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COMMENTARY

Fostering multidisciplinary research on interactions between chemistry, biology, and physics within the coupled cryosphere-atmosphere system

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The cryosphere, which comprises a large portion of Earth's surface, is rapidly changing as a consequence of global climate change. Ice, snow, and frozen ground in the polar and alpine regions of the planet are known to directly impact atmospheric composition, which for example is observed in the large influence of ice and snow on polar boundary layer chemistry. Atmospheric inputs to the cryosphere, including aerosols, nutrients, and contaminants, are also changing in the anthropocene thus driving cryosphere-atmosphere feedbacks whose understanding is crucial for understanding future climate. Here, we present the Cryosphere and ATmospheric Chemistry initiative (CATCH) which is focused on developing new multidisciplinary research approaches studying interactions of chemistry, biology, and physics within the coupled cryosphere – atmosphere system and their sensitivity to environmental change. We identify four key science areas: (1) micro-scale processes in snow and ice, (2) the coupled cryosphere-atmosphere system, (3) cryospheric change and feedbacks, and (4) improved decisions and stakeholder engagement. To pursue these goals CATCH will foster an international, multidisciplinary research community, shed light on new research needs, support the acquisition of new knowledge, train the next generation of leading scientists, and establish interactions between the science community and society.

Keywords: Cryosphere; Atmospheric chemistry; Science coordiation

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Introduction and context

A large portion of Earth's surface is covered by frozen water including seasonal snow; sea, river, and lake ice; alpine and high latitude glaciers; ice sheets and ice shelves; and permafrost. These regions are collectively referred to as the *cryosphere*. Glaciers and ice caps in polar regions and high mountains cover 10% of the land area on Earth (730,000 km^2) (National Snow and Ice Data Center – a, 2019). A much larger area of 17 million to 27 million km^2, equivalent to approximately 15% of the world's oceans, is covered by sea ice on average during the year (Spreen and Kern, 2017). Seasonal snow, the most dynamic single component of the cryosphere, covers up to ~20% of the Northern Hemisphere land surface (National Snow and Ice Data Center – b, 2019). In addition, permanently frozen ground (permafrost) covers a significant portion of the Arctic as well as some parts of Antarctica and some mountains (9–12% of global land surface, Vaughan et al., 2013). The extent of snow and ice covering the Earth's surface is shown in **Figure 1**, which combines winter-time ice and snow cover in both the Southern and Northern Hemisphere. Finally, the atmosphere contains ice particles in clouds and fog, which are chemically and physically similar to snow and ice at the Earth's surface (e.g. Bartels-Rausch et al., 2014).

The cryosphere is rapidly changing as a consequence of global and regional climate change (Vaughan et al., 2013). Both the spatial extent and thickness of Arctic sea ice has drastically declined in the past 40 years. The large polar ice sheets and lower-latitude glaciers are losing mass at unprecedented rates (Vaughan et al., 2013). The spatial extent and duration of seasonal snow cover in the Arctic

