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Assessing Sea Ice Trafficability in a Changing Arctic

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ABSTRACT. Arctic sea ice has undergone rapid changes during the last few decades, with negative implications for over-ice travel and on-ice operations, which benefit from services provided by the sea ice. A Parameter-based Trafficability Hierarchy (PATH) is presented here as a framework for developing quantitative assessment strategies that can guide planning and execution of operations on or near sea ice and quantify the impacts of recent changes on ice use. A PATH assessment has been completed for three case studies in Arctic Alaska. These cases, which correspond to a range of different icescapes and ice uses, identify and quantify different parameters linked to trafficability and safe operations. For ice road applications, PATH was used to determine an ice thickness compensation factor, a factor increasing the minimal thickness threshold for operations, to help translate sporadic auger ice thickness measurements along the Kotzebue–Kiana community ice road into an envelope for safe operations. A compensation factor as high as 1.5 was found to be necessary to ensure safety because of the high local thickness variability that is currently a concern for ice road operators. A PATH assessment of ice roughness for ice trail routing at Utqiaġvik draws on satellite remote sensing and is relevant for over-ice travel in general, including escape, evacuation, and rescue. We compared the routing of local snowmobile trails with Synthetic Aperture Radar (SAR) data products to identify specific ranges of ice conditions, roughness, and topography favored for ice trail construction. The same combination of data sources was used to identify potentially beneficial trail routes. Finally, an ice stability and safety assessment was completed for ice road construction and maintenance by industry near the Northstar Island oil production facility. We evaluated small-scale ice displacement data obtained from SAR interferometry to infer internal ice strain and stress and used these data in assessing the potential for fractures to reduce load-bearing capacity.

Key words: sea ice; sea ice use; sea ice system services; ice roads; synthetic aperture radar

RÉSUMÉ. Au cours des quelques dernières décennies, la glace de l’Arctique a connu des changements rapides. Les déplacements et les activités sur glace pour lesquels la glace de mer revêt de l’importance subissent des conséquences négatives. Une hiérarchie de traficabilité en fonction de paramètres (PATH) est présentée ici comme cadre de référence en vue de l’élaboration de stratégies d’évaluation quantitative pour guider la planification et l’exécution des activités sur glace ou à proximité de la glace ainsi que pour quantifier les incidences des changements récents sur l’utilisation de la glace. Trois études de cas visant l’Extrême-Arctique de l’Alaska ont fait l’objet de la hiérarchie PATH. Ces études de cas correspondent à une gamme d’utilisations et de paysages glaciaires différents. Elles permettent de déterminer et de quantifier divers paramètres liés à la traficabilité et à la sécurité des activités qui y sont exercées. Dans le cas des activités sur routes de glace, PATH a servi à déterminer un facteur de compensation de l’épaisseur de la glace, facteur augmentant le seuil de l’épaisseur minimale nécessaire aux activités, pour aider à traduire les mesures de l’épaisseur de la glace prises sporadiquement au moyen d’une tarière le long de la route de glace communautaire de Kotzebue à Kiana afin de donner lieu à la sécurité des activités qui y sont menées. Un facteur de compensation aussi élevé que 1,5 s’est avéré nécessaire pour assurer la sûreté des activités en raison de la grande variabilité de l’épaisseur de la glace locale, qui est actuellement une source de préoccupation pour les utilisateurs des routes de glace. L’évaluation de la rugosité de la glace au moyen de PATH pour le tracé des routes de glace à Utqiaġvik fait appel à la télédétection satellitaire et est adéquate pour les déplacements sur glace généralement parlant, notamment pour ce qui est de l’échappement, de l’évacuation et du sauvetage. Nous avons comparé le tracé des pistes de motoneige aux données obtenues par radar à synthèse d’ouverture SAR afin de déterminer les gammes précises d’état de la glace, de rugosité de la glace et de topographie qui conviennent le mieux à la construction de routes ou pistes sur glace. La même combinaison de sources de données a servi à déterminer les tracés de routes susceptibles d’être avantageux. Et enfin, l’évaluation des données relatives à la stabilité et à la sûreté de la glace a été faite pour ce qui est de la construction et de l’entretien de routes de glace par l’industrie, près de l’installation de production pétrolière Northstar. Nous avons évalué les données de légers déplacements de la glace obtenues par interférométrie SAR afin de déduire la tension et le stress de l’intérieur de la glace. Ces mêmes données ont également permis d’évaluer les fractures potentielles dans le but de réduire la capacité de charge.

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Mots clés : glace de mer; utilisation de la glace de mer; services d'un système de glace de mer; routes de glace; radar à synthèse d'ouverture

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INTRODUCTION

Sea Ice Use and Recent Change

Arctic sea ice provides a range of important services in social-environmental systems, such as regulating global climate, protecting coastlines from erosion, and providing habitat for marine species. Such sea ice system services (Eicken et al., 2009) also support ice use by people, including travel or hunting on landfast ice by coastal residents as well as the construction of ice roads by resource extraction industries. Sea ice system services extend beyond operational or logistical benefits and include historical, cultural, and educational components that are critical to the well-being of coastal communities. Sea ice can also inhibit activities like boat travel and traditional hunting of marine mammals, and it presents a hazard for marine craft. The different uses of sea ice (see overview in Table 1 and illustration in Fig. 1) all depend on specific ice processes or properties, which in many cases can be represented by geophysical parameters or sets of parameters that describe the state of the ice, and these parameters can be used to track relevant changes.

