key source of uncertainty in our knowledge of the Arctic SRB (Kato et al. 2018).

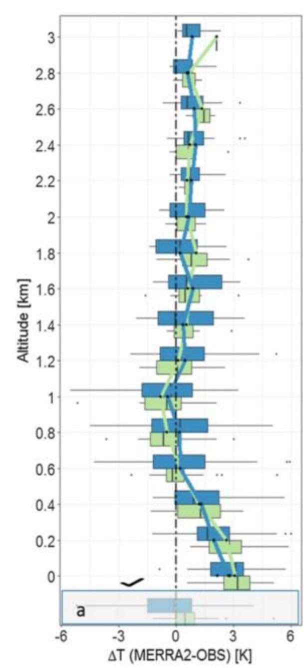

Figure 6: Difference between MERRA-2 temperature profiles and observations above ice (blue) and open water (green) during ARISE.

Aircraft observations also give direct access to Arctic surface albedo and its variability (e.g., Wendisch et al., 2019; Chen et al., 2020). Most large-scale models and remote sensing approaches do not account for the variability of surface reflectance – a situation that can be resolved through development and evaluation of Arctic-specific remote sensing algorithms that are validated by systematic aircraft observations. In addition, while the summertime *direct* radiative effect of aerosols in this region is likely small, *indirect* aerosol effects are potentially significant and highly uncertain. Aircraft measurements are the only way to access the required observations for both *direct* and *indirect* aerosol effects. For example, validation of Arctic aerosol transport modeling and sources is sorely lacking (particularly at the sea ice edge and for CCN or INPs, complex aerosol, and in-cloud particle chemistry). These uncertainties are compounded by the fact that CALIPSO and other remote sensors frequently miss dilute aerosol layers (**Fig. 4**), which may include marine aerosol and local dust emissions that could nonetheless be important cloud-active aerosol sources (Tobo et al., 2019; Burrows et al., 2013; Wilson et al., 2015). Moreover, the absence of CALIPSO-detectable aerosol layers does not mean that aerosol layers are not present. This further motivates *in situ* observation of the aerosol environment in this region.

ARCSIX provides the opportunity to fill many of these gaps. Since FIRE.ACE 20 years ago, observational technology, remote sensing algorithms, sampling strategies, and conceptual/process model understanding of Arctic clouds and their coupling with the surface have all significantly advanced. For example, Raman lidars are now capable of retrieving temperature and humidity profiles as *curtains* along the flight track of a low-flying aircraft; similarly, high-spectral resolution lidars (HSRL) provide cloud and aerosol extinction profiles; multi-frequency radar systems far exceed their space-borne cousins; they are sensitive to precipitation, while offering scanning, Doppler, and polarimetric capabilities for assessing cloud dynamics. In addition, advancements have improved our ability to detect INP concentrations at lower thresholds. These developments set the stage for rapid science advances in our understanding of the Arctic SRB and sea ice melt with ARCSIX.

1.6. Multi-scale Modeling Challenge

Alongside observational advancements, modeling capabilities have improved significantly over the last 20 years. For instance, the large-ensemble approach to climate modeling has led to a better understanding of the role of natural variability in the Arctic (e.g., Kay et al. 2015). Improved physics-based parameterizations for processes such as cloud microphysics and ice formation have also been widely implemented, transferring findings from field observations into the numerical weather prediction and climate modeling domains. Lagrangian LES studies (Pithan et al. 2018; Neggers et al., 2019; Goren et al., 2019; de Roode et al., 2019) are emerging as a tool to study the evolution of clouds in an advecting air mass, rather than in the traditional Eulerian framework. However, significant uncertainties remain. Because the Arctic is an interconnected, continuously evolving, and multi-scale system, modeling it is fraught with complexity. Much of this complexity stems from non-linear interactions between the multiple dynamic, thermodynamic, microphysical, and radiative processes occurring at the air-water-ice interface. Advancing our understanding requires the integration of process, weather, and climate models with observations enabling the simultaneous characterization of local processes and large-scale advection required to drive and constrain model simulations.

Surface albedo is a key factor influencing seasonal, decadal, and multi-decadal sea ice predictions and projections within the Arctic climate system. The large-scale Arctic surface albedo is not only influenced by the reduction in snow and sea ice area but also by the darkening of these surfaces due to increased melt pond formation, snow melt, transition from perennial to first-year ice, black carbon deposition, etc. Alternatively, Arctic precipitation changes also affect surface albedo as snowfall brightens the surface; however, climate projections indicate a transition from solid to liquid precipitation (Bintanja and Andry 2017) with the potential to accelerate sea ice melt and reduce surface albedo. Climate models also exhibit significant differences in the contributions of sea ice area loss and reduced sea ice albedo to surface albedo change (personal comm. M. Holland). Quantifying the relationship between melt pond fraction and sea ice albedo is needed to serve as the basis for model parameterizations.

Statistical and dynamical approaches can skillfully predict pan-Arctic SIE (Sea Ice Extent) at lead times ranging from 1-6 months, but the current levels of skill are generally too modest to offer significant practical utility (Wang et al. 2013, Sigmond et al. 2013, Chevallier et al. 2013). Crucially, the forecast skill of these systems is substantially lower than estimates of potential prediction skill as quantified by "perfect model" experiments, suggesting that future improvements in Arctic sea ice predictions are possible (Tietsche et al. 2014, Bushuk et al. 2018). Closing this skill gap requires improved initial conditions of sea ice albedo and reductions in model error of the sea ice albedo evolution.

The surface state of Arctic sea ice in spring and early summer provides a key control on its evolution through the melt season. In particular, the areal fraction of spring surface melt ponds has been shown to be a skillful predictor of the September SIE minimum (Schroder et al. 2014, Liu et al. 2015). This predictive skill is attributed to the ice-albedo feedback: early melt onset reduces surface albedo, increases absorbed shortwave radiation, melts additional snow and sea ice, and further lowers the albedo. Additionally, spring anomalies of downwelling longwave radiation and atmospheric water vapor have been shown to skillfully predict September SIE, and a similar melt onset and ice-albedo feedback mechanism has been proposed (Kapsch et al. 2014). Recent work indicates a spring predictability barrier for Arctic sea ice (Bushuk et al. 2017), in which forecasts initialized prior to May 1 have substantially less skill than those initialized after May 1. Given this barrier, data collected in the months of May, June, and July are particularly valuable for September sea ice predictions (Huang et al. 2019a).

Clouds also represent a significant multi-scale modeling challenge in the Arctic. Arctic cloud properties in climate models impact the SRB by (1) responding to Arctic climate change and (2) modifying the SRB response to Arctic sea ice loss. Climate and weather models exhibit significant Arctic cloud biases, including unrealistic cloud cover, often too little supercooled liquid and too much cloud ice, and unrealistic seasonal variations that result in large biases in the SRB (English et al. 2015; Li et al. 2012; Cesana et al. 2012; Kay et al. 2016; Komurcu et al. 2014; Karlsson and Svensson 2010; Karlsson and Svensson 2013; Boeke and Taylor 2016; Segal-Rozenhaimer et al., 2018; Taylor et al. 2019; Dodson et al. 2020). Climate, weather, and process models generally struggle to simulate these cloud systems. This is due to: 1) general difficulties with sustaining cloud liquid water due to multi-phase processes that involve complex interactions among vapor, liquid, and ice; 2) difficulties capturing the atmospheric boundary layer structure, surface property evolution, and the interactions with clouds; 3) deficiencies in our understanding of the interactions between surface type dependent turbulent fluxes with clouds and the atmospheric boundary layer; and 4) a lack of knowledge of Arctic aerosols, their properties, sources, vertical distribution, and interactions with clouds. Key microphysical processes that contribute to these biases include ice formation, ice properties (size, shape, phase), aerosol scavenging, ice cloud radiative properties, and aerosol-cloud interactions as well as cloud top radiative cooling and surface turbulent fluxes (Sulia and Harrington, 2011; Jackson et al., 2012). The cloud challenge itself is multi-scale as the relative influences of dynamical and microphysical processes operating at the micron and second space and time scales interact with the large-scale advection processes operating at the several thousand-kilometer scale and over the course of hours to days must be considered. ARCSIX provides the critical data to synergistically leverage process and large-scale models to advance our understanding of these key processes and improve cloud parameterization.

2. Science Objectives

ARCSIX focuses on 1) the sea ice north of Greenland, the last bastion of multi-year sea ice in the Arctic, 2) the sea ice to the east, which is a region of rapid climate change, and 3) the Fram Strait, through which large pulses of moisture enter the Arctic. Even north of Greenland, the sea ice is now punctuated by the formation of persistent polynyas caused by off-shore winds (http://marine.copernicus.eu/last-sea-ice-area-arctic-breaks-up/) and an increasing areal extent of melt ponds.

ARCSIX is organized around three science questions focused on radiation, cloud life cycle, and sea ice and processes (**Fig. 7**):

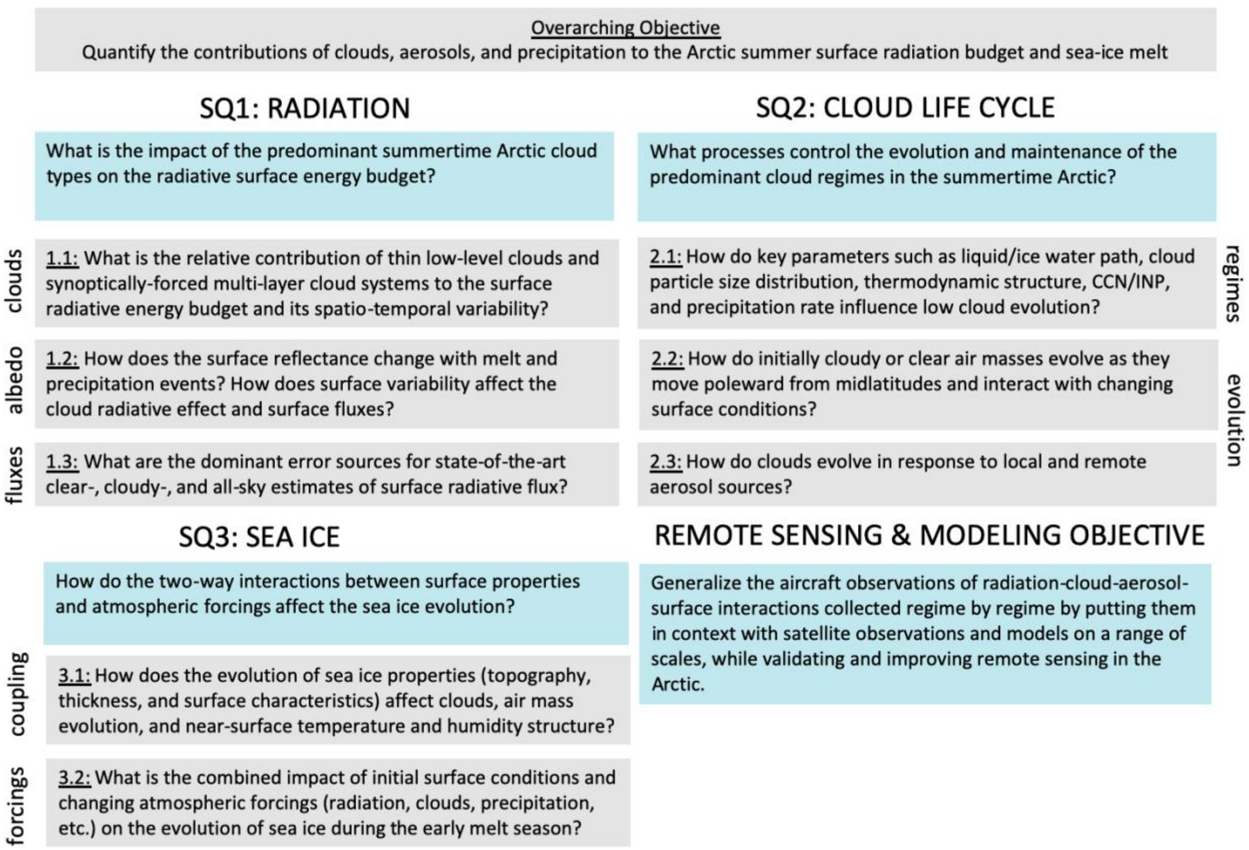

Figure 7: ARCSIX Science Objectives

2.1. Science Question 1 (Radiation)

Even without clouds, it is challenging to determine the SRB from space because of the difficulty in capturing near-surface structure of temperature and water vapor, as well as the spatial, temporal, and spectral variability of surface albedo. Clouds complicate the situation significantly because of the weak contrast relative to ice and snow throughout much of the solar wavelength range, and due to similar brightness temperatures of low clouds and the underlying surface. Summertime clouds in the Arctic are often optically thin, which means that a significant fraction of them could go undetected, with largely unquantified and potentially substantial effects (Fig. 2) on the SRB.