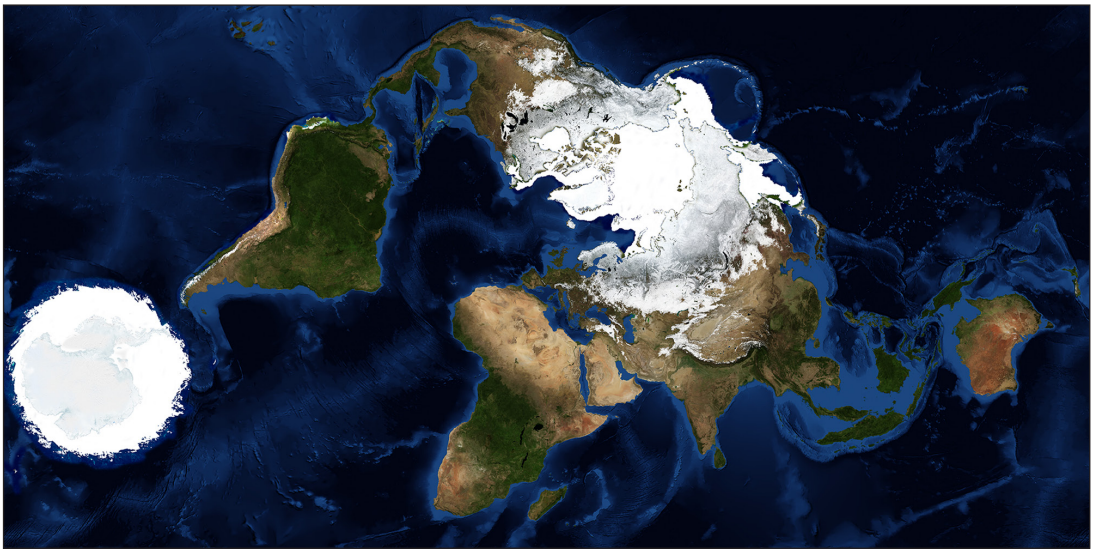

Figure 1: Map of snow and ice covered surfaces (white) on Earth during Northern and Southern Hemisphere winters combined from NASA's Blue Marble collection, with Northern Hemisphere sea ice extent from the National Snow and Ice Data center. The map projection is described in Grieger (2019), which shows Antarctica and the Arctic region with only small spatial distortions. DOI: https://doi.org/10.1525/elementa.396.f1

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and mountain regions is also substantially declining (e.g. Bormann et al., 2018). These changes are expected to continue in the next decades, with important implications for the physics, chemistry, and biology of the coupled cryosphere-atmosphere system.

Over the past decades, many chemical and physical processes that link the cryosphere and atmosphere in the Arctic, Antarctica, high latitude oceans, and low-latitude mountain regions (shown as white in **Figure 1**) have been identified (e.g. Dominé and Shepson, 2002; Grannas et al., 2007; Vancoppenolle et al., 2013; Gabric et al., 2018; Abbatt et al., 2019). **Figure 2** summarizes a range of ways in which the atmosphere, cryosphere, and polar oceans are interconnected through chemical, biological, and physical processes. For example, deposition of both natural and anthropogenic aerosols formed locally or transported from distant biomass burning, industrial, and dust emissions impact the cryosphere by introducing light absorbing impurities, nutrients, and toxic contaminants to snow, sea ice, glaciers, and ice sheets. The extent of the Earth's surface potentially impacted by these processes is highlighted in white in **Figure 1**. Transport in the atmosphere within meteorological systems determines the vertical distribution of gases and aerosols as well as wet and dry removal rates (Monks et al., 2015; Eckhardt et al., 2015; Qi et al., 2017). The presence of snow and ice also profoundly modifies atmospheric boundary layer dynamics (Anderson and Neff, 2008), including surface inversions and stable layers (e.g. Mayfield and Fochesatto, 2012) that can trap any emitted chemical species near the surface. Ice and snow have important roles in determining both local and large-scale atmospheric circulation as well as climate processes through a complicated chain of large-scale feedbacks. There is also a need to understand spatial and temporal heterogeneity using observations and process studies in order to upscale knowledge to the regional and global scale. Therefore, atmospheric chemistry and dynamics, and their uncertainties, are inherently coupled at the surface.