Arctic sea ice has declined substantially in extent (Stroeve et al., 2012; Comiso and Hall, 2014) and thickness (Kwok and Rothrock, 2009) in recent decades. In light of these changes, it is important to evaluate future ice use (Stephenson et al., 2011) through strategies capable of determining climatological and seasonal change relevant to specific stakeholder needs (Eicken et al., 2009; Lovecraft et al., 2013). It is especially important to understand factors that determine the feasibility and safety of ice use and to evaluate potential hazards in particular locations (Eicken et al., 2011; Eicken and Mahoney, 2015). This task is challenging for several reasons: (1) ice properties that govern ice use are relevant at the local or regional scale and use-specific; hence, they depend upon individual user or stakeholder perspectives; (2) user or stakeholder information needs are not necessarily directly linked to typical geophysical properties that are assessed through ongoing Arctic scientific research or monitoring; and (3) we mostly lack quantitative information that describes a safe sea ice use or operating space.

Some studies have identified generic ice-thickness thresholds for safe travel over ice (Gold, 1971; Squire et al., 1996; USACE, 2002), but did not identify specific threshold values for safe use in different sea ice regimes or local ice conditions. Also, while broader categories of parameters relevant to ice use have been identified (Potter et al., 1981; Bashaw et al., 2013), it is unclear which specific parameters and processes need to be tracked, and over what spatiotemporal scales, to provide ice users with reliable information on ice stability. Relying strictly on qualitative information may be appropriate for individual Indigenous user groups, who can draw upon a vast body of traditional environmental or Indigenous knowledge and associated responses to hazards and opportunities. However, for operators with a shorter presence in the Arctic, deriving additional quantitative data has the potential to greatly improve surveys, which in the past have relied heavily on qualitative information gathered from often decades-old strategies such as aerial reconnaissance. The changing Arctic sea ice also affects local knowledge holders' ability to rely on their body of expertise (Jolly et al., 2002), increasing the need for new assessment strategies to inform ice use.

Motivation for Case Studies on Landfast Sea Ice

Along the Arctic coast, sea ice commonly attaches to shore as landfast ice and has been used for travel by coastal communities throughout the circumpolar north for millennia, as well as by oil and gas companies in recent decades (Masterson and Spencer, 2001). Landfast ice duration and extent have been reduced significantly in recent years (Mahoney et al., 2014; Yu et al., 2014; Selyuzhenok et al., 2015), affecting and potentially jeopardizing sea ice services and ice use (Eicken et al., 2009). It is therefore widely recognized that recent Arctic change has resulted in more difficult travel conditions (Fienup-Riordan and Rearden, 2010; Laidler et al., 2010) and increasingly dangerous ice (Aporta and Higgs, 2005; Huntington and Fox, 2005; Ford et al., 2008; AMAP, 2011; Aporta, 2011; Druckenmiller et al., 2013).

We focus on the use of landfast ice as a platform for transportation and on-ice operations because of the range of stakeholder interests and the urgency of understanding these environmental changes. The use of landfast ice as a platform depends on the trafficability of the ice, which we define as the ability to operate on the ice within the limitations of feasibility, efficiency, and safety. Trafficability hence depends on quantifiable parameters that relate to surface properties, composition, and structural integrity. Here we present a Parameter-based Trafficability Hierarchy (PATH), a framework to identify critical parameters relevant to sea ice use guided by regional analysis, local knowledge, and specific user resources and needs. This framework supports the development, evaluation, and synthesis of new methods and techniques to help ice users and stakeholders cope with rapidly changing ice environments. The PATH framework helps guide process studies and sustained observations conducted by the research community. PATH was used

TABLE 1. Different types of sea ice use by humans in the Arctic.

User groups	Type of activities	Examples of activities and benefits
Arctic communities	• Hunting and fishing • Transportation • Travel • Recreation • Education / social events • Cultural activities	• Subsistence, cultural tradition, identity • Transporting fuel, food, goods, etc. • Travel across ice (e.g., hunting, visiting nearby communities) • Dog mushing, exercising, snowmobile riding, competitions • Teaching navigation, ice safety, and other skills to younger generations • Ceremonies and rituals
Industry	• Natural resource development • Shipping	• Oil and gas exploration and production, small-scale operations such as placer gold mining • Transport of goods to and from Arctic ports and trans-Arctic cargo shipping
Tourism	• Cruise-ship tourism • Solo trips / exploration	
Science	• Field work and expeditions	• Use of coastal ice as a platform or natural laboratory for broader understanding of relevant sea ice processes
Defense	• Naval operations and training	• Concealing nuclear submarines as part of the Mutual Assured Destruction Doctrine during the Cold War