ARCSIX takes on these challenges by providing measurements of cloud microphysical properties along with their radiative effects (SQ1.1) and relating them back to satellite observations, by mapping surface reflectance (SQ1.2), and by sampling atmospheric vertical structure (SQ2), all of which affect the surface radiative flux (SQ1.3), and thereby sea ice evolution and melt processes (SQ3). Because radiative effects and associated measurement biases are *cumulative* over the melt season, it is imperative to characterize the SRB and evolution of the sea ice floe and snow pack characteristics through a sufficiently long period of net "investment" of radiative fluxes into the surface.

For a recent campaign, **Figure 8** illustrates that key radiative observations cluster around hotspots in a parameter space (here, spanned by surface albedo and net surface radiative flux), which we call *radiative regimes*. ARCSIX seeks to sample these regimes statistically over the duration of the campaign, quantify any biases between aircraft observations, space-borne remote sensing, and numerical weather prediction (NWP) modeling, and link those back to the underlying processes in SQ2. Sampling emphasis is placed on cloud-containing regimes and occurrences of on-ice advection, thought to be significant factors influencing sea ice melt (Pithan et al. 2018; Hegyi and Taylor 2018; Huang et al. 2019a,b).

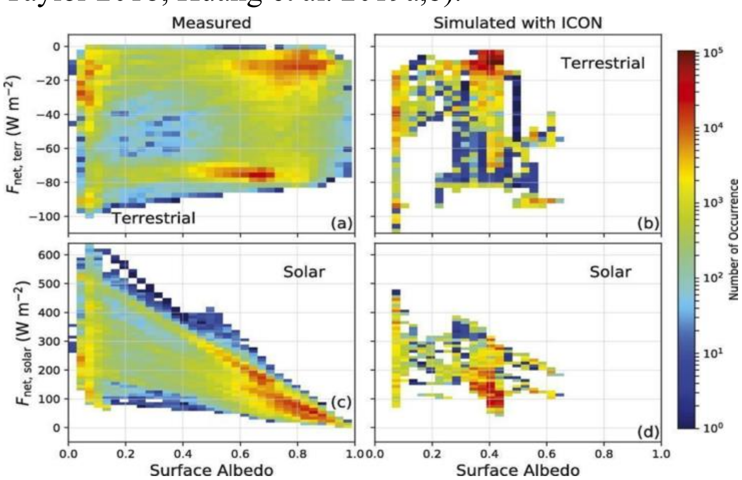

Figure 8: Radiation statistics for the ACLOUD campaign (Wendisch et al., 2019) along low-level legs: Net irradiance (longwave: top; shortwave: bottom) as a function of surface albedo (temperature) as measured (left) and modeled by NWP (right). The four modes correspond to cloudy and clear conditions, and above snow/ice and open ocean. For example, the longwave broadband irradiance at -20 (-80) W m^{-2} is indicative of clouds (clear sky) above the aircraft. From Wendisch et al. (2019).

Sampling distinct regimes in detail enables the integration of the observations into remote sensing (remote sensing and modeling objective, Fig. 7). The concept of regimes will be used to associate the spatially and temporally limited field measurements with environmental conditions that can be observed much more extensively with remote sensing and simulated in models, so the detail provided by field data can be applied more generally.

2.1.1. Science Question 1.1

SQ1.1: What is the relative contribution of thin low-level clouds and synoptically-forced multi-layer cloud systems to the surface radiative energy budget and its spatio-temporal variability?

A key question is which cloud types most strongly drive SRB variability and thus modulate the flux of energy into the surface during the early melt season. Recent results from ARISE (Chen et al. 2020; **Fig. 6**) and ACLOUD (**Fig. 8**; Wendisch et al., 2019) suggest that space-based passive remote sensing algorithms may miss as much as one-third of radiatively-relevant, optically thin (single-layer), low clouds over sea ice. ARCSIX aims to determine the relative contribution of optically thin, low-level clouds and multi-layer cloud systems to the longwave and shortwave components of the SRB and its variability, starting from the following hypotheses:

- *Hypothesis 1.1a: During the early melt season (May-July), low (< 3.4 km), single-layer clouds contribute at least as much to the cumulative surface cloud radiative effect above the ice north of Greenland as multi-layer cloud systems.*
- *Hypothesis 1.1b: Heritage passive-imagery cloud retrievals detect less than 50% of low clouds with COD<2, leading to the underestimation of surface warming by low, single-layer clouds.*

Approach (details on observations and implementation in §3)

- Characterize cloud systems with coordinated legs of a high-flying aircraft (active and passive remote sensing for cloud properties and thermodynamic profiles) and a low-flying aircraft (*in-situ* cloud microphysical properties, cloud property vertical profiles, and radiation).
- Systematic, recurring radiative closure flights over the same sea ice floe (collocated and mutually consistent *in-situ* and radiation measurements along with remote sensing observations) conducted in cloudy and clear-sky surface conditions measuring the below-cloud and above-surface radiation fields.
- Radiative flux and imager observations (CERES and MODIS) from polar orbiters to extend aircraft observational record in space and time to characterize the CRE and cloud type frequency of occurrence.
- Evaluate the skill of current satellite algorithms to (1) detect optically thin low clouds and (2) characterize multi-layer clouds (abundance, phase partitioning, CRE); improve retrieval algorithms with aircraft observations.

2.1.2. Science Question 1.2

SQ1.2: How does the surface reflectance change with melt and precipitation events? How does surface variability affect the cloud radiative effect and surface fluxes?

Anomalies in the SRB early in the melt season have emerged as a good predictor of anomalies in September sea ice extent (Huang et al., 2019a), raising the importance of understanding the relationship between the surface properties, precipitation and radiation at appropriate scales. Yet satellite surface albedo, reflectance, and precipitation products are either unavailable, insufficiently calibrated, or too coarse spatially or temporally to resolve the relevant melting and thawing processes from space with adequate accuracy. For this reason, we require high-resolution and accurate aircraft observations to develop more reliable space-borne surface albedo and reflectance products, and, in the short-term, to test the following hypotheses:

- *Hypothesis 1.2a: Spatial heterogeneity of surface albedo (increasing significantly during the early melt season) dictates the formation and spatial distribution of melt ponds later on.*
- *Hypothesis 1.2b: Precipitation events reduce surface albedo heterogeneity before melt pond formation and enhance surface albedo heterogeneity after melt pond formation.*
- *Hypothesis 1.2c: Surface albedo variability has a greater impact on the shortwave cloud radiative effect than the cloud properties themselves.*

Approach (details on observations and implementation in §3)

- Determine and monitor surface albedo and bi-directional surface reflectance, their spatial heterogeneity and temporal evolution throughout the region for the duration of the campaign using airborne and satellite radiometer and imager data. If possible, monitor other factors such as sea ice topography and snow depth.
- Precipitation and melt pond area coverage measurements from airborne and satellite imager measurements with repeated samples to assess impacts of precipitation on surface albedo and bi-directional surface reflectance.
- Develop/evaluate new/existing satellite products (e.g., surface reflectance, atmospheric heating rate, precipitation) in the region.

2.1.3. Science Question 1.3

SQ1.3: What are the dominant error sources for state-of-the-art clear-, cloudy-, and all-sky estimates of surface radiative flux?

This radiation science question is the synthesis of SQ1.1 and SQ1.2 with the high-level goal of deriving the surface radiative fluxes with minimal errors to estimate the cumulative impact of radiation on melt processes in the region. Errors in the surface fluxes stem from cloud detection and retrieval limitations (SQ1.1), surface albedo and reflectance uncertainty (SQ1.2), and vertical cloud and thermodynamic structure (SQ1.1/SQ2.1). Their contributions to the overall error budget vary by atmospheric regime (e.g., clear vs. cloudy, different types of cloud, aerosol, and atmospheric thermodynamic state) and surface conditions. Obviously, aircraft observations cannot cover every point for the entire melt season. They can, however, provide statistics of key parameters that can be used to understand errors in satellite-based radiative flux and cloud property retrievals and model simulations, as illustrated in **Fig. 8**. To this end, ARCSIX aircraft observations will be used to test the following hypotheses:

- *Hypothesis 1.3a: Under clear-sky conditions, surface albedo and lower-tropospheric temperature structure are the respective dominant error sources for imagery-based surface SW and LW radiative flux estimates.*
- *Hypothesis 1.3b: Under cloudy-sky conditions, undetected low, thin clouds over sea ice are the dominant error source for imagery-derived surface SW and LW radiative flux estimates.*

Approach (details on observations and implementation in §3)
- Evaluate satellite- and model-derived near-surface radiative fluxes by regime (various cloud/surface types, clear, etc.) using collocated aircraft (radiative fluxes, surface albedo and spectral reflectance, cloud and aerosol optical properties, as well as temperature and humidity profile observations).
- Attribute errors separately for clear/cloudy SW/LW surface flux estimates.
- Assess the cumulative surface cloud radiative effect in the region over the duration of the campaign by nudging satellite- and model-based estimates with aircraft observations.

2.2. Science Question 2 (Cloud Life Cycle)

Addressing key unanswered questions on cloud processes, their radiative impacts and coupling with surface properties requires consideration of the complete cloud lifecycle with adequate characterization of the aerosol, moisture, and surface environment. Understanding the controls and influences of clouds and aerosols on the Arctic SRB requires an observational data set that is complete by several measures. First, we require statistically robust observations of the surface, aerosol, and meteorological parameters that directly determine radiative flux profiles. Second, we need sufficiently extensive observations of specific coherent cloudy scenes to develop process modeling case studies. For instance, large-scale models vary widely in their ability to reproduce low clouds across the Arctic (i.e., liquid- or ice-containing, optically thin or thick and/or multi-layer clouds; e.g., Cesana et al. 2015) and exhibit biases that depend upon the meteorological regime with implications for cloud phase feedback (e.g., Tan et al. 2016) and predicting changes in the SRB. Addressing SQ2 relies on aircraft observations in the case of CCN/INP concentration fields, details of thermodynamic structure (e.g., water vapor structure), precipitation (e.g., ice morphological properties), process occurrence (e.g., riming or aggregation), and cloud top and base radiative heating rates.

2.2.1. Science Question 2.1

SQ2.1: How do key parameters such as liquid/ice water path, cloud particle size distribution, thermodynamic structure, CCN/INP, and precipitation rate influence low cloud evolution?

The process interactions that regulate Arctic low liquid cloud evolution range from microphysical processes/properties to the large-scale atmospheric thermodynamic and dynamic state. Many questions remain about how these scales interact and the role of specific key processes/parameters in determining Arctic low cloud evolution.

