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Defining the "Ice Shed" of the Arctic Ocean's Last Ice Area and Its Future Evolution

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Key Points:

- By mid-century, the major source of sea ice to the Arctic's Last Ice Area (LIA) will shift from the Russian shelves, to the central Arctic
- If global mean warming stabilizes at 2C, the LIA should stabilize, with younger ages and different sources than in recent history
- If current warming rates continue, LIA ice will likely be local and seasonal, devastating ice-obligate ecologies in this century

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Sea ice will persist longer in the Last Ice Area (LIA), north of Canada and Greenland, than elsewhere in the Arctic. We combine earth system model ensembles with a sea-ice tracking utility (SITU) to explore sources of sea ice (the "ice shed") to the LIA under two scenarios: continued high warming (HW) rates and low warming (LW) rates (mean global warming below ca. 2°C) through the 21st century. Until mid-century, the two scenarios yield similar results: the primary ice source shifts from the Russian continental shelves to the central Arctic, mobility increases, and mean ice age in the LIA drops from about 7 years to less than one. After about 2050, sea ice stabilizes in the LW scenario, but continues to decline in the HW scenario until LIA sea ice is nearly entirely seasonal and locally formed. Sea ice pathways through the ice shed determine LIA ice conditions and transport of material, including biota, sediments, and pollutants (spilled oil and industrial or agricultural contaminants have been identified as potential hazards). This study demonstrates that global warming has a dramatic impact on the sources, pathways and ages of ice entering the LIA. Therefore, we suggest that maintaining ice quality and preserving ice-obligate ecologies in the LIA, including the Tuvaijuittuq Marine Protected Area north of Nunavut, Canada, will require international governance. The SITU system used in this study is publicly available as an online utility to support researchers, policy analysts, and educators interested in past and future sea ice sources and trajectories.

1. Introduction

In this study, we address the sources of sea ice to the "Last Ice Area" (LIA), where sea ice is expected to last the longest in the face of anthropogenic warming. We are motivated in doing so by a major ongoing conservation effort. As the Arctic warms and summer sea ice disappears, species that depend on a year-round ice platform (referred to as ice-obligate species or ice-obligate ecologies) are at risk of extinction. A range of actors are organizing in support of marine protected areas in which such species and assemblages may be preserved as long as possible. The hope is that if global warming is reversed in the future, populations will recover along with Arctic sea ice. To illustrate potential ice conditions, we consider three scenarios: the recent past, and two simulated futures, assuming lower and higher degrees of global warming. Our focus is on the histories of ice that ultimately winds up in the LIA: ice history sets conditions such as ice thickness, topography, and accumulated biota, which are important underpinnings for ice-obligate communities of organisms.

1.1. The LIA

It is clear where the Arctic's last summer sea ice will be located (Pfirman et al., 2009). The region north of Canada and Greenland historically has the oldest (and therefore the thickest) ice, and models project that sea ice will persist longer there than anywhere else (Wang & Overland, 2009). It is also where ice-associated species, from charismatic mega-fauna like polar bears and ringed seals, to crustaceans and microscopic plankton, will continue to find habitat (Durner et al., 2009; Hamilton et al., 2014; Kelly et al., 2010). For about a decade, conservationists and scientists working on Arctic climate change have called for the creation of a protected area in the LIA, where ice-obligate species might be preserved longest. Models indicate that sea ice is likely to rebound on a time scale of years if the current global warming trend is reversed (Notz & Stroeve, 2016), which supports speculation that ice-obligate ecologies might also be able to eventually rebound.

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1.2. Tuvaijuittuq: An Ice-Covered Marine Protected Zone

On August 1, 2019, following ca. 10 years of research, planning and lobbying by conservationists, representatives of northern peoples' organizations, scientists, and other stakeholders (including the Qikiqtani Inuit Association, the Territory of Nunavut, and the World Wildlife Federation/Canada), the Canadian government established the Tuvaijuittuq Marine Protected Area (Figure 1; Rogers, 2019; WWFO-Canada, 2019). As a result, commercial and industrial development is proscribed within Tuvaijuittuq, "the place where the ice never melts," for 5 years, while Indigenous harvesting of resources is permitted. The protected area is part of a broader agreement on a "conservation economy," which includes $55M for Inuit training and employment.

Tuvaijuittuq encompasses an area set aside for Inuit use of 319,411 km^2, making it the 10th largest marine protected area in the world (Lewis et al., 2017). Classified as interim between now and 2024, a feasibility study will examine the possibility of permanent protection from oil, gas, mining, and other development within the protected area. Tuvaijuittuq only protects about one third of the region identified by climatologists as the LIA (Figure 1). Managing the entire LIA is one element of an international effort to protect marine environments in the Arctic, including a proposal to UNESCO for a Remnant Arctic Multiyear Sea Ice World Heritage Site (Fisheries and Ocean Canada, 2020; Speer et al., 2017).

1.3. Protecting the LIA Means Protecting the Ice Source Regions

Protecting the LIA is a unique scientific challenge. Its ecology shares some characteristics of terrestrial settings: on the time scale of days to a few months, the ice has historically been fixed or very slow-moving. Ringed seals and polar bears, for example, have relied on their dens in the ridged and corrugated sea-ice surface to stay approximately in one place. At the same time, the underlying primary production and lower trophic levels are largely marine, and mobile. There have been few scientific explorations in the LIA, but satellite and modeling studies indicate that in the last two decades, ice conditions have been changing, with ice mass loss exceeding many Arctic regions, and an extreme case of open water in summer, 2020 (Moore et al., 2019; Schweiger et al., 2021).

As we explore below, much of the ice in the LIA originates from remote formation sites, driven across the Arctic Ocean by wind and ocean currents (Pfirman et al., 2004). This imported ice, converging against the Canadian coastline, accounts for ridging, thickening, and the persistence of ice in the LIA. Imported ice brings with it materials that include minerals from remote coastal seas, airborne dust, and biological material such as diatom threads and mats attached to the bottom of the ice (Melnikov et al., 2002; Nurnberg et al., 1994; Pfirman et al., 1995). Ice-associated ecology depends on ice quality, including its rough topography, stability, and accumulated flora, which in turn depend on ice age and the history of the ice between formation and its convergence into the LIA.

Ice also rafts pollutants such as polychlorinated biphenyls, pesticides, heavy metals, and microplastics (Newton et al., 2017; Peeken et al., 2018; Pfirman et al., 1995, 2009). Thousands of square kilometers of ice arrive annually from Alaskan or Russian waters, where companies such as Rosneft, Gasprom, PAO Novatek, Royal Dutch Shell, and Chevron hold exploration and development leases, representing potentially disastrous sources of pollutant releases into the ice pack (Blanken et al., 2017; National Research Council, 2014; Newton et al., 2017; Rosen, 2020). To protect sea-ice habitats in the LIA requires, therefore, scientifically sound stewardship of ice sources and pathways, what we refer to as the LIA's ice shed (Pfirman et al., 2009), in addition to managing development within the LIA itself.