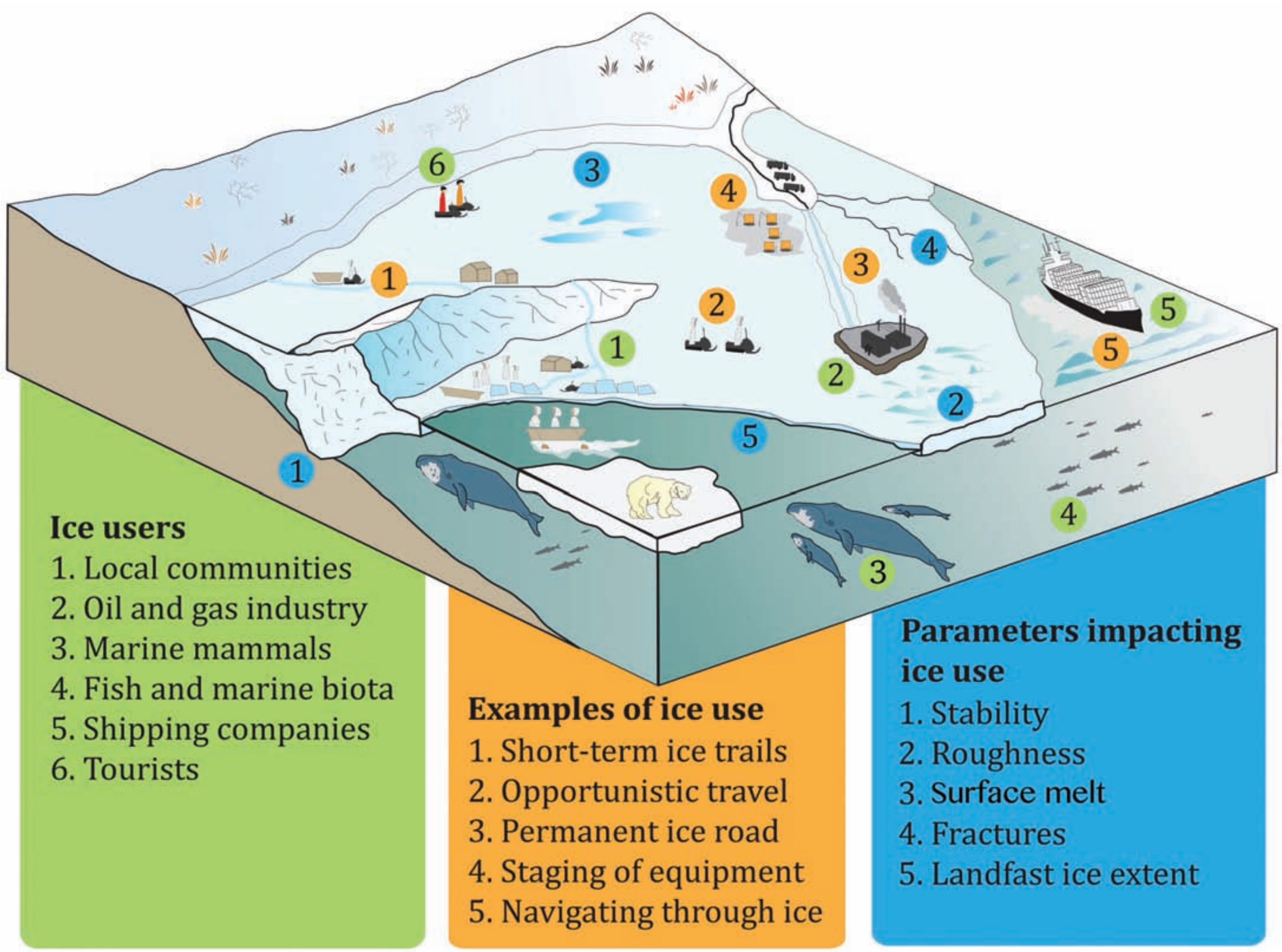

FIG. 1. Schematic showing examples of ice users, ice use activities, and ice-related parameters affecting ice users. Here, blue lines represent seasonal ice trails (left) and ice road (right). The other lines are fractures.

in three case studies in Alaska (Kotzebue, Utqiaġvik, and Prudhoe Bay) in an effort to test its utility for different ice regimes and uses and to develop techniques relevant to multiple regions.

Kotzebue is situated on an isolated isthmus separating Kotzebue Sound and Hotham Inlet (known locally as Kobuk Lake). The community of Kotzebue emerged in the 1970s as a major local transportation and services hub for

TABLE 2. Examples of ice use and associated user needs

Ice use	User needs
Community ice road constructed by local government agency (Case study 1)	Ability to operate an ice road safely within a strict financial budget, and hence without the possibility for modifications such as artificial thickening. Ability to operate within a time window when ice thickness is sufficient to sustain the bearing capacity required for road maintenance equipment.
Subsistence ice trails constructed by local community members (Case study 2)	Ability to excavate trails manually through rough ice from shore to the landfast ice edge within constraints of financial budget, construction time, and trail length.
Industry ice road (Case study 3)	Ability to operate on ice that can hold construction vehicles and will remain immobile during the season. Ability to travel across the ice multiple times without compromising its load-bearing capacity or surface conditions.