Figure 9 summarizes our current hypothesized understanding of the main processes involved in the formation and evolution of widespread Arctic liquid-containing clouds. Cloud formation requires clear-air to reach saturation, occurring either through a source of weak large-scale ascent or clear-sky radiative cooling. The air in which cloud formation occurs may be advected from lower latitudes, in which case it is generally warmer and moister than the air below. As it encounters colder ocean and sea ice surfaces, a recently established conceptual model shows how near-surface fog may commonly first accompany the stable arrangement of warmer air over a colder surface, followed by increasing cloud top and base heights (Tjernstrom et al. 2019). This presents a contrast to the more familiar cold air outbreak structure that results from off-ice flow of colder air over a warmer surface (e.g., Wang et al. 2016), where surface coupling is driven from an unstable surface layer. In aged Arctic air masses transiting sea ice, liquid-containing clouds commonly occurring at temperatures >-35°C may alternatively first appear as a thin supercooled liquid layer that may or may not be coupled with the surface (e.g., de Boer et al. 2011, Silber et al. 2019). Once a liquid layer forms, longwave radiative cooling increases substantially, potentially leading to turbulent mixing in the case of an initially decoupled cloud. It is only after supercooled liquid is present that ice particle formation generally begins (de Boer et al. 2011)—the immersion freezing process. Once ice crystals are present, they grow and precipitate rapidly into and below the supercooled liquid layer, thus serving as a moisture and INP sink from the liquid-containing

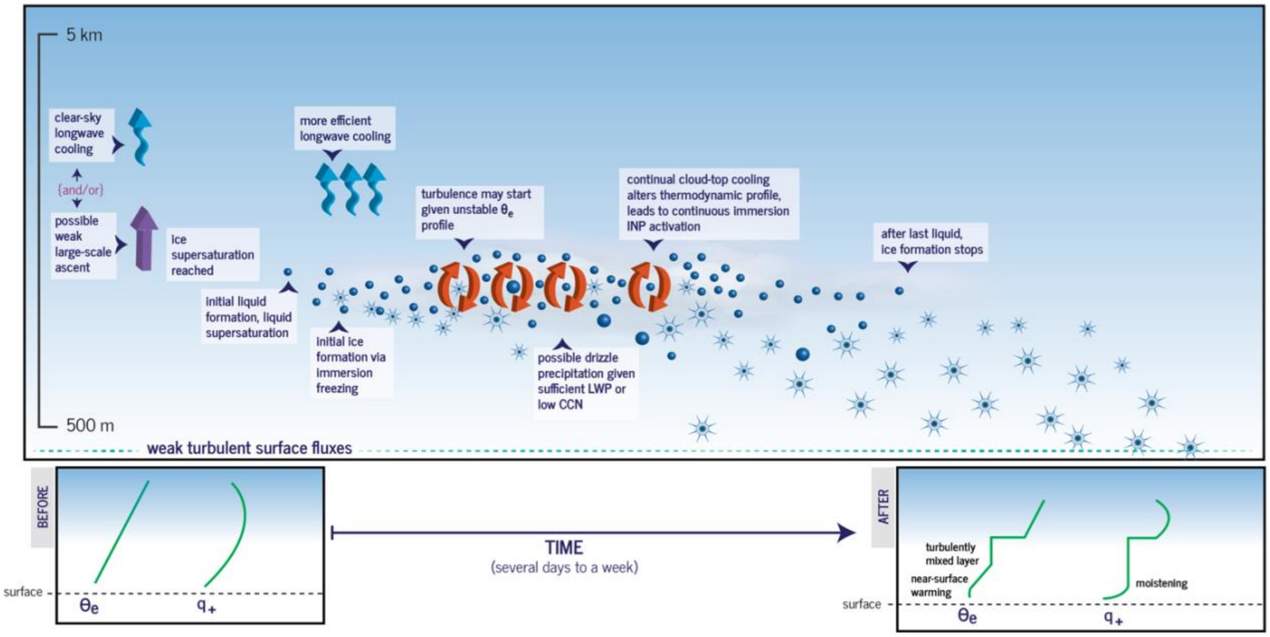

Figure 9: Thin, low cloud processes: Ascending or cooling air, possibly associated with the advection of a warm, moist air mass, first generate a supercooled liquid cloud, which then provides the conditions capable of supporting efficient ice nucleation (Graphic design by Aimee Amin).

cloud layer. The initial spatial and vertical variation of specific humidity, CCN and INP influence other processes that affect cloud evolution, including the presence of drizzle (at low CCN and sufficient LWP) and the ice crystal number. Continued cloud top radiative cooling may provide a means of entraining ambient air into the cloud layer, replenishing the INPs lost to precipitation. Depending upon the initial specific humidity and temperature characteristics, CCN/INP concentration and composition, and the presence and magnitude of large-scale advection replenishing INP/CCN and moisture, the liquid-containing layer can persist over hours or days. During this time, the cloud layer increases the downwelling longwave radiation to the surface, may turbulently mix the atmosphere, and remove INPs. After liquid formation stops and the last ice crystal precipitates or sublimates, the result is a distinct, turbulently mixed layer and a warmer surface temperature due to the radiative effect of the cloud layer over time.

Past field experiments have advanced our understanding of Arctic cloud processes and their radiative impacts, especially for single-layer mixed-phase cloud systems and spurred important technological advances. Detection limits and uncertainties of INP measurements have been reduced in recent years (DeMott et al., 2018), and methods have been refined to ascertain the source composition of INPs (Kanji et al., 2017). Water vapor mixing ratios can be measured with higher precision and at far greater spatio-temporal resolution. This means more robust tests of ice nucleation parameterizations, as a function of mechanism, can be determined over a more diverse set of atmospheric conditions. Since immersion freezing appears as the dominant ice nucleation pathway in the Arctic, nucleating clouds much more efficiently than depositional or contact freezing (**Fig. 10**), this implies that even fully glaciated ice clouds commonly encountered in the Arctic have likely been preceded by the liquid phase. Therefore, quantifying the frequency of immersion freezing in comparison to other ice formation mechanisms provides a strict constraint on model microphysical process parameterizations.

A comprehensive set of measurements on cloud, aerosol and precipitation characteristics is required to test the following hypotheses:

- *Hypothesis 2.1a: Arctic cloud systems most important to sea ice melt are formed and maintained primarily by advection of moisture and CCN from lower latitudes, radiative cooling, and (when supercooled) a sparsity of INP owing to both low ambient concentrations and rapid consumption.*
- *Hypothesis 2.1b: Pre-existing water vapor structure largely determines initial water cloud vertical structure upon formation, the magnitude of longwave radiation cooling, and turbulence.*
- *Hypothesis 2.1c: Immersion freezing is responsible for effectively all (>90%) ice formation in clouds with tops warmer than -35°C.*

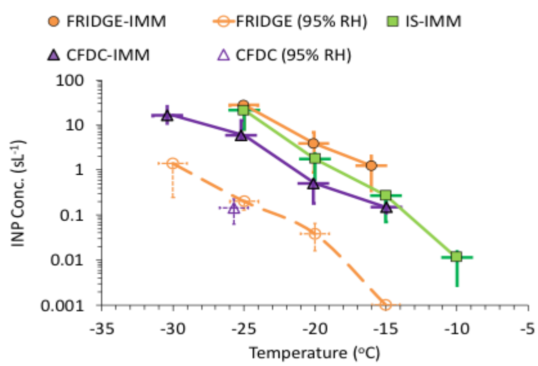

Figure 10: Immersion freezing ("-IMM") is more effective than deposition ice nucleation at near-saturated (95% RH) conditions. Larger sample volumes and new methods reduce measurement uncertainties and extend the temperature range assessed. ARCSIX will articulate the dependence on temperature and characterize the composition of aerosols acting as INPs in the Arctic region. Data sources: Ambient data are from real-time (CFDC) and offline (FRIDGE, IS) ice nucleation measurements during the Fifth International Ice Nucleation Workshop (2015), courtesy of Paul DeMott and Heinz Bingemer.

Approach (details on observations and implementation in §3)

- Collect measurements of aerosol and cloud evolution parameters (including liquid and water content, LWP/IWP, cloud liquid and ice particle size distribution, in-cloud turbulence, aerosol size distribution and composition, CCN/INP concentration and composition, INP mode, precipitation, and cloud top radiative fluxes) concurrently with thermodynamic profile information from the surface up to ~5 km to characterize the spatial and temporal variability.
- Perform flights to sample conditions below, in, and above clouds in a range of meteorological regimes to assess the influence of different microphysical processes on cloud properties as a function of atmospheric conditions and cloud life cycle stage.

2.2.2. Science Question 2.2

SQ2.2: How do initially cloudy or clear air masses evolve as they move poleward from midlatitudes and interact with changing surface conditions?

The dynamic processes that shape the radiative conditions of the Arctic are contained within the evolution of initially cloudy or clear air masses as they advect over changing surfaces (from Greenland ice cover to the Arctic sea ice, and offshore over open water). The influence of aerosols, surface fluxes, and meteorology on the evolution of these clear and cloudy air masses is an important question (Pithan et al. 2018). Northeast Greenland and the extent of its offshore sea ice are changing quickly, with changes in the accompanying atmospheric processes, are still poorly understood. Atmospheric circulation impacts the vertical distribution and sources of anomalous moisture, temperature, and aerosols, ultimately affecting cloud processes and in turn the surface radiative fluxes over land ice, sea ice, and the open ocean.

The climatological winds in the lower free troposphere rotate anticyclonically over southeast Greenland from May through July, with northward winds near Thule, Greenland and southward winds over the Fram Strait, off of the sea ice edge. The climatological flow over the Fram Strait is interrupted by synoptic events that transport moisture and aerosol northward (e.g., Bednorz et al., 2016). This anomalous transport may explain transitions from clear to cloudy conditions through variations in on/off sea-ice flow and may provide outsized support for the formation and maintenance of Arctic clouds through changes in the moisture/aerosol environment, whereas a relaxation back to a southward flow may lead to cloud dissipation or cold-air outbreaks, depending on the sea-ice conditions.

Extreme synoptic conditions are thought to be governed by two distinct flow patterns (Bednorz et al. 2014):

1. <u>Anomalously clear air conditions</u> develop when the anticyclone strengthens and moves northeast towards Svalbard, primarily enhancing the zonal circulation. However, and most interestingly for this study given the loss of sea ice in the Kara and Barents Seas (a loss of approximately -10^5 km^2/decade in July since 1979; Onarheim et al., 2018), this circulation may cause increased off-ice flow, increased air-sea fluxes, near-surface turbulence, deepening boundary layers, and stratocumulus cloud formation, similar to the cold temperature advection known to support the major planetary stratocumulus decks in the lower latitudes.
2. <u>Anomalously cloudy conditions</u> develop when the anticyclone weakens and spreads over the Barents Sea, enhancing the flow of humid, aerosol-laden air masses from the south (Bednorz et al. 2014) and providing energy for surface warming and ice melt to the Arctic. However, clouds that form in warm, moist air masses advected from the south may preferentially form deeper mixed-phase clouds with a smaller surface radiative impact than stratocumulus, but with a larger precipitation flux.

The evaluation of observed thermodynamic conditions and their evolution, cloud formation, maintenance and dissipation processes as a function of the air mass flow, including examination within a Lagrangian framework, is required, to assess if the synoptic inflow of moisture is crucial for Arctic cloud formation and test the following hypotheses:

- *Hypothesis 2.2a: The process of air mass transformation is substantially different in initially clear or cloudy airmasses.*
- *Hypothesis 2.2b: More than 50% of the atmospheric moisture and aerosol enters the ARCSIX study domain through episodic moisture intrusion events (90th percentile).*
- *Hypothesis 2.2c: The thermodynamic characteristics of lower latitude air reaching the ARCSIX study domain take more than a week to be entrained into the local Arctic surface boundary layer and this timescale is dependent upon the initial cloud characteristics of the air mass.*

<u>**Approach**</u> (details on observations and implementation in §3)

- Characterize the air mass thermodynamic and aerosol properties (temperature and humidity curtains, aerosol size distribution, vertical distribution, and composition), air mass cloud

properties (cloud particle size distribution, LWP/IWP), regional cloud distribution (satellite image retrievals), and radiative fluxes.
- Attempt to perform Lagrangian flights with two coordinated aircraft to track the coupled evolution of air mass thermodynamic transformation, aerosol and cloud properties, and radiation informed by temperature and moisture advection from data assimilation and satellite imager derived cloud properties.
- Evaluate the moisture and aerosol conditions associated with background and episodic events.