1.4. Increasing Development Brings Increased Risk of Oil Spills

As Arctic marine resource development and shipping accelerates, the risk of oil spills increases, and the Arctic is a perfectly bad environment for oil-spill response. Cold waters, often-impossible navigation, and long travel times to ports with emergency response resources combine to make mitigation extremely difficult (National Resource Council, 2014). In ice-covered waters, it is expected that oil would become entrained in and trapped below sea ice and be deposited in the water column wherever the ice melts or becomes land-fast (National Resource Council, 2014). Blanken et al. (2017) demonstrated that sea ice can transport oil faster

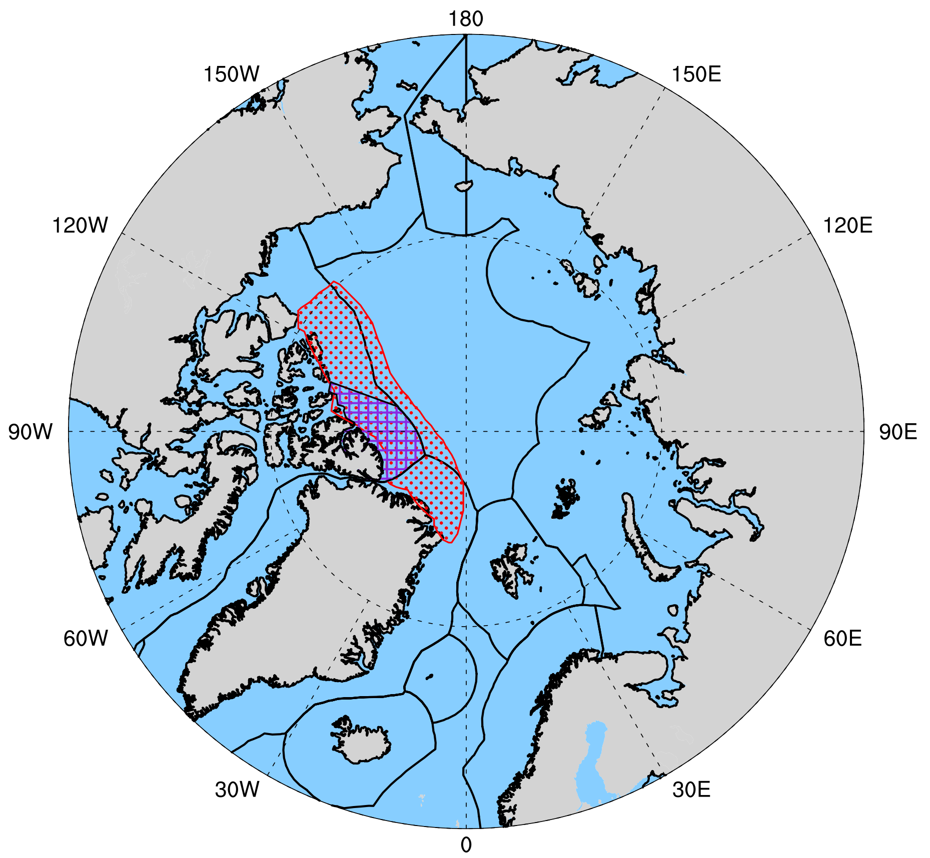

Figure 1. Map of the Arctic. Tuvaijuittuq Marine Protected Area (purple crosshatched region; Fisheries and Oceans Canada, 2020), the Last Ice Area (red stippled region), and the exclusive economic zones of the Arctic nations (black outlines).

than ocean currents when ice concentrations are high, and prevents it from dispersing, bringing significant impacts to areas thousands of kilometers from a spill.

1.5. Research Questions

The goal of this study is to assess how the source regions and pathways of LIA ice are likely to change over the remaining decades of the 21st century. In the past, ice in the LIA has mostly originated from remote areas of the Arctic, in particular over the Siberian shelf seas (Newton et al., 2017; Pfirman et al., 2009). As this ice travels to the LIA, it compacts and ridges, forming thick, multi-year ice, which provides year-round habitat to ice-dependent species. In addition, sea ice carries sediments and biological communities that reflect both the ice sources and the history of ice floes (e.g., Bluhm et al., 2017; Gradinger et al., 2005). Thus the environmental conditions that sustain ecologies in the LIA depend in significant part on the sources, pathways, and disposition of ice from remote areas of the Arctic. Those connections have been changing for the past 30 years (Newton et al., 2017; Rampal et al., 2009), and are expected to continue to change over the next several decades (DeRepentigny et al., 2016, 2020). During that timeframe, the Arctic will complete the ongoing transition from a perennial to a seasonal ice cover. The nature of the transition (when, how quickly, and what specific source regions remain) will depend on what emission pathway is realized (i.e., to what degree humans can mitigate carbon dioxide emissions). We will address that scenario uncertainty by considering two different ensembles with high and low global warming. To a lesser extent, the nature of the transition will depend on "internal" dynamics of the system, those that depend on very small-scale variations in the initial conditions and are related to the chaotic nature of the climate system. We address uncertainty due to these internal dynamics by looking at ensembles of runs with slightly perturbed initial-conditions, averaging across multiple realizations of a single scenario.

2. Materials and Methods

2.1. Sea-Ice Tracking Utility

The sea-ice tracking utility (SITU: http://icemotion.labs.nsidc.org/SITU/) used in this analysis is described in detail in DeRepentigny et al. (2016) (referred to there as the Lagrangian Ice Tracking System). SITU uses gridded fields of sea-ice concentration and sea-ice drift to identify individual ice-formation events, advect ice parcels, and identify ice melt events. SITU can be used to move parcels forward or backward in time, by reversing the direction of the estimated sea-ice drift fields. SITU is currently configured to operate either with motion and concentration fields from satellite observations, or with the same fields from model output. In prior work, we have used satellite-based ice-drift estimates from the National Snow and Ice Data Center (NSIDC) (Tschudi et al., 2016) to improve seasonal sea-ice predictions (Brunette et al., 2019; Williams et al., 2016) and study long-range transport (DeRepentigny et al., 2016; Newton et al., 2017). These observational fields, available from 1980 to the present, are derived from sea ice buoys, satellite imagery and, where no better estimates can be found, wind fields from the NCEP Reanalysis (Kalnay et al., 1996). In this study, we use model output from the Community Earth System Model (CESM).

2.2. Community Earth System Model

To estimate changes in sea ice sources and pathways over the 21st century, sea-ice drift vectors from the CESM1 have been integrated into SITU. The CESM1 is a fully coupled climate model with a nominal 1° horizontal resolution in all components (Hurrell et al., 2013). For the current study, we use monthly average outputs from the CESM-large ensemble (CESM-LE; Kay et al., 2015) and the CESM-low warming (CESM-LW) ensemble (Sanderson et al., 2017). For clarity, we refer to the CESM-LE runs as "high warming," HW, or CESM-HW throughout the remainder of the text. The CESM-HW ensemble is composed of 40 members, each with very slightly perturbed initial conditions. In this ensemble, climate change is simulated using an increase in greenhouse-gas concentrations through the 21st century based on the Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2011; van Vuuren et al., 2011). The CESM-LW ensemble is composed of 11 ensemble members, with forcing identical to the HW scenario up to 2006, and future forcing through the 21st century designed to limit the global mean temperature to 2°C above pre-industrial levels. For relevant details on SITU, the underlying data, and the CESM-HW (LE) and CESM-LW, see DeRepentigny et al. (2020). SITU is coded in MATLAB; the scripts and a sample of the MATLAB-formatted input data are available online: https://doi.org/10.5281/zenodo.4609295).