Biological and (photo)chemical processes in snow, sea ice, and polar oceans emit gases and aerosols that influence the cloud life cycle, the lifetime of greenhouse gases (such as CH_4) and atmospheric pollutants, as well as the radiative budget (e.g. Levasseur et al., 1994; Leck and Bigg, 2005; Grannas et al., 2007; Chang et al., 2011; Orellana et al., 2011; McNeill et al., 2012; Sipila et al., 2016; Gia marelou et al., 2016; Mungall et al., 2016; Kim et al., 2017; Park et al., 2017; Abbatt et al., 2019). A warming cryosphere with large ice losses will also alter sea ice ecosystems with poorly known impacts on food webs (Tedesco et al., 2019), air-ice chemical exchange fluxes, and ultimately climate. These interactions represent multiple coupled systems that connect the atmosphere and cryosphere throughout the globe from the most remote areas, such as Antarctica

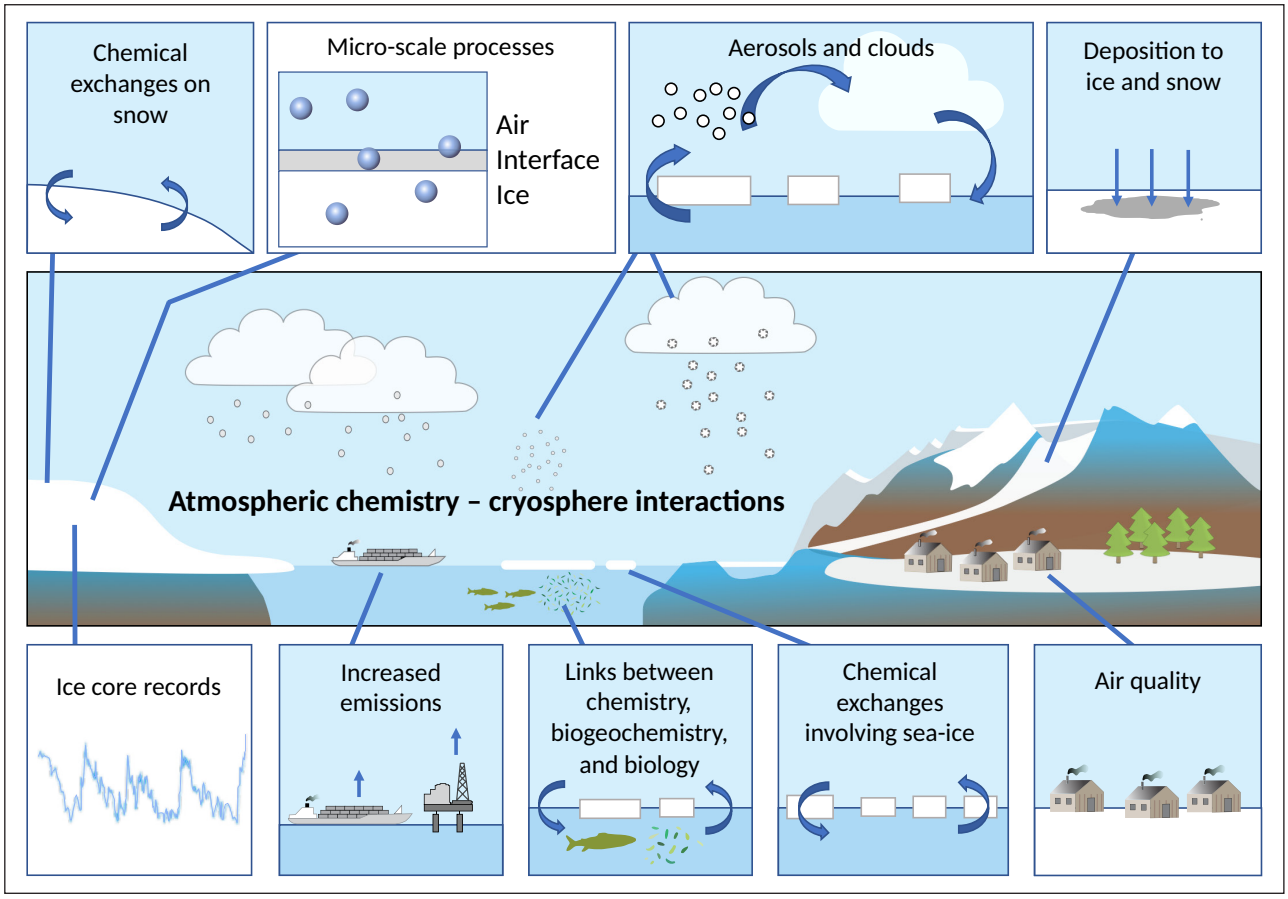

Figure 2: Schematic of selected cryosphere-atmosphere interactions relevant to understanding current, past, and future atmospheric composition and feedbacks including processes involving the polar oceans, snow, biology, biogeochemistry, and physics. DOI: https://doi.org/10.1525/elementa.396.f2

and the high Arctic, to polluted urban/industrial regions. These are only a few examples of the many ways that atmospheric composition is fundamentally linked to the cryosphere. Human-caused environmental change and activities are already influencing these coupled systems in snow and ice dominated environments through ice and snow loss as well as through increasing anthropogenic inputs to snow/ice covered regions.

The intrinsically interconnected chemical, physical, and biological processes involving the atmosphere and cryosphere create a complex multi-scale, multi-compartment system that is currently not well understood. Knowledge gaps remain that limit our ability to develop accurate models at process, regional, and global scales (for example as discussed in Thomas et al., 2011; Domine et al., 2013; Grannas et al., 2013; Bartels-Rausch et al., 2014; Toyota et al., 2014; Murray et al., 2015; Steiner et al., 2016; Bock et al., 2016; Falk and Sinnhuber, 2018). This limited knowledge also impacts our understanding of ice core records as a critical tool to determine past atmospheric composition (recent examples: Kunasek et al., 2010; Wolff et al., 2010; Yeung et al., 2019). Most importantly, we lack the knowledge to extrapolate our knowledge of atmospheric composition-cryosphere interactions to make short and long-term projections.