rural communities. A significant portion of the population regularly travels on the ice to hunt, fish, and transport fuel and goods to summer cabins and nearby communities, which makes the sea ice around Kotzebue a significant ice use region in the Arctic. Utqiaġvik (formerly Barrow) is an important location for ice-based marine mammal hunting where community members construct seasonal trails on the landfast sea ice (Druckenmiller et al., 2013). The Prudhoe Bay region is important to the oil and gas industry, and as in other regions of strategic importance, the landfast sea ice around Prudhoe Bay is important for economical transport of equipment across ice roads (Potter et al., 1981; Sooäär and Jaagus, 2007; Bashaw et al., 2013). An example of an ice road leading to an offshore drilling operation is illustrated in Figure 1. This road partly traverses sheltered ice, but is still influenced by offshore pack ice interaction, as is the road leading to Northstar Island west of Prudhoe Bay (Krieger et al., 2003) discussed here.

Kotzebue and Utqiaġvik, like other coastal and near-coastal communities in northwestern Alaska, are facing challenges related to climate change through delayed freeze-up and a shorter landfast ice season. In Kotzebue, over-ice travel has been delayed by eight days per decade (Uhl, 2013), threatening continuation and safety of ice travel (F. Smith and S. Kantner, pers. comm. 2014). In Utqiaġvik, changing ice conditions are becoming the primary constraint on ice-related travel (Druckenmiller et al., 2009; Johnson and Eicken, 2016). The ice road in Kotzebue (case study 1) traverses a mostly sheltered, river-influenced, estuarine location dominated by smooth ice, while the ice trails in Utqiaġvik (case study 2) often cross severely deformed ice shaped by processes representative of offshore ice dynamics. Together, Kotzebue and Utqiaġvik serve as end members that delimit a wide span of ice conditions (insofar as they limit ice use) and types of ice use (professionally surveyed ice road to connect settlements vs. local ice trails to access hunting sites). The information collected from these two communities therefore helps to identify critical properties for other areas and ice use scenarios for which less local information is available, such as the Prudhoe Bay region (case study 3).

Our goal here is to outline the steps needed to develop new assessment approaches to support sea ice use (PATH), while documenting the process and success of the framework through three case studies. Case studies 2 and 3 are presented only briefly here, since the full studies are published elsewhere (Dammann et al., 2017, 2018).

ASSESSMENT FRAMEWORK FOR ICE USE

Description of the Parameter-based Trafficability Hierarchy

Assessment frameworks in support of ice use require a thorough understanding of individual stakeholder needs. For on-ice operations, these needs are most often driven by a combination of feasibility (i.e., is it possible to carry out an activity?), safety (i.e., is it safe to do so?), and efficiency (i.e., can it be done in an economically viable fashion or with sustainable use of community resources?) and constrained by parameters and thresholds applicable for the individual ice user or ice regime. Examples of specific ice use scenarios with associated examples of user needs are listed in Table 2, and each scenario is addressed in the results section. We introduce a framework to guide assessment strategies capable of evaluating and tracking landfast ice properties and processes tied to specific user needs at a time of rapid change and high interannual variability in ice conditions. This framework arranges critical trafficability parameters based on user-specific needs into a Parameter-based Trafficability Hierarchy (PATH). PATH consists of three stages, each composed of separate steps (Fig. 2).

The first PATH stage identifies the relevance of ice-associated parameters for a specific type of ice use (e.g., ice road, ice trail, equipment staging), ice user (e.g., local government, industry, coastal communities) and ice regime. For instance, this stage could narrow down parameters relevant to construction of ice roads around Kotzebue by local governments. This process comprises several steps. Step 1a identifies all potentially relevant parameters, drawing also on ice user knowledge including Indigenous knowledge from around the Arctic. Step 1b excludes less relevant parameters for a specific ice regime, drawing on a range of climate and remote sensing data, local maps, or weather data. Step 1c gathers information from ice users