2.3. Last Ice Area

For this study, we defined the LIA as in Figure 1 (red stippled area north of the Canadian Arctic Archipelago [CAA]). Our LIA is approximately the area proposed to UNESCO, excluding areas within the CAA (Fisheries and Ocean Canada, 2020; Speer et al., 2017). It contains, but is not limited to, the portion of the Tuvaijuittuq Marine Protected Area that is in the Arctic Ocean. We exclude areas within the CAA because SITU is not defined there. The narrow passages make estimation of ice drift from satellite imagery difficult, and the coarse resolution of climate models does not even allow for many of these passages to be represented. As such, we do not study the portion of Tuvaijuittuq that reaches into the sounds and inlets of northern Ellesmere Island. SITU operates on the EASE-25 grid, an equal-area grid with approximately 25 km spacing (Brodzik et al., 2012). The NSIDC publishes many of its gridded ice products, including its estimated ice-motion fields over the satellite observational period interpolated to the EASE-Grid. Our LIA covers 1719 EASE-25 grid points, just over 1 million km^2.

2.4. SITU Runs Analyzed in the Study

For each year from 2010 to 2100, and for each of the ensemble members in the HW and LW ensembles, we backtrack ice from the LIA grid points for 10 years, beginning in March. We chose March because even at the end of the HW runs, when there is no summer ice remaining in the Arctic (Jahn et al., 2016), the LIA is ice-covered at the end of winter. For each ensemble member and each year, we define the ice shed to be all grid cells crossed by ice on back-trajectories between the LIA and the locations where LIA ice was formed.

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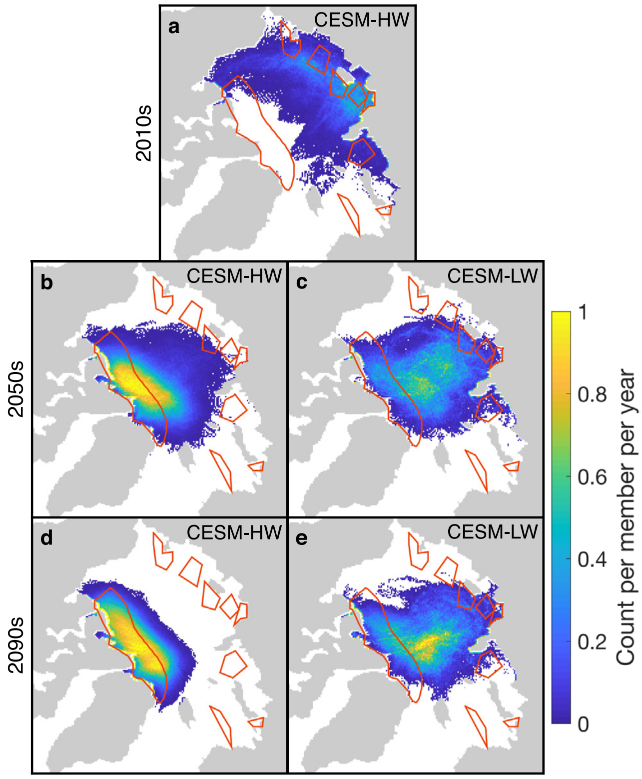

Figure 2. Origins of Last Ice Area (LIA) ice. Location of LIA ice origins based on 10-year backtracks using output from the Community Earth System Model-high warming (CESM-HW) (a, b, d) and the CESM-low warming (CESM-LW) (c and e). Each map is a 10-year time-average and ensemble-average of the incidence of sea-ice formation events. Polygons over the Siberian shelves indicate Rosneft hydrocarbon exploration lease sites. The bounded area north of Canada and Greenland shows the LIA. Supporting informations include Movies S1 and S2 of annual ice-origin density maps from which these 10-year averages were constructed.

Our focus is on the evolution of this ice shed over time. Both the historical record and the CESM model runs indicate large year-to-year variations in drift patterns. Therefore, when we report on ice origins or sea-ice pathways, we average results, whether the number of times a grid cell is crossed by a path, or the number of freezing events in a grid cell, over a decade. This suppresses inter-annual variability and exposes longer-term trends and shifts in the mean state.

We take advantage of the CESM ensemble runs to put changes due to greenhouse gas forcing in the context of the unforced, or "internal" variability of the climate system. For each of the two forcing scenarios, the individual ensemble members differ only by a miniscule (order of 10^{-14} K) shift in initial surface temperature and no difference in total model energy. After evolving for about 100 years, large-scale features of the ice circulation (e.g., the Beaufort Gyre, the Transpolar Drift, the East Greenland Current) are reflected across all ensemble members, as is the approximate location and size of the LIA. However, specific features of the backtrack pathways and origins differ widely across members, as does the timing of the loss of summer sea ice. We integrate that uncertainty into our presentation of the results by treating the projected future ice shed as a statistical distribution across all ensemble members. We display the ice origins as 2-D distributions in map view. Each EASE-grid cell is painted with a value from 0 to 1 reflecting the fraction of ensemble members for which that cell is an origination point. That is: for each ensemble member we paint the map with 0s (if the cell does not participate) or 1s (if it does). We then add up the maps by grid cell and divide by the number of ensemble members (40 for the CESM-HW and 11 for the CESM-LW). We believe this provides a reasonable estimate of the likelihood that a grid point is an LIA ice source, given the CESM model physics and forcing scenarios as prior assumptions. To suppress short-term (inter-annual) variability, we present decadal averages of the 2-D distributions. As an example, ice in the LIA in March 2010 is backtracked using the CESM-HW ice drift vectors to March 2000. If the ice was formed between 2000 and 2010, its formation location is logged; if it was formed before 2000, then that parcel of ice is not used in the "origins" calculations and maps. At each grid cell, the values (0 or 1) are averaged across the ensemble members, to create a distribution for each year and each ensemble (CESM-HW and CESM-LW). The distributions for each decade shown are time-averaged. For example, the values in Figure 2a are the average of values from 2010 through 2019. Note that only very few ice parcels persist in the Arctic for over 10 years; experiments using 20-year backtracks are not noticeably different from those shown here.

When backtracking, each ice parcel links backward in time to a single ice formation point. However, a parcel may have traveled through any number of locations on its way (forward) to the LIA, and in estimating the ice shed, we include all of the points along that trajectory. On its way, ice will collect dust, snow and pollutants from above, and is vulnerable to pollution, for example, from oil spills, in the water below. In addition, pathways are critical to an ice floe's survival to become thick, ridged multi-year ice. Therefore, the full ice shed is important for the management of ice refugia such as Tuvaijuittuq. For this analysis, we counted the number of times that a parcel of LIA ice passed through each grid point on its journey from its formation point. We summed these counts over all ensembles in a scenario, and averaged the sums over each decade.

The resulting maps (Figure 3) show the points from which ice moves into the LIA, whether that point is a formation or a "pass-through" location. The values of the distributions can be greater than 1, as many floes might past through the same point, and the values displayed in Figure 3, are proportional to the likelihood of ice from that point moving into the LIA.