To foster a multidisciplinary international community we have established the Cryosphere and ATmospheric CHemistry (CATCH) initiative. The central focus of CATCH is **to understand the fundamental interactions within the coupled cryosphere-atmosphere chemical system and the two way connections with environmental change**. We have identified four themes as part of CATCH, which together provide a framework for understanding these interlinked systems.

1. Micro-scale processes on snow and ice

Chemical transformations on ice are known to have widespread impacts on atmospheric composition. However, at present the nature of cryospheric chemistry and physics at the molecular level are poorly understood (Abbatt et al., 2014; Burkholder et al., 2017). For example, the distribution and migration of chemicals in snow and ice reservoirs such as: brine, dissolved impurities, crystalline deposits, and aerosol deposits are still largely unknown (Obbard et al., 2009; Hullar and Anastasio, 2016; Morenz and Donaldson, 2017; Eichler et al., 2017). There are major uncertainties in our fundamental understanding of cryospheric chemical mechanisms and kinetics under a wide variety of environmental conditions. Of particular significance is chemistry at the surface of ice and snow that is in contact with the surrounding air, because it is at this air–ice interface where the exchange of chemicals takes place (Kahan and Donaldson, 2008; Ye et al., 2016; McFall et al., 2018; Hullar et al., 2018). Properties of ice surfaces, such as acidity, are important to understand many chemical processes that are currently uncertain (e.g. Abbatt et al., 2012; Wren and Donaldson, 2012; Krepelova et al., 2013; Kong et al. 2017).

Laboratory studies using advanced analytical techniques can provide unique insights into these processes (e.g. Ammann et al., 2018). For example, identification of the location of chemicals in the complex multi-phase system of environmental ice and snow (Grannas et al., 2007; Bartels-Rausch et al., 2014) would considerably advance our ability to describe the system at a micro-scale level. Improved understanding of the chemical reactions, combined with existing knowledge, would allow for better quantitative descriptions of the evolution of the system with time. Translating this micro-scale knowledge to improved modeling capabilities is essential for determining how the cryosphere impacts atmospheric chemistry on longer time scales. To accomplish this, we need to develop models at different scales, including small scale models that are fully explicit and larger scale models that include simplified descriptions or parameterizations of the underlying micro-scale chemical and physical processes occurring.