2.2.3. Science Question 2.3

SQ2.3: How do clouds evolve in response to local and remote aerosol sources?

Although the sea ice surface is a weak aerosol source (Chang et al., 2011; Mauritsen et al., 2011), other local sources of aerosol emanating from the open ocean surface, melt ponds, exposed soil, and from mining and industry can make important contributions to the Arctic aerosol environment. Advection from the south is another significant aerosol source. An important goal is an improved understanding of the effects of these aerosols on Arctic clouds, given the variety of changes being recorded in the "New Arctic." These changes include warmer conditions (which impact INP effectiveness and in-cloud freezing processes), more exposed land and open ocean surfaces (which impacts local terrestrial, marine, and anthropogenic aerosol emissions, circulation patterns, moisture/heat fluxes, and atmospheric stability), and the stronger and more frequent biomass burning events in the subarctic (Flannigan et al., 2009). The hypotheses below address local versus remote sources, as well as the dependence of cloud evolution to contrasting aerosol environments, for example across air mass boundaries or over ice-covered vs. open ocean.

- *Hypothesis 2.3a: Substantial local sources of CCN and INP (e.g. dust, marine, melt ponds) play an important role in low cloud lifecycles over ice-free ocean, whereas over sea ice covered areas, the free troposphere is the primary source for near-surface CCN/INP, potentially limiting cloud formation over sea ice.*
- *Hypothesis 2.3b: Episodic mid-latitude transport events drive the presence of aerosols and water vapor in the Arctic free troposphere, but their impact on Arctic boundary layer clouds is governed by sea ice coverage and the near-surface atmospheric thermodynamic stability.*

Approach
- Determine the spatial structure of aerosol properties (size distribution and composition), proxies/gas tracers and CCN/INP concentrations and composition surrounding Arctic clouds, along with cloud droplet/crystal size distributions (by phase) for a range of contrasting aerosol environments (e.g., pristine vs. advection-influenced by dust or pollution), meteorological conditions and surface types, as well as across air mass boundaries.
- Determine cloud responses to CCN and INP vary under different meteorological conditions and validate poorly constrained aerosol models over the region.

2.3. Science Question 3 (Sea Ice)

Addressing key unanswered questions on the coupling between the sea ice surface and the atmosphere throughout the melt season requires coincident measurements of the sea ice surface characteristics and thickness as well as atmospheric variables (e.g., Curry et al. 1996; Huang et al. 2019a). Airborne measurements provide critical information on the evolving sea ice surface and thickness throughout the melt season and the coincident atmospheric boundary layer structure and cloud properties, addressing SQ3.1. SQ3.2 provides insight into the relative importance of initial/early melt season sea ice and snow properties and atmospheric forcing mechanisms on surface conditions and sea ice thickness evolution. The data collected will inform the development of large-scale model surface property parameterizations, provide a better understanding of surface-atmospheric coupling processes and improve the interpretation of satellite retrievals of sea ice during the melt season.

2.3.1. Science Question 3.1

SQ 3.1: How does the evolution of sea ice properties (topography, thickness, and surface characteristics) affect clouds, air mass evolution, and near-surface temperature and humidity structure?

Observations of summer sea ice thickness and surface characteristics remain highly uncertain. In addition, remotely sensed temperature and humidity profiles are sparse and limited in vertical resolution. Numerical weather prediction and climate models have difficulty reproducing the near-surface temperature and humidity as well as the inversion strength in the Arctic due to the poor representation of sea ice-atmosphere coupling (Cullather et al. 2016). Large-scale models often represent sea ice as a frozen, non-evolving slab with uniform thickness and no snowpack. Process-level insights into how the sea ice/snow and surface characteristics alter the temperature and humidity structure, radiative fluxes, low cloud properties, and the air-mass transformation of the overlying atmosphere are requisite for advancing our understanding of the Arctic climate system, and for predicting its evolution through improved sea ice/snow surface parameterizations. Recent work arrives at the unexpected and contradictory conclusion that increased sensible heat flux from an increased lead fraction reduces low-cloud cover (Li et al., 2020a,b). Satellite and airborne observations that enable the measurement and monitoring sea ice and snow properties evolution coincident with atmospheric and surface properties enable testing of the following hypotheses:

- *Hypothesis 3.1a: In contrast to winter, low-cloud coverage in spring and summer increases with lead fraction and over heavily ponded areas.*
- *Hypothesis 3.1b: Sea ice characteristics have a measurable impact on the lower tropospheric temperature and humidity structure influencing the modification rate of air masses advected from lower latitudes.*
- *Hypothesis 3.1c: Different sea ice regimes (snow-cover sea ice, bare sea ice, high lead fraction, and melt ponding) have measurable differences in average cloud properties, such as cloud amount, cloud liquid water, cloud ice water contents.*

Approach (details on observations and implementation in §3)

- Monitor the evolution of sea ice and snow characteristics from satellite and airborne measurements of sea ice concentration, lead fraction, sea ice thickness, and snow depth to defined surface-type regimes of the same floe.
- Measure radiative fluxes, surface albedo, spectral reflectance, surface temperature, cloud and aerosol optical properties, as well as temperature and humidity profiles in tandem with sea ice and snow cover evolution.

2.3.2. Science Question 3.2

SQ 3.2: What is the combined impact of initial surface conditions and changing atmospheric forcings (radiation, clouds, precipitation, etc.) on the evolution of sea ice during the early melt season?

In addition to extent, a number of sea ice properties affect the link between Arctic sea ice and the atmosphere. These properties include melt pond fraction, surface roughness, albedo, snow cover, and sea ice thickness. The evolution of these properties throughout the melt season are influenced by the both initial surface conditions as well as atmospheric forcing mechanisms. Quantifying the impacts of these two factors on the early melt season evolution is necessary to provide process-level insights for advancing our understanding of how these two factors influence the sea ice evolution on seasonal to decadal time scales.

Co-located and simultaneous measurements of atmospheric and sea ice properties are required to quantify the influence of atmospheric forcing mechanisms (large-scale advection transport, radiation, clouds, precipitation, etc.) on surface properties during the early melt season. However, currently available satellite laser altimeters over sea ice require clear skies to monitor sea ice surface property evolution through summer with requisite accuracy (Kwok et al. 2019). Since the melt season is often associated with extensive cloud cover, accurate aircraft observations at high-resolution (spatially and temporally) are required to measure sea ice characteristics (e.g. roughness, snow and ice thickness) before melt and throughout the early melt season even under cloudy conditions. In this way, ARCSIX can quantify the relative contributions of initial surface conditions and atmospheric forcing on the evolution of sea ice and snow cover properties. ARCSIX enables the quantification of the contributions from these two factors to the rate of early season melt in the study domain and the testing of the following hypotheses:

- *Hypothesis 3.2a: Sea ice topography and snow depth dictate the location and geometry of melt ponds during the melt season.*
- *Hypothesis 3.2b: The early melt season surface characteristics (pre-melt onset albedo and melt pond fraction) are more important than atmospheric forcing in determining the summer surface sea ice melt rate.*
- *Hypothesis 3.2c: The sensitivity of sea ice melt to atmospheric forcing (radiation and precipitation phase) is surface regime dependent. The susceptibility to melt increases with more ponding and decreasing thickness.*

Approach (details on observations and implementation in §3)
- Measure and monitor melt ponds, their spatial heterogeneity and temporal evolution throughout the region for the duration of the campaign using satellite and airborne active and passive remote sensing data.
- Coincident measurements of surface topography, sea ice and snow thickness, surface radiative properties, and clouds.
- Repeated sampling of the same ice floes to assess the property evolution from pre-melt onset through the early melt season.
- Develop/evaluate new/existing satellite products (e.g., surface topography, snow depth, ice thickness, melt pond coverage and evolution) in the region.

2.4. Remote Sensing and Modeling Objective

Generalize the aircraft observations of radiation-cloud-aerosol-surface interactions collected regime-by-regime by putting them in context with satellite observations and models on a range of scales, while validating and improving our ability to interpret remote sensing observations in the Arctic.

Aircraft observations alone are insufficient to achieve the overarching ARCSIX objective and science questions, especially in an inter-connected system such as the Arctic. As melt processes are linked to the *cumulative* SRB over time and space, aircraft measurements need to be tied to satellite observations, validating and improving them for a range of conditions (regimes). In this way, ARCSIX aims to improve the observational system as a whole, which can then better constrain GCM and NWP models in the entire region and season. Blind spots in active and passive remote sensing due to the specific conditions in the Arctic (e.g., low sun angle, bright surface, low cloud and aerosol optical thickness, surface clutter for low-altitude clouds) will be revealed and quantified by validating existing data products (e.g., surface reflectance; passive-imagery cloud mask; thermodynamic phase from active/passive methods; altimeter freeboard). Remote-sensing proxies for key environmental factors and regime types will be assessed to the extent possible as part of the validation process. Emerging remote sensing technology for later use in orbit will be tested. ARCSIX aims to prototype new remote sensing algorithms tailored for the Arctic and improve existing retrievals.

Parameters crucial to an understanding of cloud life cycle processes and melt season sea ice evolution that are insufficiently accessible from space-borne remote sensing (such as Aitken-mode particles, INP/CCN, water vapor profile, cloud and precipitation microphysics; melt season sea ice thickness, melt pond coverage) are also acquired by ARCSIX and will be used directly to drive process model studies embedded in the meteorological context from NWP. Conducted for a representative cross section of prevailing regimes, the measurements will also be used collectively to validate reanalysis products and help identify remote-sensing proxies for key properties unobservable from space directly.

Summarizing, the ARCSIX strategy for addressing its overarching goal and science questions is:
- Validation of existing space-borne passive and active remote sensing (including laser altimetry) with aircraft under-flights, for a range of regimes representative for the target region and season.

- Development of improved heritage or new prototype retrieval algorithms tailored to the Arctic
- Deployment of emerging technology with the potential for improved observations in the Arctic.
- Synthesis of aircraft and satellite data to deliver best estimates of the temporally- and spatially-dependent SRB and CREs in the region.
- Drive process models with aircraft and satellite observations to understand the dependence of low cloud evolution on local conditions versus the larger-scale meteorological context and advection.
- Use observations (e.g. albedo, cloud characteristics, and radiative fluxes) to adjust and guide future improvements and parameterizations in climate models.
- Use sea ice surface and thickness information to inform and improve sea ice predictions.

Much of this strategy hinges on acquiring sufficient measurement statistics for relevant target regimes (**Section 3**), which need to be reassessed after the selection of the science team. The investigation calls for teams leading data collection through novel measurements and dedicated teams performing model studies with the field data and synthesized aircraft and remote sensing data as outlined above. These synthesis and interpretive analysis efforts are integral to ARCSIX, and the selected teams must collaborate with forecasters and mission leadership to guide flight planning *before* and *throughout* the mission to ensure that data are collected in the appropriate manner for a productive post-campaign analysis.