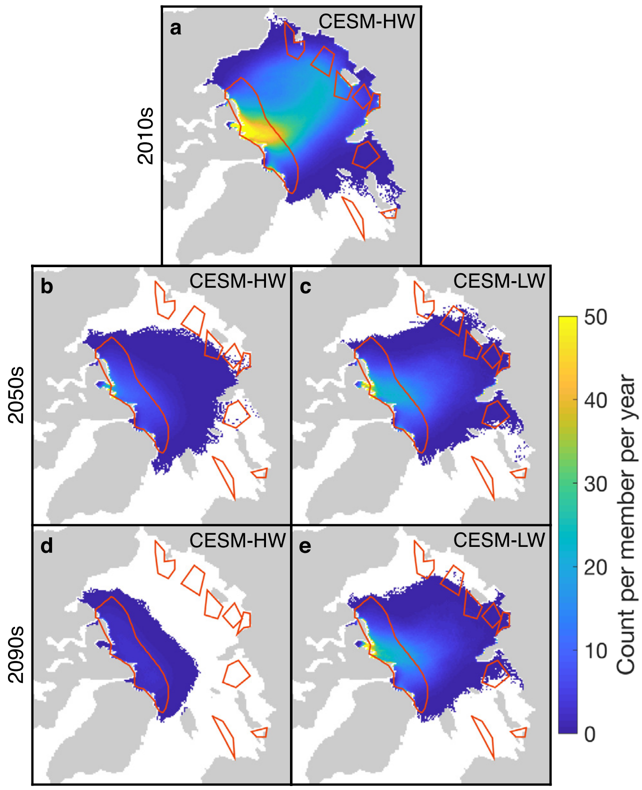

Figure 3. Last Ice Area (LIA) ice shed. Number of ice parcels passing through each grid point on their way to the LIA, averaged over all ensemble members in a scenario and over 10 years (a) from 2010 to 2019 in the Community Earth System Model-high warming (CESM-HW); (b) CESM-HW, 2050–2059; (c) CESM-low warming (CESM-LW), 2050–2059; (d) CESM-HW, 2090–2099; (e) CESM-LW, 2090–2099. Polygons over the Siberian shelves indicate Rosneft hydrocarbon exploration lease sites. The bounded area north of Canada and Greenland shows the LIA. Supporting informations include Movies S3 and S4 of annual ice shed maps from which these 10-year averages were constructed.

We ran two sets of forward tracking experiments. Many of the backtracks transit through or originate in locations on the Siberian continental shelf that have been leased for oil and natural gas exploration, raising the specter of ice-rafting of oil to the LIA. To examine the impact of a hypothetical future spill, we ran forward trajectories from one of Rosneft's exploration lease sites north of the New Siberian Islands, for each year between 2000 and 2069. For each scenario, for each ensemble member, for each year, we tracked ice from the oil exploration patch forward for a maximum of 10 years. As usual, we average the number of ice formation events, and the number of times a grid-point appears in a sea-ice pathway over all ensemble members in a scenario and over a decade of outputs. By the end of the century, ice in the HW scenario does not last long enough for ice rafting of pollutants to be a concern for the LIA, and from about 2070 onward, the LW scenario has stabilized. Therefore, we focus on three time slices: 2000–2010, 2030–2040, and 2060–2070. As above, the values on the maps are proportional to the likelihood, assuming the CESM model physics and forcing scenario, that ice from the exploration patch will reach a grid point.

The other forward run was used to assess the convergence of ice into the LIA. The latter requires forward trajectories, because backward trajectories operate over a unique path toward a single point of origin. They cannot account for multiple ice floes combining under convergent forcing onto a single track.

To assess the convergent behavior along pathways into the LIA, which is critical also to ice volumes, total ice fluxes, and therefore LIA ice residence times, we performed a second forward experiment. For each year and each ensemble member, we identified all ice formation events over the Arctic basin. We tracked each newly formed ice parcel for 10 years forward and flagged each parcel that crossed into the LIA as a LIA precursor. The total number of precursors was then calculated for each ensemble member, and as above, averaged across a scenario and each decadal time slice.

3. Results

The geographic distribution of the LIA ice shed undergoes constant change, responding in particular to the energy balance at the Arctic Ocean surface (which determines where ice forms and melts) and wind patterns (which largely determine the paths that ice floes take between formation and melt). Sea ice is famously subject to the "ice-albedo positive-feedback loop," amplifying small changes in ice cover. So one might expect the ice shed to be highly variable as the Arctic transitions from a perennially ice-covered to a seasonally ice-free environment. Indeed, our results indicate that this century will see major changes in the source regions and pathways that compose the ice shed.

3.1. LIA Ice Formation Locations

Historically, the LIA is perennially covered in multi-year ice with very little new ice coverage created in the LIA itself. New ice migrates in from the marginal seas as well as parts of the central Arctic. During the decade from 2010 to 2019, the most likely formation points of LIA ice are over the Siberian shelf, and especially the Laptev and East Siberian seas (Figure 2a).

In the HW scenario, by mid-century, the region of greatest LIA ice formation is in, or immediately adjacent to, the LIA itself (Figure 2b). Ice continues to migrate from the central Arctic and the outer Eurasian shelves, but sources in the Chukchi and coastal Eurasian areas have been lost. This pattern reflects the retreat of summer sea ice under the HW scenario (Jahn et al., 2016). The summer melt front proceeds northward so quickly that ice from Siberia melts before it can cross the Arctic to the LIA. By the end of the century in the HW runs (Figure 2d), all LIA ice is formed locally, mostly in the LIA itself, and to a lesser degree from locations immediately adjacent (see Movies S1 and S2 for time-sequences of annual maps of LIA ice origins). There is no perennial sea-ice cover, even in the LIA. Such an environment would be a disaster for ice-obligate ecologies, including predators such as polar bears and ringed seals, and small-scale ecosystems such as ice-attached diatom strands and the amphipods that graze them.

The LW scenario proceeds quite differently. By 2050, each year sees new ice formation inside the LIA, reflecting the shift from multi- to first-year ice there. However, most ice in the LIA still originates externally, and the main locus of ice formation is the central Arctic (Figure 2c). Ice from the Siberian shelves sometimes reaches the LIA, but within the shelves, the formation regions are shifted from the historical pattern. LIA ice no longer originates in the East Siberian Sea, but rather from further west, in the Laptev Sea and to a lesser extent the Kara Sea. LIA ice formation in the central Arctic is centered over the Makarov and Nansen basins, on either side of the Lomonosov Ridge. By the end of the 21st century, the LW scenario has changed only incrementally from its mid-century state (Figure 2e). Ice sources are absent from the inner shelf in the East Siberian and Kara seas, but still strong in the Laptev Sea and the outer edges of the Eurasian shelf. The region of greatest formation of ice destined for the LIA is now over the central Arctic. Overall, the pattern is similar to the 2050s, indicating that in the LW scenario the pattern of LIA ice formation has stabilized.