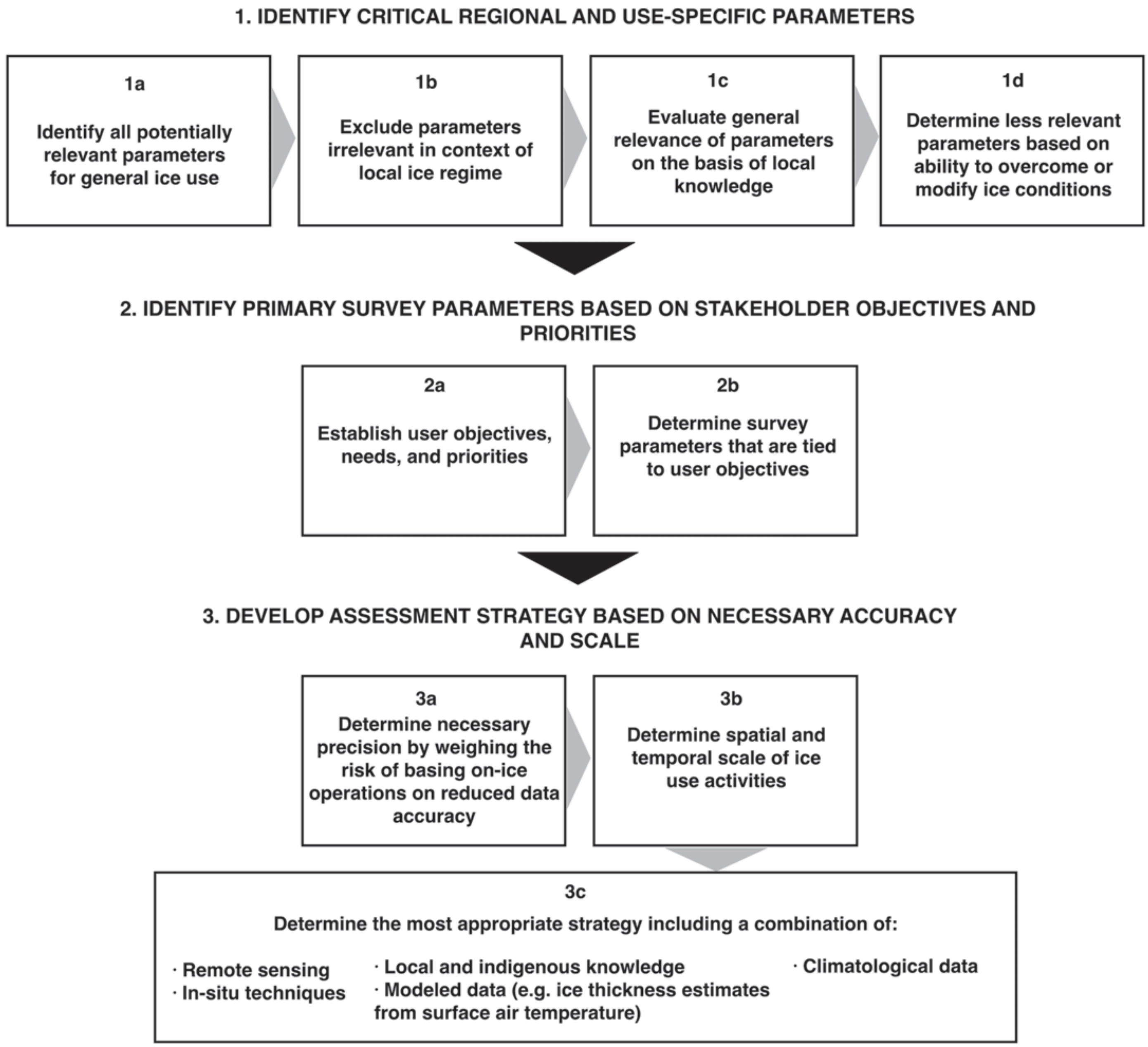

FIG. 2. Overview of the three steps in PATH for developing assessment strategies in response to stakeholder needs.

to evaluate general relevance of parameters on the basis of their experience with regional ice use. Step 1d identifies parameters of lesser importance for particular ice users: for example, adequate ice thickness is more relevant for community ice roads constructed with limited resources than for an ice road constructed by industry, which has resources to artificially thicken the ice.

The second PATH stage identifies user needs and priorities (Step 2a) from specific user objectives (see examples in Table 2). Although stage 1 identifies the general relevance of parameters for a particular ice use and region, stage 2 is critical to identify associated considerations and limitations on the basis of specific objectives. In the case of ice roads near Kotzebue, the Alaska Department of Transportation is exploring the feasibility of an ice road extending from the east to the west side of the Baldwin Peninsula with the objective of transporting gravel. At the same time, the Northwest Arctic Borough is constructing an ice road from Kotzebue to Kiana each year, with the main objective of allowing people to travel easily between communities. These two cases are associated with a similar ice regime and ice use, but priorities and user needs differ in terms of (1) the specific location and timing, including the necessary temporal extent of the ice use, (2) whether alternative routes can be created or different locations used, and (3) required levels of efficiency and safety. For instance, an ice road managed solely by contractors could potentially operate closer to a safety threshold since the contractor may be able to continuously monitor and adhere to narrow safety margins, as opposed to an ice road that is open to the wider community.