3. Implementation and Experimental Design

3.1. ARCSIX Regime Approach, Priorities, and Flight Hours

The overall objective of ARCSIX is to quantify atmospheric contributions to the summertime SRB and sea-ice melt over the Arctic. However, the aircraft campaign alone can cover only a small fraction of the region in space and time; satellite data and models are required to extend the coverage. Although polar-orbiting satellites provide frequent coverage at high latitudes, aerosol data is extremely limited in the Arctic, due to cloud cover, low AOD, and (for passive sensors) due to low sun angle and bright surfaces. As mentioned above, heritage imager retrievals likely underestimate the cloud cover of low clouds, and surface reflectance products are either not available operationally or insufficiently validated. Likewise, there are ambiguities retrieving the properties of multi-layer and /or mixed-phase clouds. Near-surface temperature and relative humidity are also difficult to obtain from both satellites and models, hampering progress. ARCSIX will make comprehensive observations intended to address these problems. For example, one of the highest priorities (R1 below) is the re-sampling of the surface reflectance and snow/ice properties along pre-defined transects under clear conditions over the course of the mission (accounting for movement of the ice from one overflight to the next, if possible). In this way, the effect of melt and precipitation on surface properties over time can be quantified, while robustly validating satellite products under varying conditions (passive imagery and ICESat-2), or even lay the ground work for the development of new products.

As in previous field experiments, ARCSIX leverages satellite observations and model simulations for spatial and temporal coverage and context, and aircraft observations for accuracy, detail, and process-level data. To do this, the problem is broken down statistically into regimes, identified by satellite observations and NWP models, and then characterized separately by detailed aircraft observations. For radiation (SQ1), this was illustrated with Fig. 8. The cloud life cycle questions (SQ2) will be addressed similarly. Observations related to SQ3 will be made repeatedly over the same floes or other features of interest, at the same time as surface observations are collected for SQ1.2. The selected science team will refine the regimes and flight priorities before and during the field mission and define the level of detail and measurement focus for each one of them as required by the science.

Table 2 summarizes the ARCSIX regimes and assigns sampling priorities based on the likelihood of occurrence and their perceived relative importance for addressing ARCSIX science. Regimes 1 (clear sky) and 2 (low-level clouds) occur under subsidence whereas regimes 3 (advectively-forced clouds) and 4 (advective events) are associated with upward motion. These regimes were refined based on the climatology phase of the white paper development (**Section 1.4**), from other field campaigns, and from published literature (e.g., Cesana et al. 2012; Smith et al., 2016; Taylor et al. 2015; 2019).

Table 2: Preliminary definition of regimes and flight types with likelihood of occurrence and priorities.

Regime / Flight Type	Likelihood	Priority
R1 Clear-sky	~30%	1 (high)
R2 Low clouds (quiescent)	high	4
R3 Advectively forced clouds	high	4
R4a Advective events	<50%	3
R4b Aerosol transport events	<20%	2
Flight of opportunity	n/a	5 (low)

The ARCSIX regime prioritization is based on combination of science value and likelihood of occurrence based upon available climatological data.

- The rare clear-sky regime (R1) has the highest priority (SQ1.2; SQ3)
- The advection and aerosol transport regime (R4), as suggested by the CALIPSO climatology, is only expected 1-2 times during the campaign window. Therefore, appropriate sampling patterns will be prioritized on days when/if they occur. Cloud systems will be tracked over time with a quasi-Lagrangian approach. An airmass is re-sampled over one or multiple days (for example, through suitcase flights Thule-Svalbard and back).
- Optically thin, low (quiescent) clouds (R2) and advectively-forced clouds (multi-layer, thicker clouds, R3) will be characterized through pre-defined routine flight patterns.
- Flights of opportunity provide flexibility with regard to unforeseen events (e.g., Arctic cyclones; major ice melt episodes or precipitation events). Some of these are intended to provide data to test emerging remote sensing techniques (Remote Sensing Objective).

Based on the regimes from **Table 2**, the ARCSIX science writing team recommends **175 flight hours for the low-flyer and 125 flight hours for the high-flyer**.

3.2. Optimal Sampling Region and Campaign Timing

The optimal sampling region and timing for ARCSIX is driven by the overarching objective to understand the radiative contributions to sea ice melt during the early melt season when the surface albedo characteristics are changing rapidly. This motivates the campaign timing selected to capture the ***cumulative effects*** of the investment of radiation into the surface on sea ice (SQ1.1-1.3; SQ3, **Section 2**). The ideal time period for the campaign is mid-May through mid-July, as this provides a transition of surface conditions, a range of advection regimes (affecting cloud type changes and moisture availability) and, to some extent, diverse aerosol environments (a transition from lower-latitude aerosols to pristine conditions at the end of May, as well as a transition to some dust emissions later in the summer). This is the time period when melt ponds form North of Greenland, marking a sharp transition in sea ice surface albedo and spectral reflectance that is relevant to both seasonal and climate model projections of sea ice variability and trends. In that same region, this time period provides a sufficient amount of supercooled liquid to address SQ2.

In terms of ice dynamics, the North Coast of Greenland, Fram Strait, and Beaufort Sea represent limiting cases. The Beaufort Gyre *contributes* to sea ice loss in the Beaufort Sea by moving ice southward towards the Alaskan Coast. Similarly, sea ice loss occurs through the Fram Strait. However, sea ice converges and is *concentrated* near the North Coast of Greenland providing conditions where radiative processes are expected to dominate surface melt.

Three regions were considered for this investigation (**Fig. 3**). Of these, the combination of the North Coast of Greenland and the Fram Strait region was found to be the optimal location to track the co-evolution of sea ice and atmospheric properties to quantify the role of clouds and radiation in melt processes because it offers two different ice dynamics, with a fairly consistent location of the ice edge. Other factors include:

- The impact of **radiation-induced surface warming on surface ice melt** is possible to quantify due to the slow horizontal ice movement and weak breakup in the region.
- **The Fram Strait Marginal Ice Zone** allows the sampling of clouds, radiation, and airmass properties across different surfaces to **investigate surface-radiation-cloud interactions.**
- The North Coast of Greenland offers a wide variety of radiative/cloud regimes, including **low clouds (especially the less documented optically thin clouds)**.
- **Strong spatial gradients in sea ice albedo, spectral reflectance, and other ice properties** between the North Coast of Greenland and the North Pole can be easily re-sampled due to the slow ice movement to assess the effects of precipitation events, cumulative radiation-induced melt, melt pond formation, and air mass advection.
- **Melt ponds** occur consistently in the study region, and they may have a considerable impact on the evolution of the sea ice, **acting as melt accelerators** because of their low surface albedo.
- **Aerosol transport from the lower latitudes** manifests itself in higher concentrations north of Svalbard, contrasting with low concentrations along the North Coast of Greenland and enabling aerosol-cloud interaction studies based on the spatial gradient.
- **Airmass advection events** in the Fram Strait provide a direct pathway to assess the influence of moisture and aerosol transport on thermodynamic structure and cloud properties. These events can be also be associated with **precipitation** (ice or liquid), **changing surface properties.**

3.3. Recommendations for field operations and timing

Figure 11 provides an overview of the sampling region with distance between Thule, Svalbard, and the North Pole. The primary sampling region extends from the North Coast of Greenland to the North Pole, easily accessible from Thule. By contrast, reaching the open water in the Fram Strait (secondary sampling region) requires a transit time of ~3 hours, leaving ~2 hours on station. Therefore, Svalbard should be considered as a secondary landing/overnight location for suitcase flights, required to study aerosol-cloud interactions.

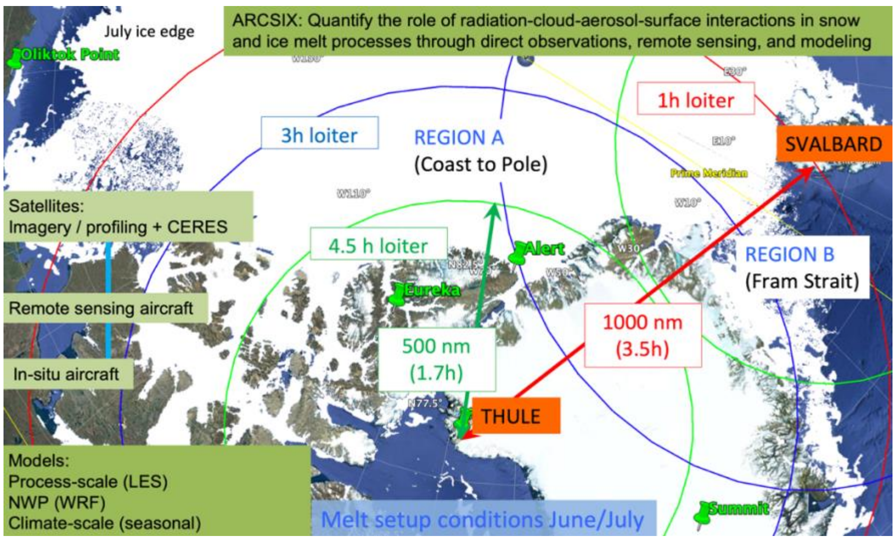

Figure 11: Overview of the ARCSIX context, with region A (Greenland north coast to pole, with Thule as base) and region B (Fram Strait, with Svalbard as alternate or additional base with potential for suitcase flights).

The recommended minimum duration for the ARCSIX campaign is six weeks. A shorter deployment diminishes the likelihood of encountering favorable, diverse aerosol conditions and advection events, significantly reducing science return and the likelihood of robust sampling of different regimes. A duration of **eight weeks** is optimal and enables ARCSIX to track the surface evolution over the complete early melt season – from melt onset and melt pond formation through significant melt pond growth.

ARCSIX science requires sampling of the *contrast* in surface albedo and BRDF before/after precipitation, and, especially given the challenges of working at high latitudes, a longer campaign allows greater sampling, as well as a greater likelihood of capturing the range of key conditions. Logistics permitting, **field operations may be split into an early (late May/early June) and late phase (late June/early July) of 3-4 weeks, separated by 2-3 weeks**.

3.4. Required platforms and measurements

ARCSIX relies on two aircraft flying in tandem. The high-flying aircraft will serve as a remote sensing platform, whereas the low flying aircraft acquires *in-situ* aerosol, cloud, atmospheric and sea ice surface properties along with radiation. In this way, ARCSIX capitalizes on the strengths of aircraft observations (detailed sampling of the vertical cloud structure and vertical temperature and humidity profiles; below-cloud measurements of radiation) that are inaccessible to satellite and ground-based observations, while simultaneously providing horizontal and vertical structure (imager and curtains) of the key atmospheric parameters from the high-flyer.

Payload:
The high-flying aircraft needs to carry remote sensing instruments (**Table 3**) that capture the full dynamic range of clouds – from extremely thin to multi-layer clouds. At minimum, an imager replicating or exceeding capabilities of on-orbit imagers (e.g., through high-resolution multi-angle, multi-spectral, and/or polarimetric measurements) is required to provide scene context and resolve the horizontal variability of the surface and cloud fields. It needs to be paired with a lidar that complements imagery-based cloud retrievals below the detection threshold (COD ~0.5-2), while providing vertical structure of aerosols, cloud boundaries, phase and droplet number concentration up to the attenuation limit (COD~3). Finally, a dropsonde system is required.