3.2. LIA Ice Shed Evolution

In recent history, the entire Arctic has been within the LIA ice shed (Figure 3a). In both future scenarios, the ice shed area shrinks precipitously between now and mid-century (Figure 4a), with pathways from the Beaufort, Chukchi, East Siberian, and Barents seas largely disappearing (Figures 3b and 3c). In the latter half of the century, the HW ice shed area continues to shrink until it reaches values equal to the area of the LIA itself (Figure 4a). Indeed, after 2060, the HW ice shed is restricted to the LIA and its immediate vicinity (Figure 3d). The relative contribution of the national sources of sea ice also change dramatically, transitioning from mainly Russian ice reaching the LIA in recent history to about 60% of the ice being formed locally (i.e., ice formation in the Canadian and Greenland EEZs) and 40% coming from the central Arctic (Figure 5a).

In contrast, in the LW scenario, the ice shed area stabilizes a little above 2 million km^2 (Figure 4a), with the 2090s ice shed nearly identical to the 2050s (Figures 3c and 3e; see also Movies S3 and S4 for animated sequences of annual maps of LIA ice shed). Imports from the Russian EEZ are small, but persistently present throughout the second half of the century (Figure 5b). As noted above, local formation, which was minor historically, becomes more prominent, accounting for 15%–20% of the LIA ice throughout the same period. The dominant ice source becomes the central Arctic rising from about a 10% contribution historically to over 70% late in the 21st century.

Under historical conditions, ice in the LIA was typically on the order of a decade old, which can be seen in Figure 4b as long transit times between its point of formation and its position in the LIA and in Figure 6 from the low sea-ice replacement rate between 1950 and about 2010. Between 2010 and 2050, there is a steep decline in transit time due both to shorter travel times between ice formation and the LIA boundary and decreased residence time in the LIA. The shorter mean travel times to the LIA are the result of two effects. First, as is evident in Figure 2, the average distance traveled diminishes, including an increasing fraction of ice that is locally produced. And second, as the ice pack thins, it becomes weaker, there is less resistance to motion and the ice responds more freely to surface wind forcing (Newton et al., 2017; Rampal et al., 2009, 2011). From about 2040 onward, in both scenarios, the ice influx is larger than the area of the LIA itself (Figure 6), peaking at about 1.5 times the area of the LIA in the HW scenario. However, in the later decades of the 21st century, under the HW scenario, the summer meltback reaches most of the LIA. The imported ice is gone before the winter freezeup. It represents a freshwater flux to the LIA, but does not participate in sea-ice habitat over winter or in the following spring. At the end of winter, when the LIA is ice covered and we begin our back-trajectories, nearly all of the ice is locally and recently formed. This can be seen in Figure 3 (maps of the ice formation regions) and 4 (which depicts the area of ice formation from backtracking the March sea ice cover). The total transit time, including time between formation and the

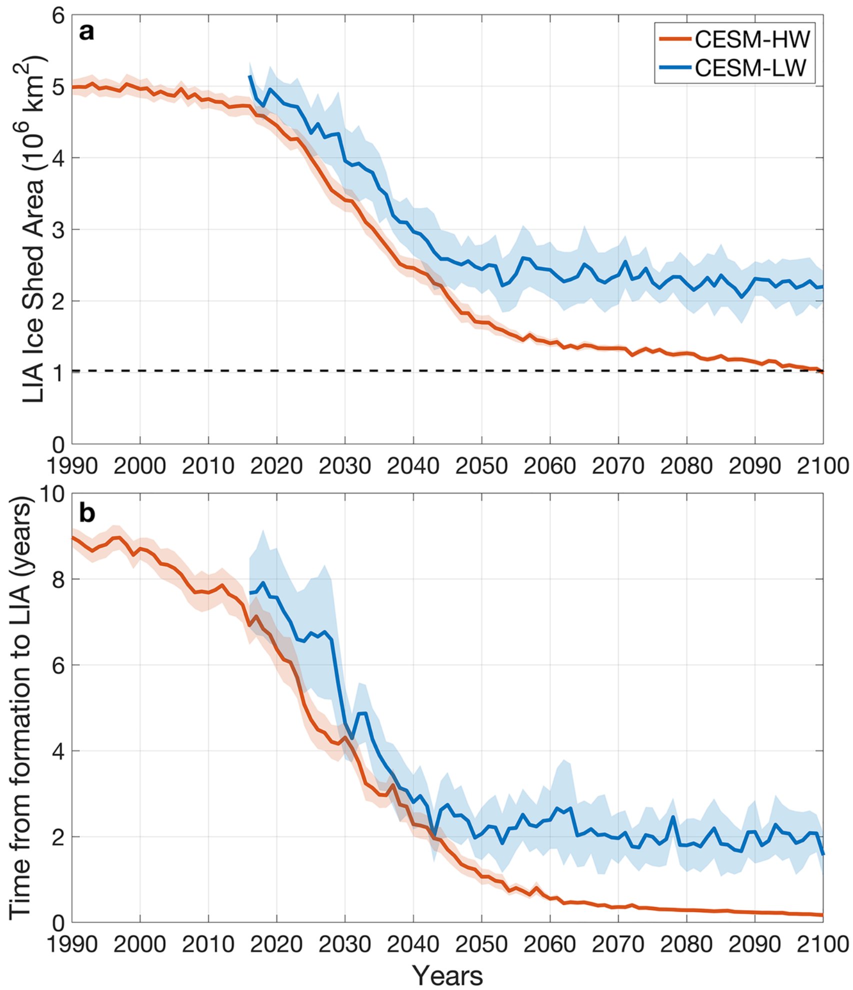

Figure 4. Time evolution of the Last Ice Area (LIA) ice shed and transit time. (a) The total area of the LIA ice shed, including pathways, and (b) mean transit time of ice from its origin to its position in the LIA from 1990 through 2100 in the Community Earth System Model-high warming (CESM-HW) (orange) and the CESM-low warming (CESM-LW) (blue). Solid lines indicate the ensemble mean; the shaded area shows the 95% confidence interval across each ensemble.

border of the LIA and residence time in the LIA, stabilizes at about 2 years in the LW scenario, but continues to decline toward zero in the HW scenario (Figure 4b). The combination of a short transit time to the LIA and short residence times in the LIA imply that there is little multi-year ice there. In particular, in the HW scenario there is virtually no ice older than 2 years.