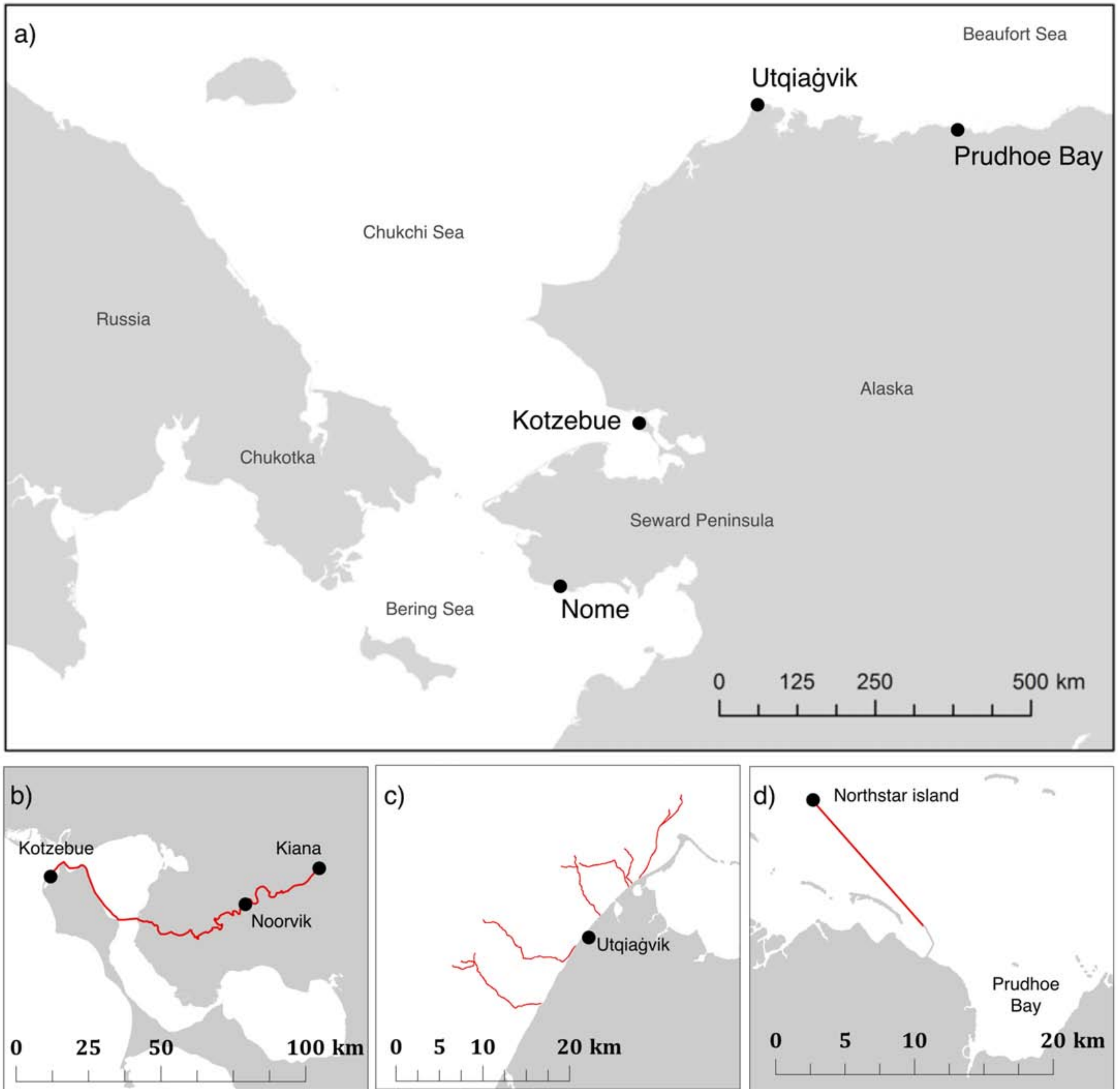

FIG. 3. a) Overview of study areas. b–d) close-up view of ice trails and roads.

The third PATH stage arrives at an assessment strategy based on parameters identified in stages 1 and 2, taking into consideration the accuracy required (Step 3a). For instance, parameters related to safety often require far greater accuracy than parameters related to efficiency, since a data misinterpretation is far more consequential for the former than for the latter. The spatial scale at which ice use takes place also determines the selection of assessment tools (Step 3b). Typically, a strategy with high accuracy is often incapable of assessing parameters over a large spatial extent, hence the last step involves compromising and developing methods, often by combining different assessment strategies such as remote sensing and in situ surveys, that can ensure that needs are met within the scope of available stakeholder resources (Step 3c).

Gathering Perspectives from Over-Ice Travel

For Step 1a of PATH stage 1, we interviewed local ice experts (hunters, ice road operators, etc.) in three Alaska communities during the winter of 2013–14, with questions focusing on sea ice and specifically on ice features considered significant for ice travel. Utqiaġvik, Kotzebue, and Nome (Fig. 3a) were selected for both the