Table 3: Instrumentation overview for the high-flyer (P=priority; v.=vertical; h.=horizontal (x,y); a.t.=along track)

Remote Sensing and Radiation	P	Uncertainty Sensitivity	Resolution	SQs
Reflectance at least 400-1600 nm	1	5%	50m h.	**1, 2, 3**
Cloud fraction (imager-based)	1	COD>0.5	50m h.	**1, 2**
Cloud optical properties	1	COD>2	50m h.	**1, 2**
Cloud top height (nadir)	1	$\beta(z) > 3\ Mm^{-1}$	50m a.t.	**1, 2**
Cloud top phase (nadir)	1	$\beta(z) > 10\ Mm^{-1}$	500m a.t.	**1, 2**
Profiles of T, P, RH (dropsondes)	1	0.2K, 0.4mb, 2%	30m v.	**1, 2**
Profiles aerosol backscatter (mid-vis)	1	3%	30 m v.	*1.2, 2.2, 2.3*
Profiles aerosol extinction (mid-vis)	1	10% / 10 Mm^{-1}	100 m v.	*1.2, 2.2, 2.3*
Cloud extinction profile $\beta(z)$ (nadir)	2	$\beta(z) > 3\ Mm^{-1}$	30m v.	**1, 2**
Cloud top droplet n. conc. (nadir)	2	$\beta(z) > 10\ Mm^{-1}$	500m a.t.	**1, 2**
Curtains of water vapor mix. ratio	2	5% VMR	500m a.t.	*1.3, 2.1, 2.2*
SW and LW Broadband Flux	2	3-5%	1 s	**1, 3**

The low-flying aircraft must not only carry aerosol, cloud, radiation, sea ice and meteorology *in-situ* sensors, but also complement the remote sensors on the high-flyer with additional instruments that provide cloud/precipitation vertical structure (multi-frequency radar) and water vapor/temperature curtains (Raman or DIAL) below the aircraft, as well as liquid and precipitable water path, column cloud and aerosol optical thickness above (see **Table 4** for details and priorities). Wide-angle, multi-spectral imagery is required for mapping of the surface reflectance in tandem with imagery on the high-flyer. A polarimeter should be included on the high or low-flyer to allow cloud and surface property retrievals (e.g., cloud droplet number concentration and BRDF) that are not currently available from satellite. The inclusion of a lidar (high-flyer) and radar (low-flyer) is all the more important (1) because the C-Train will soon become unavailable and (2) because the region north of Greenland is not captured by these instruments (see blind spot in climatology, **Fig. 3**), and (3) can provide validation data to inform the development of the A-CCP Designated Observable identified by the 2017 ESAS Decadal Survey. In addition to *in-situ* measurements of background (generally Aitken-mode) and transported aerosols, CCN and INPs need to be characterized in terms of number concentration, composition, chemical and optical properties from the low-flyer. To be able to identify the dominating INP and CCN types under difference regimes, off-line (filter-based) and/or on-line aerosol chemical composition and mixing state characterization is needed. CCN/INP composition measurements with trace gas measurements advances ARCSIX science by identifying aerosol sources.

Table 4: Instrument overview for the low-flyer.

In Situ Instruments	P	Uncertainty	Resolution	SQs
Aerosols & Meteorology:				
High Res. Met. (T, P, RH, 2-D Winds)	1	0.3K, 0.3 mb, 0.5ms^{-1}	0.1 s	**2**
High Res. Vertical Velocity	1	0.1 ms^{-1}	0.1 s	*2.1*, *2.2*
Particle Number Concentration	1	10%	1 s	**2**
Size Distribution (10 nm - 5 um)	1	20%	1-60 s	**2**
Hygroscopicity, f(RH)	1	NA	1 s	**2**
Volatility	1	NA	1 s	*2.3*
Scattering	1	0.5 Mm^{-1}	1 s	*1.3, 2.3*
Absorption	1	0.5 Mm^{-1}	1 s	*1.3*, *2.3*
CCN Concentration Spectra	1	NA	60 s	**2**
INP Concentration online	1	NA	1-600 s	**2**
INP Concentration offline	1	NA	1800 s	**2**
Black Carbon Mass Concentration	1	30%	1 s	*2*
Mass Composition	2	100 ng m^{-3}	10 s	**2**
Single Particle Comp., Mixing State	2	NA	10 s	*2.3*
INP and CCN single particle characterization; bulk composition	2	NA	NA	**2**
Profiles T, P, RH (dropsondes)	2	0.2K, 0.4 mb, 2%	11 m v.	**1**, **2**, **3**
Bioaerosol Number and Size	3	NA	1 s	*2.3*
Clouds:				
Droplet/Crystal Number	1	NA	1 s	**1**, **2**, **3**
Size Distribution (2 um - 6 mm)	1	NA	1 s	**1**, **2**, **3**
Bulk Liquid, Total Water Content	1	20% or 0.01 g m^{-3}	1 s	*1.1*, *1.3*, **2**, **3**
High-Resolution Particle Images	1	NA	NA	*1.1*, *2.1*
Cloud Water Bulk Composition	2	NA	NA	**2**
Trace Gases:				
Carbon Dioxide	1	0.1 ppm	1 s	**2**
Carbon Monoxide	1	5 ppbv	1 s	**2**
Water Vapor	1	5%	1 s	**1**, **2**
Water Vapor Isotopes	2	NA	NA	*2.2*, *2.3*
Organic Species (e.g., DMS)	2	10 ppt	10 s	**2**

Remote Sensing and Radiation	P	Uncertainty	Resolution	SQs
SW and LW Broadband Flux	1	3-5%	1 s	**1**, **3**
SW Spectral Flux	1	3-5%	1 s	**1**, **3**
Radar Reflectivity, Doppler Velocity	1	2dBZ, 1 ms^{-1}	600m x 60m	*2.1*, *2.2*
Multi-Angle, Multi-Spectral Radiance	1	3%	wide-FOV	*1.2*, *1.3*
COD via zenith SW spectral radiance	1	det. threshold: 0.02	1 s	*1.1*, *1.3*, **2**
Brightness temperature (zenith/nadir) and surface skin temperature	1	0.5 K	1 s	*1.1*, *1.3*, *2.1*, **3**
Liquid and Precipitable Water Path	1	15 g m^{-2}		*1.1*, *1.3*, *2.1*
Spectral AOD and almucantar ret.	1	AOD: 5%	1 s	*1.3*, *2.3*
Sea ice freeboard	1	2 cm v. precision	1 m h.	*3.1,3.2*
Geolocated visible imagery	1	1 m geolocation acc.	1 m h.	*3.1,3.2*
Snow depth radar	2	5 cm	10 m h.	*3.1, 3.2*
Raman lidar T & wat. vap. profiles	2	0.5 K; 5% VMR	50 m v.	*1.3*, *2.1*, *2.2, 3*
Multi-Spectral IR Flux	2	3-5%		**1**

Platforms:
A candidate platform for the high-flying aircraft would be the G-V and candidate aircraft for the low-flying aircraft are the P-3 or the DC-8. All these aircraft have ample range and duration to provide 2-3 hour transits and 2-3 hours on station.

Satellite and Modeling Field Support:
The role of satellite remote sensing and models for ARCSIX is twofold. After the field campaign, satellite and aircraft data will be combined in an interpretative modeling context and used for the development of new retrieval products (§2.4). The satellite data also provide a climatological understanding of environmental regimes in the Arctic that will be refined with ARCSIX data and applied to the longer-term satellite data record to help address the primary ARCSIX science goals. In addition, satellite observations, weather and aerosol forecast are needed before and during field operations for campaign and flight planning. For example, the forecasts will help target the position of the regimes of interest. In addition, to characterize complex systems and interactions, it is an emerging trend to use entire aircraft data sets, in addition to observations from individual cases. Previous missions such as ARISE, ORACLES, CAMP^{2}Ex, and OIB paved the way in this regard. For example, ORACLES included “routine flight patterns,” along which statistics unavailable from satellites were accumulated. For OIB, coincident underflights with satellite altimeters were undertaken. For ARISE, radiation measurements from ~100 x 100 km^2 grid boxes were used collectively to validate satellite-derived flux products in complex conditions. To leverage this paradigm shift in ARCSIX, a modeling team specialized in Arctic forecast, process modeling and related reanalysis products should be involved from the outset. Detailed post-campaign analysis and application of regime-specific remote-sensing data, along with interpretative modeling will be solicited later on.

References

Alkama, R., et al., 2020: Clouds damp the radiative impacts of polar sea ice loss, *The Cryosphere*, 14, 2673–2686, https://doi.org/10.5194/tc-14-2673-2020.

Bennartz, R., et al., 2013: July 2012 Greenland melt extent enhanced by low-level liquid clouds. *Nature* **496,** 83–86. https://doi.org/10.1038/nature12002

Bigg, E., 1996: Ice forming nuclei in the high Arctic." *Tellus B* 48 (1996): 223-233

Bigg, E. and C. Leck, 2001: Properties of the aerosol over the central Arctic Ocean. *Journal of Geophysical Research* 106: 32101-32109.

Bintanja, R. and O. Andry, 2017: Towards a rain-dominated Arctic. *Nature Climate Change*. **7**, 263-268, doi: 10.1038/NCLIMATE3240

Boeke, R. C., and P. C. Taylor, 2016: Evaluation of the Arctic surface radiation budget in CMIP5 models, J. Geophys. Res. Atmos., 121, 8525–8548, doi:10.1002/2016JD025099.

Boer, G., de Morrison, H., Shupe, M. D., and Hildner, R., 2011: Evidence of liquid dependent ice nucleation in high-latitude stratiform clouds from surface remote sensors, Geophys. Res. Lett., 38, L01803, https://doi.org/10.1029/2010GL046016.

Burrows, S. M., et al., 2013: Ice nuclei in marine air: biogenic particles or dust? *Atmospheric Chemistry and Physics*, **13**(1), 245– 267. https://doi.org/10.5194/acp-13-245-2013

Bushuk, M., et al., 2018: Regional Arctic sea-ice prediction: Potential versus operational seasonal forecast skill. Clim. Dyn., 1–23.

Chepfer, H., et al., 2013: Comparison of two different cloud climatologies derived from CALIOP-attenuated backscattered measurements (Level 1): The CALIPSO-ST and the CALIPSO-GOCCP. Journal of Atmospheric and Oceanic Technology. 30. 725-744. 10.1175/JTECH-D-12-00057.1.

Chevallier, M., et al., 2013: Seasonal forecasts of the pan-Arctic sea ice extent using a GCM-based seasonal prediction system. J. Climate, 26, 6092–6104, doi:10.1175/JCLI-D-12-00612.1.

Cesana, G.; et al., 2012: Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP. *Geophysical Research Letters*, Vol. **39**(20): p. n/a-n/a. DOI: 10.1029/2012gl053385 http://dx.doi.org/10.1029/2012GL053385.

Cesana, G., and Chepfer, H., 2013: Evaluation of the cloud thermodynamic phase in a climate model using CALIPSO-GOCCP, *J. Geophys. Res. Atmos.*, 118, 7922– 7937, doi:10.1002/jgrd.50376.

Cesana, G., et al., 2015: Multimodel evaluation of cloud phase transition using satellite and reanalysis data. Journal of Geophysical Research Atmospheres. 120. 10.1002/2014JD022932.

Cesana, G., et al., 2016: Using in-situ airborne measurements to evaluate three cloud phase products derived from CALIPSO. Journal of Geophysical Research: Atmospheres. 121. 10.1002/2015JD024334.

Cesana, G., and Waliser, D., 2016: Characterizing and Understanding Systematic Biases in the Vertical Structure Of Clouds In CMIP5/CFMIP2 Models. Geophysical Research Letters. 43. 10.1002/2016GL070515.

Chen, H., et al., 2020: Shortwave Radiative Effect of Arctic Low-Level Clouds: Evaluation of Imagery-Derived Irradiance with Aircraft Observations, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2019-344.

Coopman, Q., Garrett, T. J., Finch, D. P., and Riedi, J., 2018: High Sensitivity of Arctic Liquid Clouds to Long-Range Anthropogenic Aerosol Transport, Geophys. Res. Lett., 45, 372–381, https://doi.org/10.1002/2017GL075795.

Creamean, J. M., et al., 2018: Marine and terrestrial influences on ice nucleating particles during continuous springtime measurements in an Arctic oilfield location, Atmos. Chem. Phys., 18, 18023–18042, https://doi.org/10.5194/acp-18-18023-2018.