3.3. Risk of Ice-Rafted Oil to the LIA

To visualize the potential for pollution reaching the LIA from an oil spill, we forward-tracked ice from a region on the Siberian shelf that is both an ice formation area and a Rosneft oil exploration lease patch (Figure 7). This region remains a source of ice to the LIA until mid-century in both scenarios, and through the end of the century under LW conditions (Figures 2 and 5). Between 2000 and 2009, the most likely pathways for ice from this region ran roughly along the trans-Arctic Transpolar Drift toward the North Pole and on toward Greenland (Figure 7a). Depending on local winds and ice conditions in the Lincoln Sea, north of Greenland, and sometimes referred to as the "switchyard" of the Arctic, ice may either exit the Arctic with the East Greenland Current or veer west into the Canadian Basin, where it may become lodged in the LIA or be entrained in the Beaufort Gyre. As the Arctic warms, this transit route becomes less likely with ice more frequently melting in the central Arctic under both HW and LW scenarios (Figures 7b and 7c). After about

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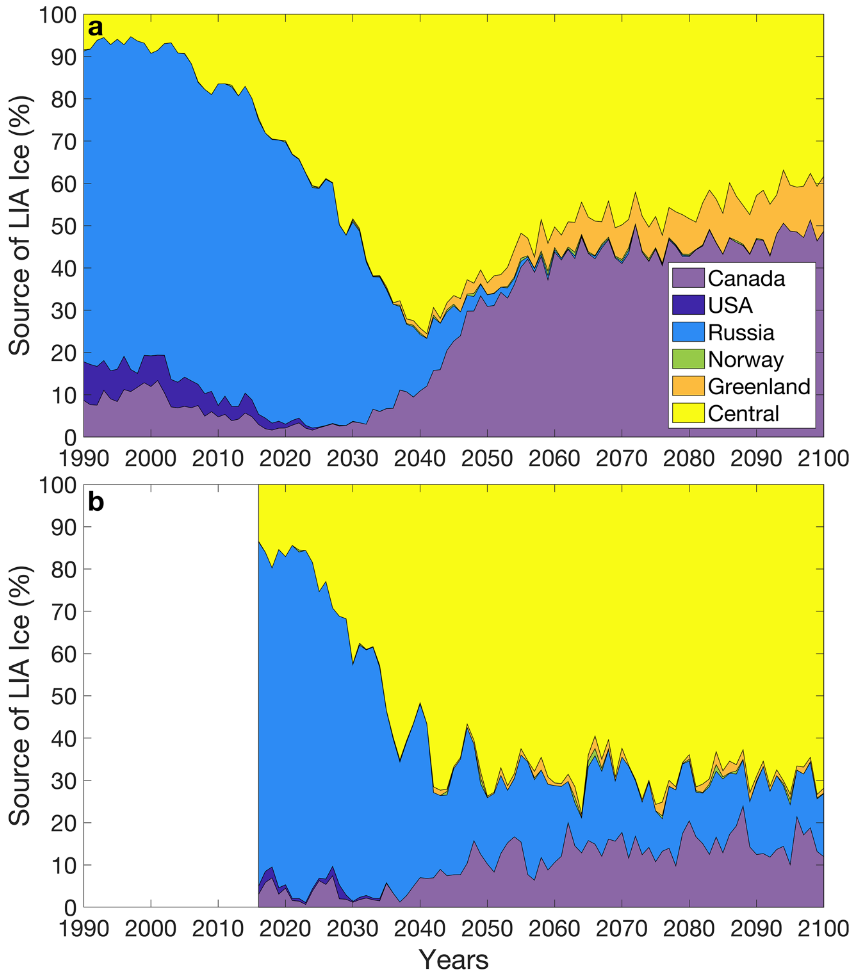

Figure 5. National sources of Last Ice Area (LIA) ice. Relative contribution of sea ice to the LIA from the different Arctic nations' exclusive economic zones (and the central Arctic) in (a) the Community Earth System Model (CESM)-high warming rates and (b) the CESM-low warming scenarios.

2030, pathways between the oil exploration patch and the LIA do not change very much in the LW scenario (Figure 7e). In the HW runs, however, the likelihood of cross-Arctic transit become negligible, as the ice melts before it can travel far (Figure 7d).

3.4. Ice Flux Into the LIA

The thick ice of the LIA is a result of converging ice that overrides and forms ridges that can be over 10 m thick. Such ice is more resistant to melting, is topographically complex (both above and below the water line), and is required for certain ice ecologies (seal denning is an oft-cited example; Kelly et al., 2010). SITU does not estimate ice thickness, but it does allow multiple ice tracks to converge onto a single location and share a trajectory from that point forward. To estimate ice flux into the LIA, we identified all sea ice formation events over the whole Arctic basin and tracked them forward for 10 years. Each sea-ice track entering the LIA during a calendar year, was counted as influx for that year. We tabulated a time series of the total influx, averaged annually across each ensemble (Figure 6). In the historical period, there is little ice added to the LIA each year, implying a slow turnover rate and an old age for the LIA ice.

The area of the LIA, as defined for these experiments, is a little above 1 million km^2. The historical influx is about 150,000 km^2, giving a mean residence time between 6 and 7 years. As the Arctic warms, the ice becomes thinner and more mobile, including in the LIA, leading to higher turnover rates and a reduction in the age of the ice (Fowler et al., 2004; Rampal et al., 2009). This is reflected in a rapid increase, between

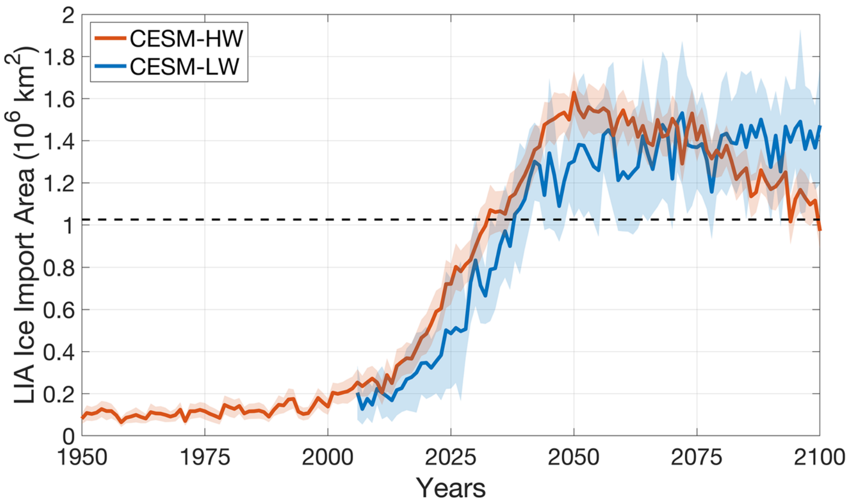

Figure 6. Area of ice imported to the Last Ice Area (LIA) annually. Area of ice imported into the LIA as a function of the year of formation in the Community Earth System Model-high warming (CESM-HW) ensemble (HW scenario, orange) and the CESM-low warming (CESM-LW) (LW scenario, blue) based on 10-year forward tracks. Solid lines indicate the ensemble mean and the shaded areas show the 95% confidence interval within each ensemble. The horizontal dashed line indicates the area of the LIA as defined in this manuscript. For each month of each year in the decade, all ice formation events are tracked forward in time, and those parcels passing into the LIA are counted. Values shown are averages across each ensemble. Note that the formation area cannot be estimated from backtracks, which systematically underestimate convergence.

about 2010 and 2050, of the area of ice imported into the LIA. The thickness of ice in the LIA does not increase in the CESM during this period (not shown), so the increase in imported ice area is concomitant with higher turnover rates and dramatically decreased mean residence times for ice in the LIA. From approximately 2050 onward, the LW scenario stabilizes, with an ensemble-mean influx area fluctuating between 1.1 and 1.5 million km^2, implying a mean residence time between 8 and 11 months. Sea-ice extent fields indicate that most of the LIA is still ice-covered in summer (DeRepentigny et al., 2020), but multi-year ice is uncommon, and open-water areas are frequent in summer. The HW scenario, on the other hand, drives a steady decline in ice flux from its peak at mid-century through the end of the century. This decline is due to an absence of ice to import as the Arctic is so warm that ice formed outside the LIA in the winter melts before it can reach the LIA. If the ensemble runs were longer, and global warming were to continue into the 22nd century, we expect that the imported sea ice area would dwindle to nothing and even the LIA would be ice-free in summer.