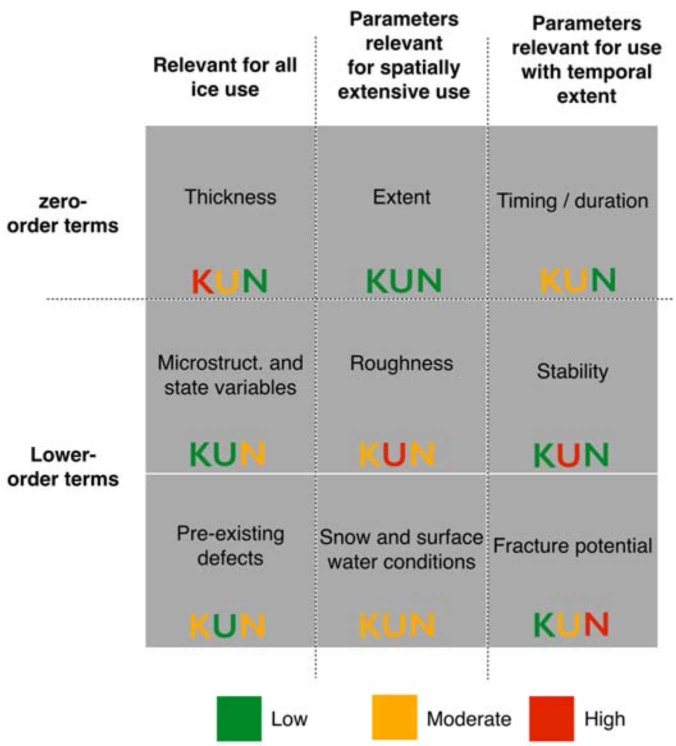

FIG. 4. General parameters related to ice use, structured in a matrix. Columns contain parameters related to (1) all ice use, (2) use with a spatial extent, and (3) use with either temporal extent or constraints. Row 1 represents zero-order parameters related to ice use and rows 2 and 3 represent lower order parameters. Colored letters indicate level of sensitivity to particular parameters determined by PATH for the three case studies Kotzebue (K), Utqiaġvik (U), and Northstar (N).

differences in their ice conditions and the breadth of their ice uses, which required identification of a broad suite of relevant parameters. The landfast ice near Nome consists of mostly level to moderately rough first-year sea ice and is susceptible to breakout events throughout winter and spring. The sea ice near Utqiaġvik is predominately first-year ice of moderate to severe roughness that is also subject to winter and spring breakout events. The ice at Kotzebue is more sheltered and features infrastructure such as marked ice trails and a fully maintained ice road used for transportation of goods.

The interviews were used in conjunction with published literature to identify a comprehensive set of parameters critical to travel on landfast sea ice. Parameters fit into nine categories, arranged in a matrix configuration according to their importance and relevant spatiotemporal scale (Fig. 4). The left column lists parameters relevant for all aspects of on-ice activities. The middle column lists additional parameters to consider for spatially extensive use such as over-ice travel. The right column lists parameters relevant for longer-term, repeated use such as ice roads or trails. The top rows contain the three zero-order terms that govern the principal feasibility of ice use while the lower rows contain lower order terms related to safety and efficiency. A full justification of the nine categories through an extensive summary of the findings from interviews and literature can be found in Dammann (2017). The relevance of each category is evaluated as low, moderate, or high for the three case studies (Fig. 4).

METHODS

Assessing Ice Thickness Variability with Ground Penetrating Radar

Ground Penetrating Radar (GPR) can be used to derive the thickness of floating ice (Kanagaratnam et al., 2007; Holt et al., 2009; Haas and Druckenmiller, 2010). The ice thickness (h) is calculated from the return time (t) of an emitted electromagnetic signal traveling with speed (v) reflecting back from the underside of the ice due to the strong dielectric contrast at the ice/water interface:

$$h = \frac{vt}{2} \tag{1}$$

The speed of light in fresh ice is roughly 0.17 m ns^{-1}, but is reduced depending on salinity down to roughly 0.10 m ns^{-1} for sea ice (Liu et al., 2014).

We surveyed the Kotzebue-Kiana ice road (Fig. 3b) using a GPR, which provided continuous ice thickness measurements from Kotzebue to the Kobuk River Delta (Fig. 5a). The GPR unit was a 1 GHz pulseEKKO-Pro system mounted in a plastic sled and towed behind a snowmobile on the ice road from Kotzebue to the mouth of the Kobuk River. The unit was towed at a speed of roughly 8 m s^{-1} (30 km h^{-1}), which was slow enough for the sled not to bounce on the ice surface. GPR is susceptible to a significant loss of signal strength in sea ice because of impurities in the ice (brine channels, air bubbles, fractures) and hence is most reliable on fresh, thin, and undeformed ice. Ice salinity ranged between 0 and 1 ppt (D.O. Dammann, 2014, unpubl. data) at Lockhart Point, indicating predominance of fresh ice across most of the road that would result in sufficient signal for accurate ice thickness measurements.

Low ice salinity (< 1 ppt) along most of the road also results in a negligible bias caused by changing signal velocity in the derived thickness data. Examples of raw datasets from the GPR survey are displayed in Figure 5b. GPR can resolve the snow layer separately only if snow exceeds a certain depth, in this case roughly 1 m (i.e., if snow is much deeper than is typical on Alaska landfast ice). However, the ice road was cleared, eliminating the potential for biased thickness readings due to snow. To validate the GPR measurements, eight auger holes were drilled along the survey route.