Cullather, R., et al., 2016: Systematic Improvements of Reanalyses in the Arctic (SIRTA): A White Paper. Inter-agency Arctic Research Policy Committee (IARPC) Principals. https://www.iarpccollaborations.org/news/6004

Curry, J. A., J. L. Schramm, W. B. Rossow, and D. Randall, 1996: Overview of Arctic Cloud and Radiation Characteristics. J. Climate, 9, 1731–1764, https://doi.org/10.1175/1520-0442(1996)009<1731:OOACAR>2.0.CO;2.

DeMott, P. J. et al., 2016: Sea spray aerosol as a unique source of ice nucleating particles, Proc. Natnl. Acad. Sci., 113 (21), 5797-5803, doi:10.1073/pnas.1514034112

DeMott, P. J., et al., 2018: The Fifth International Workshop on Ice Nucleation phase 2 (FIN-02): laboratory intercomparison of ice nucleation measurements, Atmos. Meas. Tech., 11, 6231-6257, https://doi.org/10.5194/amt-11-6231-2018

de Roode, S. R., et al., 2019: Turbulent transport in the gray zone: A large eddy model intercomparison study of the CONSTRAIN cold air outbreak case. *Journal of Advances in Modeling Earth Systems*, 11, 597– 623. https://doi.org/10.1029/2018MS001443

Dodson, J. B., et al., 2020: Evaluation of Simulated Cloud Water in Low Clouds over the Beaufort Sea in Arctic System Reanalysis using ARISE Airborne In Situ Observations. Under review Atmos. Chem. Phys. Disc.

Duncan, B. N., et al., 2020: Space-Based Observations for Understanding Changes in the Arctic-Boreal Zone. *Reviews of Geophysics*, **58**, e2019RG000652, https://doi.org/10.1029/2019RG000652.

English, J. M., A. Gettelman, and G. R. Henderson, 2015: Arctic radiative fluxes: Present-day biases and future projections in CMIP5 models,
J. Clim., 28(15), 6019–6038, doi:10.1175/jcli-d-14-00801.1.

Engvall, A.-C., et al., 2008: In-situ airborne observations of the microphysical properties of the Arctic tropospheric aerosol during late spring and summer. Tellus B, 60: 392-404. doi:10.1111/j.1600-0889.2008.00348.x

Flannigan., M., et al., 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest Glob. Change Biol. 15, 549–60

Fridlind, A.M., et al., 2012: A FIRE-ACE/SHEBA case study of mixed-phase Arctic boundary-layer clouds: Entrainment rate limitations on rapid primary ice nucleation processes. *J. Atmos. Sci.*, **69**, 365-389, doi:10.1175/JAS-D-11-052.1

Fridlind, A. M.; and Ackerman, A. S., 2018: *Chapter 7 - Simulations of Arctic Mixed-Phase Boundary Layer Clouds: Advances in Understanding and Outstanding Questions A2 - Andronache, Constantin*, in *Mixed-Phase Clouds*., 2018, Elsevier. p. 153-183.

Goren, T., Kazil, J., Hoffmann, F., Yamaguchi, T., and Feingold, G., 2019: Anthropogenic Air Pollution Delays Marine Stratocumulus Break-up to Open-Cells. Geophys.l Res. Lett., **46**, https://doi.org/10.1029/2019GL085412

Hartmann, D. L., and P. Ceppi, 2014: Trends in the CERES Dataset, 2000–13: The Effects of Sea Ice and Jet Shifts and Comparison to Climate Models. *J. Climate*, **27**, 2444–2456, https://doi.org/10.1175/JCLI-D-13-00411.1.

Hegyi, B. M., & Taylor, P. C., 2018: The unprecedented 2016–2017 Arctic sea ice growth season: The crucial role of atmospheric rivers and longwave fluxes. Geophysical Research Letters, 45, 5204–5212. https://doi.org/10.1029/ 2017GL076717

Hobbs, PV, and AL Rangno, 1998: Microstructure of low and middle-level clouds over the Beaufort Sea. *Quarterly Journal of the Royal Meteorological Society* 124(550): 2035-2071, doi:10.1002/qj.49712455012

Huang, Y., Chou, G., Xie, Y., & Soulard, N., 2019: Radiative control of the interannual variability of Arctic sea ice. *Geophys. Res. Lett.*, **46**, 9899– 9908, https://doi.org/10.1029/2019GL084204

Huang, Y., et al., 2019b: Thicker clouds and accelerated Arctic Sea ice decline: The atmosphere-sea ice interactions in spring. *Geophysical Research Letters*, *46*. https://doi.org/10.1029/2019GL082791

Jackson, R. C., et al., 2012: The dependence of ice microphysics on aerosol concentration in arctic mixed-phase stratus clouds during ISDAC and M-PACE, *J. Geophys. Res.-Atmos.*, **117**, D15207, https://doi.org/10.1029/2012JD017668

Jahn, A., J. E. Kay, M. M. Holland, and D. M. Hall, 2016: How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters*, **43**, 9113–9120, doi:10.1002/2016GL070067

Kanji, Z. A., L. A. Ladino, H. Wex, Y. Boose, M. Burkert-Kohn, D. J. Cziczo, and M. Krämer, 2017: Overview of Ice Nucleating Particles. Meteorological Monographs, 58, 1.1 1.33, doi: 10.1175/AMSMONOGRAPHS-D-16-0006.1

Kapsch, M.-L., R. G. Graversen, T. Economou, and M. Tjernström, 2014: The importance of spring atmospheric conditions for predictions of the Arctic summer sea ice extent, *Geophys. Res. Lett.*, *41*, 5288–5296, doi:10.1002/2014GL060826

Karlsson, J., and G. Svensson, 2010: The simulation of Arctic clouds and their influence on the winter surface temperature in present-day climate in the CMIP3 multi-model dataset, Clim. Dyn., 36(3-4), 623–635, doi:10.1007/s00382-010-0758-6.

Karlsson, J., and G. Svensson, 2013: Consequences of poor representation of Arctic sea-ice albedo and cloud-radiation interactions in the CMIP5 model ensemble, Geophys. Res. Lett., 40, 4374–4379, doi:10.1002/grl.50768.

Kato, S., et al., 2010: Relationships among cloud occurrence frequency, overlap, and effective thickness derived from CALIPSO and CloudSat merged cloud vertical profiles, J. Geophys. Res.-Atmos., 115, D00h28, https://doi.org/10.1029/2009jd012277.

Kato, S., et al., 2011: Improvements of top-of-atmosphere and surface irradiance computations with CALIPSO-, CloudSat-, and MODIS-derived cloud and aerosol properties, J. Geophys. Res.-Atmos., 116, D19209, https://doi.org/10.1029/2011jd016050

Kato, S., et al., 2018: Surface Irradiances of Edition 4.0 Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Data Product. *J. Climate*, **31**, 4501–4527, https://doi.org/10.1175/JCLI-D-17-0523.1.

Kay, J. E.; et al., 2008: "The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum." *Geophysical Research Letters*, Vol. **35**(8), DOI: 10.1029/2008gl033451 http://dx.doi.org/10.1029/2008GL033451.

Kay, J. E., and Gettelman, A., 2009: Cloud influence on and response to seasonal Arctic sea ice loss, J. Geophys. Res., 114, D18204, doi:10.1029/2009JD011773.

Kay, J. E. and L'Ecuyer, T., 2013: Observational constraints on Arctic Ocean clouds and radiative fluxes during the early 21st century, J. Geophys. Res.-Atmos., 118, 7219–7236, https://doi.org/10.1002/jgrd.50489.

Kay, J. E., et al., 2016: Recent advances in Arctic cloud and climate research, Curr. Clim. Change Rep., 2, 159, https://doi.org/10.1007/s40641-016-0051-9.

Kay, J. E., L. Bourdages, N. B. Miller, A. Morrison, V. Yettella, H. Chepfer, and B. Eaton (2016), Evaluating and improving cloud phase in the Community Atmosphere Model version 5 using spaceborne lidar observations, J. Geophys. Res. Atmos., 121, 4162–4176, doi:10.1002/2015JD024699.

Kecorius, S., et al., 2019: New particle formation and its effect on cloud condensation nuclei abundance in the summer Arctic: a case study in the Fram Strait and Barents Sea, Atmos. Chem. Phys., 19, 14339–14364, https://doi.org/10.5194/acp-19-14339-2019.

Klein, S. A. et al., 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. I: Single-layer cloud. *Quart. J. Roy. Meteor. Soc.*, **135**, 979–1002, doi:https://doi.org/10.1002/qj.416.

Klein, S., et al., 2013: Are climate model simulations of clouds improving? An evaluation using the ISCCP simulator. *J. Geophys. Res.*, 118, 1329–1342, doi: 10.1002/jgrd.50141

Komurcu, M., et al., 2014: Intercomparison of the cloud water phase among global climate models, J. Geophys. Res.-Atmos., 119, 3372–3400, https://doi.org/10.1002/2013JD021119.

Kwok, R. et al., 2019: Surface height and sea ice freeboard of the Arctic Ocean from ICESat-2: Characteristics and early results. *Journal of Geophysical Research: Oceans*, 124, 6942– 6959. https://doi.org/10.1029/2019JC015486

Kwok, R., et al., 2020: Decay of the snow cover over Arctic sea ice from ICESat-2 acquisitions during summer melt in 2019. *Geophysical Research Letters*, *47*(12), e2020GL088209.

Lannefors, H., Hansson, H.-C., Granat, L., 1983: Background aerosol composition in Southern Sweden—Fourteen micro and macro constituents measured in seven particle size intervals at one site during one year. *Atmospheric Environment* (1967). 17. 87-101. 10.1016/0004-6981(83)90012-4.

Leck, C., Norman, M., Bigg, E. K., and Hillamo, R., 2002: Chemical composition and sources of the high Arctic aerosol relevant for cloud formation, J. Geophys. Res., 107, 4135, doi:10.1029/2001JD001463

Lebsock, M., and Su, H., 2014: Application of active spaceborne remote sensing for understanding biases between passive cloud water path retrievals, *J. Geophys. Res. Atmos.*, 119, 8962– 8979, doi:10.1002/2014JD021568.

Leck, C. and Svensson, E., 2015: Importance of aerosol composition and mixing state for cloud droplet activation over the Arctic pack ice in summer, Atmos. Chem. Phys., 15, 2545–2568, https://doi.org/10.5194/acp-15-2545-2015.

Leaitch, W. R., et al., 2016: Effects of 20–100 nm particles on liquid clouds in the clean summertime Arctic, Atmos. Chem. Phys., 16, 11107–11124, https://doi.org/10.5194/acp-16-11107-2016.

Li, X., et al., 2020a: Midwinter Arctic leads form and dissipate low clouds. *Nat Commun* **11,** 206. https://doi.org/10.1038/s41467-019-14074-5

Li, X., et al., 2020b: Relationship between Wintertime Leads and Low Clouds in the Pan-Arctic. Journal of Geophysical Research: Atmospheres. 10.1029/2020JD032595

Liu, J., M. Song, R. M. Horton, and Y. Hu, 2015: Revisiting the potential of melt pond fraction as a predictor for the seasonal Arctic sea ice extent minimum. Environ. Res. Lett., 10, 054017, doi:10.1088/1748-9326/10/5/054017

Maahn, M., et al., 2017: The observed influence of local anthropogenic pollution on northern Alaskan cloud properties, Atmos. Chem. Phys., 17, 14709–14726, https://doi.org/10.5194/acp-17-14709-2017.

Maillard, J., Ravetta, F., Raut, J.-C., Mariage, V., and Pelon, J., 2020: Characterisation and surface radiative impact of Arctic low clouds from the IAOOS field experiment, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2020-918, in review.

Malinka, A., et al., 2018: Reflective properties of melt ponds on sea ice, The Cryosphere, 12, 1921–1937, https://doi.org/10.5194/tc-12-1921-2018.

Mauritsen, T., et al., 2011: An Arctic CCN-limited cloud-aerosol regime, Atmos. Chem. Phys., 11, 165–173, https://doi.org/10.5194/acp-11-165-2011.