4. Discussion

Our results are, of course, subject to the limitations of our methods. The CESM projections are simulations whose uncertainties have been discussed at length elsewhere (Hurrell et al., 2013; Kay et al., 2015; Sanderson et al., 2017 and references therein). The CESM is among the most extensively validated climate models available, and the version used here, CESM1.1 has been widely applied to study Arctic sea ice and has been found to perform well in comparison with observations during the "overlap" period (Barnhart et al., 2016; DeRepentigny et al., 2016; England et al., 2019; Jahn et al., 2016; Kirchmeier-Young et al., 2017; Smith & Jahn, 2019). However, the CESM resolution, nominally at 1°, is rather coarse for the Arctic. In addition, there is the inherent issue of "internal" variability of the system (i.e., the degree to which multiple states are possible with the same model physics and external forcing). To visualize this model uncertainty, we compared backtracks of individual ensemble members (not shown). The trends apparent in the averages presented here are present in all members, but the timing of changes can vary by as much as a decade between members. In addition, individual backtracks (i.e., the trajectories of specific ice parcels) can be very different between ensemble members. Thus, the results presented here should be viewed as probabilistic, not deterministic in a detailed way. Applying Lagrangian tracking "off line" to the CESM output has some inherent limitations of its own. Tracks that converge in forward time diverge when going back in time.

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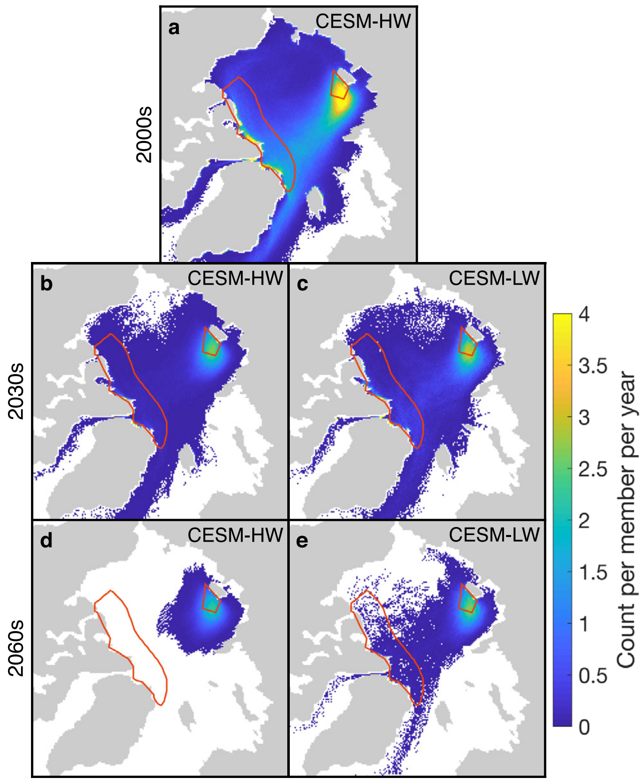

Figure 7. Tracking a potential oil spill forward in time. The orange quadrilateral near Siberia is a Rossneft oil lease site (recently forgone by its partner Exxon). Colors indicate the number of ice parcels passing through each grid point on their way to the Last Ice Area (LIA), averaged over all members in an ensemble and over 10 years. The bounded area north of Canada and Greenland shows the LIA. Figure 6a: for ice formed between March 15, 2000 and March 15, 2009. Figures 6b and 6d: using the Community Earth System Model-high warming (CESM-HW) scenario from 2030–2039 (6b) and 2060–2069 (6d). Figures 6c and 6e: using the CESM-low warming (CESM-LW) scenario from 2030–2039 (6c) and 2060–2069 (6e).

If modeled at fine temporal and spatial resolution, one might want to calculate divergence and split an ice parcel along two or more directions. However, "choosing" how to make such splits would require integrating winds and ocean currents, as well as parameterizing sea-ice rheology and thickness in the model (i.e., one would have to recreate much of the dynamics of the climate models themselves). SITU, which has been explicitly designed as a "light-weight" system that can be run on a personal computer and can be used by most researchers and educators, does not have that capacity. It moves whole ice parcels backward along the unique drift vector available for that time and place in the CESM output. Finally, in this version based on CESM simulations, SITU does not carry sea ice thickness as a variable. Thus, our results apply to sea ice areas rather than volumes.

We have shown previously that as ice has accelerated in the recent past, there has been an increase in sea ice exchange between Arctic nations' EEZs (Newton et al., 2017). DeRepentigny et al. (2020) showed using the HW (CESM-LE) ensemble that this trend is expected to continue into the near future, as the trend toward increased ice motion overcomes the tendency toward increased summer melt. However, eventually the summer melt front moves northward so quickly that even relatively fast-moving sea ice is caught. At that point there can be no multi-year ice, and internation exchange of sea ice shrinks.

The Arctic Ocean is in the midst of a vast physical reorganization, from a perennially sea ice-covered environment to one in which there is no ice cover in summer. The summer minimum in Arctic sea-ice volume has been declining at a rate of about 28% per decade since 1979, for a total loss of nearly 75% over the era of satellite observations (Kwok, 2018; Mioduszewski et al., 2019 and references therein). As summer sea ice declines, the length of the ice-covered season is shortening over most of the Arctic Ocean (Barnhart et al., 2016). Open-water seasons are expanding nearly everywhere and the variance in ice coverage is growing, especially along the ice pack's edge (Barnhart et al., 2016; Mioduszewski et al., 2019). These changes will have severe consequences for ice-obligate ecologies, some of which depend on year-round ice and others on summer openings at specific times and places. To preserve these ecologies, which are important to fisheries and the livelihoods and cultures of Indigenous peoples in the coastal Arctic, as long as possible, and to harbor their eventual recovery, the semi-autonomous territory of Nunavut is hosting the Tuvaijuittuq Marine Protected Area.

Management of the quality of sea ice in Arctic marine protected areas, including Tuvaijuittuq and potentially the larger UNESCO multi-site preserve, will require cooperation from nations and local governance structures responsible for ice source regions. Our analysis indicates that those ice sources are likely to shift dramatically over the current century (Figure 5). As noted above, the Russian continental shelf has historically been the focus of sea-ice production and export to the LIA. Beginning in the very recent past, the center of action shifts north to the outer portion of the Russian EEZ and the central Arctic. That trend increases toward the middle of the century, at which point in the HW scenario the Russian contribution is eliminated and the dominant source becomes the open ocean of the central Arctic (a region outside the control of any single nation; Figure 5a). In the second half of the century local sources rise in prominence, with the Canadian and Greenland EEZs dominating and approximately 50% of the ice forming in immediately adjacent central Arctic areas. Assuming that development of shipping and hydrocarbon extraction accelerate as the Arctic warms, our results show that the risk of oil-contaminated ice reaching the LIA will increase in the near future, and remain high throughout the century in the LW scenario. These results highlight the need for regional cooperation among the Arctic nations and with nations investing in infrastructure there or using the Arctic's emerging shipping routes.