2. The coupled cryosphere-atmosphere system

(Photo)chemical and biological processing of trace species (defined as gases and aerosols) occur simultaneously in the atmosphere, ocean, and ice/snow. This, together with synoptic scale meteorology, small scale atmospheric mixing, as well as ice/snow physical processes, creates a complex interconnected system (e.g. Dominé and Shepson, 2002). While we have a basic understanding of some processes, full system understanding has been elusive. It is now clear that (photo-)chemistry in and on the snow-pack plays an active role in atmospheric chemistry (Grannas et al., 2007). Unequivocal evidence for some of these processes come from direct observations of active chemistry in snowpack interstitial air (Van Dam et al., 2015) and fluxes of reactive nitrogen (Honrath et al., 1999; Jones et al., 2001; Frey et al., 2015), halogen species (Simpson et al., 2007; Saiz-Lopez et al., 2007; Abbatt et al., 2012; Pratt et al., 2013; Raso et al., 2017), and other species (Erbland et al., 2013; Hutterli et al., 2001). Emissions of halogen species from snow and ice lead to well-known polar ozone and mercury depletion events (Barrie et al., 1988; Steffen et al., 2008; Oltmans et al., 2012; Helmig et al., 2012), significantly altering atmospheric chemistry. In contrast, snow emissions of reactive nitrogen in the Antarctic lead to episodic ozone production (Jones et al., 2000; Crawford et al., 2001; Helmig et al., 2008).

Transport processes that connect the various compartments (ocean, snow, ice, atmosphere, etc.) to each other and as well as transport within compartments require further study. Knowledge gaps in our understanding of surface-atmosphere exchange processes, boundary layers over snow/ice, synoptic scale meteorology, and snow/ice/ocean physics lead to uncertainties in our understanding of chemical cycling. For example, the presence of open leads (large fractures exposing open water within sea ice) is known to directly influence both atmospheric mercury and ozone depletion events (Moore et al., 2014). Cryospheric processes also impact the lifetime of atmospheric mercury, by emitting species that convert elemental mercury to more reactive forms that are readily deposited to the cryosphere and oceans (Angot et al., 2016). Another example involves the role of solar radiation in determining photochemistry and oxidation processes, which is often influenced by the presence of clouds.

Accurate quantitative, and in cases qualitative, descriptions of many coupled cryosphere-atmosphere chemical processes have still not been achieved. Often, the controlling processes, such as emissions, recycling on surfaces, replenishment of reactive species from aloft, and the relationship with the physical and chemical state cryosphere are still not fully understood. This is due to uncertain micro-scale processes (see section 1) as well as lack of knowledge of transport of chemical species between the atmosphere, oceans, and snow/ice via both deposition (Petroff and Zhang, 2010) and wind-driven transport (Domine et al., 2004; Huwald et al., 2012). We also highlight that there is very limited knowledge of the chemical processes occurring during polar night, hindering understanding during this season (Jones et al., 2014; Abrahamsson et al., 2018; Simpson et al., 2018).