McIlhattan, E. A.; L'Ecuyer, T. S.; and Miller, N. B., 2017: Observational Evidence Linking Arctic Supercooled Liquid Cloud Biases in CESM to Snowfall Processes. *Journal of Climate*, Vol. **30**(12): p. 4477-4495. DOI: 10.1175/jcli-d-16-0666.1 https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-16-0666.1

Meier, W. N., Fetterer, F., Savoie, M., Mallory, S., Duerr, R., and Stroeve, J., 2017: NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3, Boulder, CO, USA, NSIDC: National Snow and Ice Data Center, https://doi.org/10.7265/N59P2ZTG

Meredith, M., et al., 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E., Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

Mioche, G., Jourdan, O., Ceccaldi, M., and Delanoë, J., 2015: Variability of mixed-phase clouds in the Arctic with a focus on the Svalbard region: a study based on spaceborne active remote sensing, Atmos. Chem. Phys., 15, 2445–2461, https://doi.org/10.5194/acp-15-2445-2015.

Mioche, G. and O. Jourdan, 2018: Spaceborne Remote Sensing and Airborne In Situ Observations of Arctic Mixed-Phase Clouds. Vol.: p. 121-150. DOI: 10.1016/b978-0-12-810549-8.00006-4.

Morrison, H.; et al., 2012: Resilience of persistent Arctic mixed-phase clouds. *Nature Geoscience*, Vol. **5**(1): p. 11-17. DOI: 10.1038/ngeo1332 http://dx.doi.org/10.1038/ngeo1332.

Morrison, A. L., Kay, J. E., Chepfer, H., Guzman, R., and Yettella, V., 2018: Isolating the Liquid Cloud Response to Recent Arctic Sea Ice Variability Using Spaceborne Lidar Observations, *J. Geophys. Res.-Atmos.*, **123**, 473–490, https://doi.org/10.1002/2017JD027248.

Neggers, R. A. J., Chylik, J., Egerer, U., Griesche, H., Schemann, V., Seifert, P., et al., 2019: Local and remote controls on Arctic mixed-layer evolution. *JAMES*, **11**, 2214–2237. https://doi.org/10.1029/ 2019MS001671

Palm, S. P., S. T. Strey, J. Spinhirne, and T. Markus, 2010: Influence of Arctic sea ice extent on polar cloud fraction and vertical structure and implications for regional climate, J. Geophys. Res., 115, D21209, doi:10.1029/2010JD013900.

Norgren, M., G. de Boer and M.D. Shupe, 2018: Observed aerosol suppression of cloud ice in low-level Arctic mixed-phase clouds, *Atmos. Chem. Phys.*, 18, 13345-13361, https://doi.org/10.5194/acp-18-13345-2018.

Onarheim, I. H., T. Eldevik, L. H. Smedsrud, and J. C. Stroeve, 2018: Seasonal and Regional Manifestation of Arctic Sea Ice Loss. *J. Climate*, **31**, 4917–4932, https://doi.org/10.1175/JCLI-D-17-0427.1.

Perovich, D. K., Grenfell, T. C., Light, B., and Hobbs, P. V., 2002: Seasonal evolution of the albedo of multiyear Arctic sea ice, *J. Geophys. Res.*, 107(C10), 8044, doi:10.1029/2000JC000438.

Pithan, F., et al., 2018: Role of air-mass transformations in exchange between the Arctic and mid-latitudes. *Nature Geosci* **11,** 805–812 (2018). https://doi.org/10.1038/s41561-018-0234-1

Prenni, A. J., et al., 2007: Can Ice-Nucleating Aerosols Affect Arctic Seasonal Climate?. *Bull. Amer. Meteor. Soc.*, **88**, 541–550, https://doi.org/10.1175/BAMS-88-4-541.

Schmale, J., et al., 2017: Collocated observations of cloud condensation nuclei, particle size distributions, and chemical composition. *Sci Data* **4,** 170003. https://doi.org/10.1038/sdata.2017.3

Schröder, D., et al., 2014: September Arctic sea-ice minimum predicted by spring melt-pond fraction. Nature Clim Change 4, 353–357, https://doi.org/10.1038/nclimate2203

Schweiger, A., et al., 2011: Uncertainty in modeled arctic sea ice volume, J. Geophys. Res., doi:10.1029/2011JC007084

Sedlar, J., et al., 2011: A transitioning Arctic surface energy budget: the impacts of solar zenith angle, surface albedo and cloud radiative forcing , Climate Dynamics. doi: 10.1007/s00382-010-0937-5, https://epic.awi.de/id/eprint/22044/1/Sed2010a.pdf

Segal Rozenhaimer, M., et al., 2018: Bias and sensitivity of boundary layer clouds and surface radiative fluxes in MERRA-2 and airborne observations over the Beaufort Sea during the ARISE campaign. Journal of Geophysical Research: Atmospheres, 123, 6565– 6580. https://doi.org/10.1029/2018JD028349

Serreze, M. and Barry, 2011: Processes and impacts of Arctic amplification: A research synthesis. *Global and Planetary Change*, **77**, 85–96, doi:10.1016/j.gloplacha.2011.03.004

Sigmond, M., J. Fyfe, G. Flato, V. Kharin, and W. Merryfield, 2013: Seasonal forecast skill of Arctic sea ice area in a dynamical forecast system. Geophys. Res. Lett., 40, 529–534, doi:10.1002/ grl.50129.

Silber, I., et al., 2019: Persistent supercooled drizzle at temperatures below −25°C observed at McMurdo Station, Antarctica. *Journal of Geophysical Research: Atmospheres*, **124**, 10,878– 10,895. https://doi.org/10.1029/2019JD030882

Sledd, A. and L'Ecuyer, T., 2019: How Much Do Clouds Mask the Impacts of Arctic Sea Ice and Snow Cover Variations? Different Perspectives from Observations and Reanalyses, Atmosphere, 10, 12, https://doi.org/10.3390/atmos10010012.

Shupe, M. D. and Intrieri, J. M., 2004: Cloud Radiative Forcing of the Arctic Surface: The Influence of Cloud Properties, Surface Albedo, and Solar Zenith Angle, J. Climate, 17, 616–628, https://doi.org/10.1175/1520-0442(2004)017<0616:CRFOTA>2.0.CO;2.

Smith, W. L., et al., 2017: Arctic Radiation-IceBridge Sea and Ice Experiment: The Arctic Radiant Energy System during the Critical Seasonal Ice Transition. *Bull. Amer. Meteor. Soc.*, **98**, 1399–1426, https://doi.org/10.1175/BAMS-D-14-00277.1.

Soja, A., et al., 2008: ARCTAS: The perfect smoke. The Canadian Smoke Newsletter.

Solomon, A., de Boer, G., Creamean, J. M., McComiskey, A., Shupe, M. D., Maahn, M., and Cox, C., 2018: The relative impact of cloud condensation nuclei and ice nucleating particle concentrations on phase partitioning in Arctic mixed-phase stratocumulus clouds, Atmos. Chem. Phys., 18, 17047–17059, https://doi.org/10.5194/acp-18-17047-2018.

Stevens, R. G., et al., 2018: A model intercomparison of CCN-limited tenuous clouds in the high Arctic, Atmos. Chem. Phys., 18, 11041–11071, https://doi.org/10.5194/acp-18-11041-2018.

Stohl, A., 2006: Characteristics of atmospheric transport into the Arctic troposphere, *J. Geophys. Res.*, 111, D11306, doi:10.1029/2005JD006888.

Stramler, K., A.D. Del Genio, and W.B. Rossow, 2011: Synoptically driven Arctic winter states. *J. Climate*, **24**, 1747-1762, doi:10.1175/2010JCLI3817.1

Stubenrauch, C., et al., 2013: Assessment of Global Cloud Datasets from Satellites: Project and Database Initiated by the GEWEX Radiation Panel. Bulletin of the American Meteorological Society. 94. 1031-1049. 10.1175/BAMS-D-12-00117.1.

Sulia, K., and J. Harrington, 2011: Ice aspect ratio influences on mixed-phase clouds: Impacts on phase partitioning in parcel models. J. Geophys. Res., 116, D21309, https://doi.org/10.1029/2011JD016298.

Tan, I. and Storelvmo, T., 2015: Sensitivity Study on the Influence of Cloud Microphysical Parameters on Mixed-Phase Cloud Thermodynamic Phase Partitioning in CAM5, *J. Atmos. Sci.*, **73**, 709–728, https://doi.org/10.1175/JAS-D-15-0152.1.

Tan, I., Storelvmo, T., and Zelinka, M. D., 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352**, 224– 227.

Taylor, P. C., Kato, S., Xu, K.-M., and Cai, M., 2015: Covariance between Arctic sea ice and clouds within atmospheric state regimes at the satellite footprint level, J. Geophys. Res.-Atmos., 120, 12656–12678, https://doi.org/10.1002/2015JD023520.

Taylor, P. C., W. Maslowski J. Perlwitz, and D. J. Wuebbles, 2017: Arctic Changes and their Effects on Alaska and the Rest of the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D. J., S. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Steward, and T. K. Maycock (eds.)]. U.S. Global Climate Change Research Program, Washington, DC, USA, pp. 303-332, doi: 10.7930/J00863GK.

Taylor, P. C., Boeke, R. C., Li, Y., and Thompson, D. W. J., 2019: Arctic cloud annual cycle biases in climate models, *Atmos. Chem. Phys.*, **19**, 8759–8782, https://doi.org/10.5194/acp-19-8759-2019.

Tietsche, S., et al., 2014: Seasonal to interannual Arctic sea ice predictability in current global climate models. Geophys. Res. Lett., 41, 1035–1043, doi:10.1002/ 2013GL058755.

Tjernström, M., et al., 2014: The Arctic Summer Cloud Ocean Study (ASCOS): overview and experimental design, Atmos. Chem. Phys., 14, 2823–2869, https://doi.org/10.5194/acp-14-2823-2014.

Tjernström, M., et al., 2019: Arctic Summer Airmass Transformation, Surface Inversions, and the Surface Energy Budget. J. Climate, 32, 769–789, https://doi.org/10.1175/JCLI-D-18-0216.1.

Tobo, Y., et al., 2019: Glacially sourced dust as a potentially significant source of ice nucleating particles. *Nat. Geosci.* **12,** 253–258 doi:10.1038/s41561-019-0314-x

Wang, W., M. Chen, and A. Kumar, 2013: Seasonal prediction of Arctic sea ice extent from a coupled dynamical forecast system. Mon. Wea. Rev., 141, 1375–1394, doi:10.1175/MWR-D-12-00057.1.

Wendisch, M., and Coauthors, 2019: The Arctic Cloud Puzzle: Using ACLOUD/PASCAL Multiplatform Observations to Unravel the Role of Clouds and Aerosol Particles in Arctic Amplification. *Bull. Amer. Meteor. Soc.*, **100**, 841–871, https://doi.org/10.1175/BAMS-D-18-0072.1.

Willis, M. D., Leaitch, W. R., & Abbatt, J. P., 2018: Processes controlling the composition and abundance of Arctic aerosol. Reviews of Geophysics, 56, 621–671. https://doi.org/10.1029/2018RG000602

Zamora, L. M., et al., 2016: Aircraft-measured indirect cloud effects from biomass burning smoke in the Arctic and subarctic, Atmos. Chem. Phys., 16, 715–738, https://doi.org/10.5194/acp-16-715-2016.

Zamora, L. M., Kahn, R. A., Huebert, K. B., Stohl, A., and Eckhardt, S., 2018: A satellite-based estimate of combustion aerosol cloud microphysical effects over the Arctic Ocean, Atmos. Chem. Phys., 18, 14949–14964, https://doi.org/10.5194/acp-18-14949-2018.