Conservation areas involve tradeoffs. The establishment of Tuvaijuittuq was based on years of dialogue and collaborative research between conservationists, local communities, Canadian federal agencies, and scientists. There are mineral resources worth hundreds of billions of dollars beneath the Canadian Arctic, including the terrain below the LIA and terrestrial regions for which the LIA sits in the way of efficient marine access. These include base and precious metals, diamonds, coal, oil and gas, with oil and gas resources accounting for the greatest economic value by far (Adams, 2014 and references therein). The relevant deliberative governing bodies, the Legislative Assembly of Nunavut and the Oikiqtani Inuit Association were parties to the process, and have expressed strong support. For context, further west on the Alaska North Slope, such a consensus does not exist: communities north and south of the Brooks Range have fallen on different sides of the resource extraction debate. Within Arctic communities, native corporations tend to align with resource exploration efforts while some tribal councils and activists focus their concerns on preservation of historical uses of the coastal environment (see, e.g., a congressional testimony from November 2017 on drilling in the Arctic National Wildlife Refuge [CNN, 2017], and recommendations in Hansen & Virginia, 2018).

The decision to make Tuvaijuittuq permanent is thus a choice between futures that will be made in the context of competing local and regional development goals. Our exploration of the difference between the HW and LW scenarios shows that regulation of greenhouse gas emissions and carbon sequestration can profoundly impact the end-state in the Arctic's coastal regions, including the LIA. However, even holding warming to about 2°C above pre-industrial does not preserve historical sea ice conditions. We do not, in fact, see any realistic scenario that will do so. The 21st century LIA will have thinner, younger, and more mobile sea ice. We do not have sufficient data to know what the difference between historical conditions and the LW scenario would mean for ice-obligate ecologies over decades of adaptation. Because rich, multi-layered ecologies thrive in areas with a mix of first-, second-, and third-year ice (Kelly et al., 2010), it is possible that these ecologies will find refuge for some time in Tuvaijuittuq and/or other UNESCO-proposed refugia. A program of long-term, pan-Arctic environmental and ecological monitoring needs to be established immediately and institutionalized to observe and assess impacts as they become measurable.

If dramatic action is not taken to abate global warming, and the atmosphere evolves along a pathway similar to (or even warmer than) the HW scenario, then ice-obligate ecologies will not survive in the LIA. Rich diatom communities will not have time to form; seals will not be able to den (Hezel et al., 2012); polar bears will not have sufficient marine food sources (Hamilton et al., 2014). This means that the preservation of endangered ice ecologies, along with human livelihoods and cultures that have co-evolved with them, requires both local conservation and systemic, global action to be successful.

Now is the time for local communities, the Arctic nations and the international community to develop governance and institutional structures supportive of sustainable ice shed management. Over the near term the large size of the ice shed requires international cooperation beyond the LIA "host" countries of Canada and Greenland/Denmark, and especially the cooperation of Russia as the primary source of multi-year ice. One possibility is to manage the international ice shed by limiting commercial activity within the ice source regions identified in Figure 2. Such a regulatory regime was recently accomplished for fisheries in the context of similar complexity and lack of scientific certainty about the future (George, 2018). As described by Hoag (2017): "This lack of scientific understanding, combined with the need to protect the sensitive and changing Arctic Ocean environment, led to the recent precedent-setting agreement among nine nations and the European Union to uphold a fishing moratorium for 16 years in Arctic Ocean waters until further scientific knowledge—including Indigenous knowledge—on fish stocks and marine health is available." Another possibility is for the Arctic Council to recognize the dynamic situation presented by the LIA and its accompanying ice shed with a consensus goal to not contaminate this critical area (Kanie & Biermann, 2017; Young, 2018). Then any future Arctic development could be required to include an ice shed analysis within its environmental impact assessment.

Any regional governance regime will need to respond to conditions set at a global scale, since ice loss is ultimately driven by greenhouse gases emitted at lower latitudes. While Arctic residents and their national governments can protect the quality of habitat, as they have in Tuvaijuittuq for a time, in the long run, they cannot preserve local sea ice ecologies unless changes are implemented by distant actors around the globe. Modeling studies indicate that Arctic sea ice responds quickly to global forcing and would recover within several years if atmospheric greenhouse gas composition shifts back to historical norms (Amstrup et al., 2010; Armour et al., 2011; Notz & Stroeve, 2016). As such, an adaptive, layered regulatory regime, linked to scientific monitoring of regional and local responses to global developments might have a realistic opportunity to oversee summer sea-ice restoration when, and if, greenhouse warming is brought under control.

5. Conclusion

Sources of sea ice and pathways to the Arctic's LIA have been discussed under three scenarios: the recent past, a LW future (below 2°C), and HW, based on the RCP 8.5 scenario. The three scenarios yield very different results regarding ice sources, pathways, and ages in the LIA. Historically, ice travels from afar, most typically the Siberian shelves, reaches the LIA after spending years in the central Arctic, and has a mean residence time in the LIA of about 7 years. This has led to a thick layer of ridged multi-year ice in the LIA, supporting complex ice-obligate ecologies. Projecting ahead, the LW scenario results in ice that is typically formed in the central Arctic and spends 1–2 years reaching the LIA, where its residence time averages slightly less than a year. This leads to a perennial sea-ice cover in the LIA that is thin, smooth, and admits tracts of open water. In contrast, the HW scenario ultimately yields only seasonal, locally formed, thin ice, even in the LIA.

We have placed these results in the context of efforts to conserve existing, ice-obligate marine ecologies, particularly the Tuvaijuittuq Marine Protected Area north of Nunavut, Canada. Spills from oil and gas development on the Russian shelves and from shipping there as well as across the central Arctic have the potential to contaminate ice within the protected area, both now and in the coming decades. Furthermore, the HW scenario is a disaster for ice-obligate species and the rich ecologies they support. Whether the LW scenario, considered optimistic by most climatologists, can support existing ecologies or not is unknown. Baseline data need to be collected now, and extensive monitoring of the biogeochemistry, primary productivity, and ecology of the region implemented and institutionalized. The historical setting is rapidly disappearing and our results imply it will not return unless greenhouse gas levels are returned to historical levels. Clearly, governance structures to preserve, and hopefully 1 day to restore, sea ice ecologies must extend to international (regional, and to some extent global) cooperation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

This study did not make use of any new data. The gridded sea-ice concentration and drift data sets on which our ice formation, melt, and motions are based are available from the National Snow and Ice Data Center at https://nsidc.org/data/g02202. The CESM experiment documentation and outputs are available from the National Center for Atmospheric Research (NCAR). The CESM-LE outputs are available at: https://www.cesm.ucar.edu/projects/community-projects/LENS/data-sets.html. Documentation of the CESM-LW experiment is available at: https://www.cesm.ucar.edu/experiments/1.5-2.0-targets.html. The CESM-LW output is available at: https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.lowwarming.html. SITU is coded as MATLAB scripts. The model setup and codes are described in detail in DeRepentigny et al. (2016). The scripts used to translate the CESM output to the EASE-25 Grid and run the simulations described above are available for download from Github: https://doi.org/10.5281/zenodo.4609295.

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