Biological activity in snow, sea ice, and oceans releases atmospheric sulfur, volatile organic species, sea-spray (containing organics and inorganic salts), and other aerosols (see recent examples in Salter et al., 2016; Willis et al., 2017; Mungall et al., 2017; Steiner and Stefels, 2017; Burkart et al., 2017; Willis et al., 2018; Gilgen et al., 2018; Giordano et al., 2018; Abbatt et al., 2019; Frey et al., 2019; Wex et al., 2019). Once in the atmosphere, aerosols in the polar regions participate in reactive atmospheric chemistry through, for example, uptake of gases and heterogeneous chemical transformations (Thomas et al., 2011, 2012; Peterson et al., 2017; Giordano et al., 2018; Yang et al., 2019; Frey et al., 2019). Snow also hosts microorganisms that participate in coupled atmosphere-cryosphere reactive nitrogen cycling (Amoroso et al., 2010; Larose et al., 2013). Aerosols are clearly linked with clouds and precipitation, but the sources and impacts of aerosols that act as cloud condensation nuclei (CCN) and ice nucleating particles (INP) at high latitudes and altitudes remain poorly understood (e.g. Orellana et al., 2011; Leck and Svensson, 2015; Croft et al., 2016; Burkart et al., 2017; Willis et al., 2017; Irish et al., 2019; McCluskey et al., 2018; Creamean et al., 2018; Si et al., 2019; Schmale et al., 2019). In the Southern Hemisphere (including the Antarctic region) models have a significant sea surface temperature warm bias caused by poor predictions of clouds (Hyder et al., 2018), which is in part due to lacking knowledge of aerosol sources and their impacts on clouds over the Southern Ocean. Many additional interconnected processes have been proposed and more are likely active, but we still lack the ability to quantify combined cryosphere-atmosphere chemistry, transport, and radiation interactions. A full understanding of the cryosphere-atmosphere system requires a multidisciplinary approach that considers the full complexity of these interconnected physical, chemical, and biological processes.

3. Cryospheric change and feedbacks

The cryosphere is one of the most rapidly changing domains within the Earth system. Consequently, we expect major changes in cryosphere-atmosphere interactions (Miller et al., 2019; Boy et al., 2019, and references therein). Sea ice decline defines the Arctic, including a shift to younger, thinner, and more widespread first-year sea ice (Stroeve et al., 2012; Meier et al., 2014; Lindsay and Schweiger, 2015; Granskog et al., 2018), more similar to Antarctic ice conditions. The increased first year sea ice fraction is thinner, more dynamic, and is associated with more open leads and greater surface water exposure. This, in turn, means future Arctic sea ice will provide more saline surfaces to promote lower atmospheric and snow/ice surface chemical reactions (Douglas et al., 2017, and references therein). Even the Antarctic, which has had stable or growing sea ice for decades, experienced the smallest observed sea ice extent ever recorded in 2017 (Turner and Comiso, 2017). The effects of sea ice loss on atmospheric composition including gas, aerosol, clouds, and elemental exchanges between the ocean and atmosphere are uncertain. For example, recent evidence demonstrates that more open water due to reduced sea ice may result in increasing sources of climate relevant aerosols and aerosol precursors (e.g. Heintzenberg et al., 2015; Dall'Osto et al., 2017, 2018; Mungall et al., 2017).

Understanding the potential impacts of sea ice change on cloud properties is currently limited by uncertainties in the relationship between sea ice and aerosol (CCN and INP), including disagreement in both the sign and magnitude of possible feedbacks (Struthers et al., 2011; Mauritsen et al., 2011; Liu et al., 2012; Browse et al., 2014; Gilgen et al., 2018; Morrison et al., 2018). Changing sea ice conditions may influence under-ice, ice, and ocean ecology (i.e. phenology, biomass, and community structure, see for example Yool et al. (2015); Assmy et al. (2017); Granskog et al. (2018)), with implications for emissions to the atmosphere and the fate of contaminants in the polar oceans. First year sea ice and snow on top of it are more saline than multi year sea ice, with implications for chemical air-snow exchanges. Deposition of atmospheric aerosols to snow and ice can trigger albedo reductions and feedbacks that accelerate snowmelt (Skiles et al., 2018). Deposited aerosols and gases provide nutrients to feed snow microbial communities that may further reduce snow albedo (Benning et al., 2014; Nicholes et al., 2019). Warmer temperatures, more frequent rain events, and shorter snow seasons also influence the composition, morphology, and optical properties of snow and influence the role of snow in the climate system. Knowledge of processes that link the atmosphere (aerosols, clouds, contaminants, nutrients) to the changing cryosphere must be established in order to quantify and predict atmospheric inputs to changing glaciers, ice, and snowpacks. Changing large-scale atmospheric dynamics and atmospheric boundary layers (e.g. Graham et al., 2019) are important because they influence chemical emissions, atmospheric processing, and the fate of gases and aerosols. Understanding these links is also key for establishing the relationships between the cryosphere and atmospheric chemistry via ice core records, for example for establishing past tropospheric ozone concentrations (Yeung et al., 2019). The interconnections between climate change, changing temperatures, sea ice and snow properties, chemical and biological processes, and the composition of the overlying atmosphere must be explored to fully understand how this coupled system will evolve in the coming decades and beyond.

4. Improved decisions and stakeholder engagement

Future changes in the physics, chemistry, and biology of the cryosphere also must be viewed in the context of human activities, decisions, and policies. There are many local and regional examples of human activities impacting the cryosphere-atmosphere system that are resulting in unique processes we are only now beginning to understand. One example is the observation that the presence of snow amplifies the negative effects of emissions from oil and gas extraction activities, leading to ozone levels comparable to those in some of the most polluted cities in summer (Edwards et al., 2014). It is also increasingly recognized that human populations living in high-latitude cities face the highest pollution levels during winter, when the complex interplay between human emissions, boundary layer meteorology over snow, and chemistry in the presence of snow and ice lead to a unique, but thus far poorly understood, urban air quality problem (Ariya et al., 2018). Anthropogenic activities will also increase in newly ice/snow free regions including: ship traffic, exploration of natural resources, and associated human population changes (Schmale et al., 2018; Arnold et al., 2016). Climate adaptation and mitigation strategies will influence these coupled systems by protecting ice in the environment or by further causing anthropogenic cryospheric change.

It is well known that persistent organic pollutants and mercury are present at toxic levels in polar biota, despite the limited local anthropogenic emission sources (e.g. Campbell et al., 2005; Braune et al., 2005; Dietz et al., 2009; Letcher et al., 2010; Fort et al., 2016). These pollutants are known to bioaccumulate in food webs, negatively impacting humans, especially in the Arctic region. There is also ongoing debate regarding the role of the oceans, tundra, and snow cover in controlling emissions, deposition, and methylation of toxic mercury within the Arctic (Heimbürger et al., 2015; Obrist et al., 2017; Douglas et al., 2017; Sonke et al., 2018; Douglas and Blum, 2019). There are many outstanding questions as to how these contaminant cycles will be impacted by climate change (Stern et al., 2012). Atmospheric contaminants deposited to glaciers, ice, and snow (discussed in Sections 2 and 3) may also negatively influence downstream water quality and influence nutrient availability upon melting (e.g. Kwok et al., 2013; Douglas et al., 2017; Bourgeois et al., 2018).

Despite progress in the last decades, at present links between atmospheric processes (aerosols, clouds, etc.) tied to cryospheric change poses a challenge in understanding, projecting, and managing environmental change. Shortcomings in knowledge of the aerosol and cloud lifecycles also influence our ability to understand and predict precipitation, which is important for the livelihood of local and indigenous populations. Specifically, the fraction of wet to dry precipitation in the Arctic is projected to increase as the summer season lengthens (Bintanja and Andry, 2017). Establishing the natural background atmospheric composition and its link to cryospheric change is needed to provide a baseline to understand the influence of anthropogenic pollution and to evaluate the effectiveness of climate and air quality protection policy options. National and international environmental legislation consistent with scientific recommendations are needed including: emission rules for ships, laws for mineral extraction including oil drilling, and plans for urbanization. Diverse stakeholders impacted by these decisions must be included in the scientific process to make this possible. In addition, research on the future state of the cryosphere and atmosphere must also consider the ongoing social and economic changes in these areas, such as environmental policies regulating emissions from shipping, mining and urbanization. This requires close collaborations among people with diverse backgrounds to optimize environmental management strategies that protect ecosystems, humans, and the natural environment.

The CATCH initiative

In order to develop transformational understanding, CATCH aims to support and develop research and outreach activities that focus on the interconnected and multidisciplinary cryosphere-atmosphere system.

Fostering an international, multidisciplinary research community

CATCH aims to foster a community that brings together scientific disciplines to address the research challenges detailed in Sections 1–4. We aim to connect researchers from atmospheric chemistry, cryospheric sciences, oceanography, marine biology/biogeochemistry, atmospheric sciences (including meteorology and climate science), and other disciplines to address these research problems together. CATCH supports this goal by hosting and participating in workshops, conferences, and informal meetings as well as establishing a culture of multidisciplinary research. CATCH supports the creation of international, multidisciplinary and transdisciplinary teams that collaboratively address science, society, and stakeholder needs.

Developing knowledge

CATCH develops and supports new and existing projects that simultaneously characterize system behavior including the physical, chemical, biological, and biogeochemical state of the atmosphere and the changing cryosphere. Process understanding is needed at molecular to global scales and from microsecond to greater than 100 year time scales. Of particular interest is linking knowledge of micro-scale processes (lab and theoretical studies) to understanding of processes occurring at larger scales. CATCH will contribute to the development of new observational technologies, harmonizing existing experimental techniques in the lab and field, and support the development/linking of multidisciplinary datasets. CATCH will contribute to the development of models at different temporal and spatial scales, including detailed regional/process models and improved descriptions of cryosphere-atmosphere processes in global scale Earth System Models.

Shedding light on research needs

Now is a critical moment to support integrating the expertise from disparate science communities to achieve a step change in understanding of the cryosphere-atmos-

phere system. The CATCH community will work together to identify overarching research needs and communicate those to the research community, stakeholders, and funding agencies. Through developing the cryosphere-atmosphere community, CATCH will aid in identifying current gaps in funding streams that inhibit research progress.

Training the next generation of leading scientists

CATCH scientists aim to engage, mentor, and train the next generation of diverse scientists including researchers in scientifically emerging countries by integrating Early Career Researchers (ECR) into all levels of CATCH activities. This will be accomplished by training ECRs as part of interdisciplinary research projects, helping to develop scientists that naturally cross traditional disciplinary boundaries. In addition, CATCH will offer both formal and informal training opportunities to scientists from all career levels.

Societal impacts

CATCH will foster interactions between the science community and society through science communication including cross-disciplinary dialogues and public engagement. We will address these issues together with existing science communities, including *air Pollution in the Arctic: Climate, Environment and Societies* (PACES, pacesproject.org) and *Biogeochemical exchanges at Sea Ice Interfaces* (BEPSII, bepsii.org), who have also recognized the importance of many of these issues. CATCH encourages researchers to engage stakeholders impacted by the coupled cryosphere-atmosphere system in order to deliver the knowledge needed for effective environmental management.

In summary, the main objective of CATCH is to understand the fundamental principles of the interlinked cryosphere-atmosphere composition system with the goal to better describe its behavior under continued global change. To find out more about CATCH and our sponsors, we encourage members of the scientific community to visit our website catchscience.org and contribute to achieving the CATCH goals. Researchers from diverse backgrounds are welcome to join the mailing list, participate in our meetings and workshops, and to help build the CATCH initiative. It is through engagement and participation of scientists and stakeholders that we can unite disparate research communities, develop knowledge, identify outstanding research needs, train new scientists, engage society, and understand the societal relevance of the atmosphere-cryosphere system.

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Competing interests

The authors have no competing interests to declare.

Author contributions

JLT, JPS, TBR, and MF wrote the manuscript. JM prepared Figure 1. JLT, JPS, TBR, and LM prepared Figure 2. All co-authors contributed to drafting manuscript text, developing CATCH, and editing the manuscript.

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