Ice Thickness Compensation Factor

Ice thickness is relevant in terms of its bearing capacity, which in an idealized case can be calculated for a continuous ice sheet using the formula:

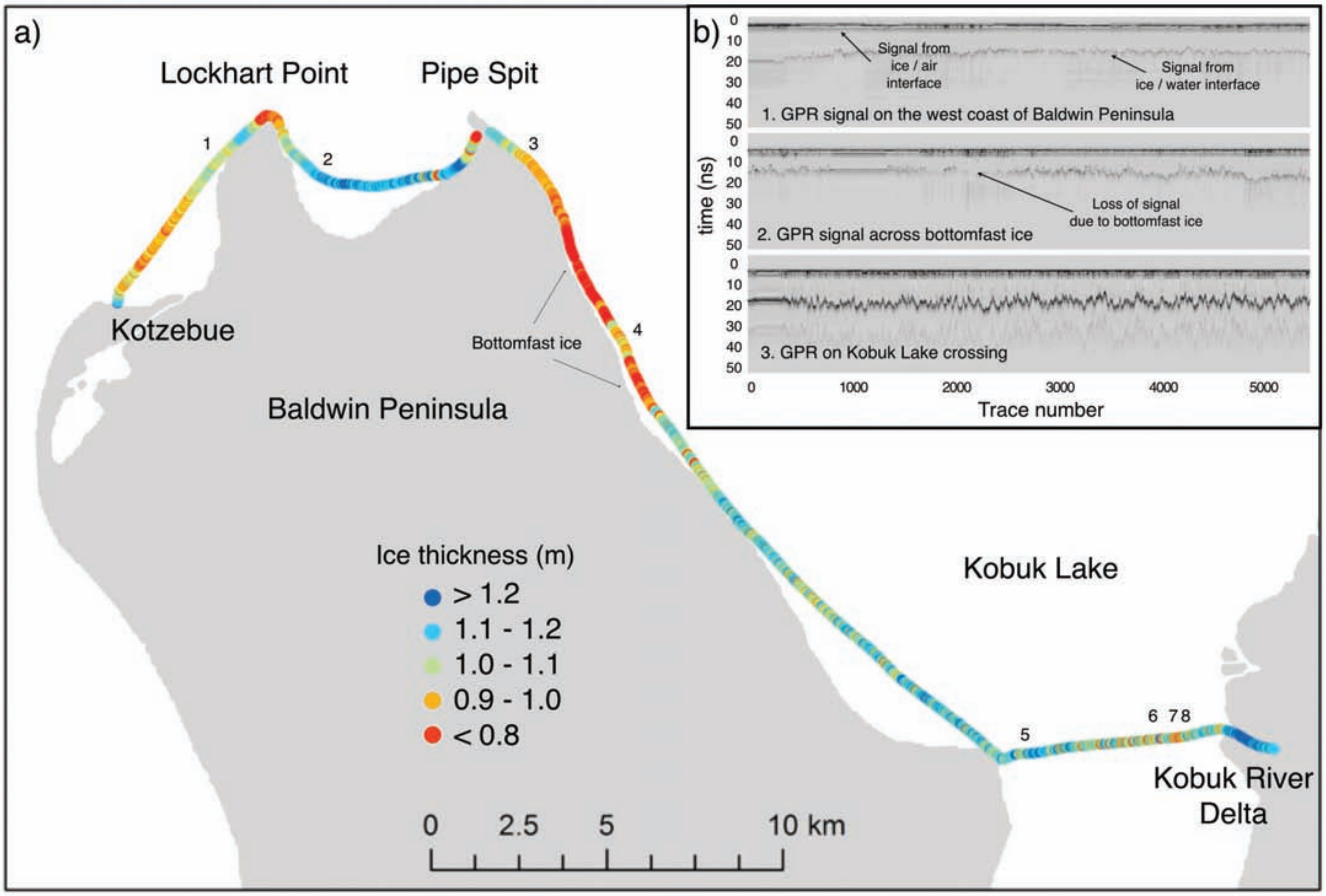

FIG. 5. a) Ice thickness along the Kotzebue-Kiana ice road from Kotzebue into the Kobuk River Delta. The red area close to shore near Lockhart Point, Pipe Spit, and south of Pipe Spit represents thin ice that is not associated with risk, produced by shallow waters that have frozen to the bottom. Numbers indicate auger validation points. b) Unprocessed GPR data from three sections of the ice road (ca. 3 km each). Panel 1 (top) shows the signal from a stretch near Kotzebue where the salinity of the ice is higher than on Kobuk Lake and brine inclusions result in a weaker signal. Panel 2 (middle) shows a signal with reduced strength across bottomfast ice. Panel 3 (bottom) shows a signal with full strength in fresh water and high thickness variability on Kobuk Lake crossing. The two horizontal lines in each panel of b) represent the ice/air (top) and ice/water (bottom) interfaces. The y-axis is in time units, which are used to derive depth, and the x-axis displays individual trace numbers.

$$h_0 = \sqrt{\frac{P}{A}} \tag{2}$$

where h_0 is required minimum ice thickness in m, P is the required load-bearing capacity in kg, and A is a constant, which can range up to $1.75 \cdot 10^5$ kg m^{-2} for strong, low-porosity ice (Gold, 1971). For ice use purposes, ice thickness is predominately measured using augers because of their unmatched accuracy. However, although this approach is accurate, it results in a point measure and hence is subject to uncertainties over larger scales where thickness may vary substantially between auger holes. Various guidelines exist for the sampling density. The U.S. Army Corps of Engineers (USACE) ice engineering guidelines (USACE, 2002) advise drilling holes at least every 45 m. The Northwest Territories Department of Transportation (NWT DOT) advises measuring as often as every 30 m close to shore (NWTDOT, 2007). However, such guidelines present a challenge for longer ice roads (Mesher et al., 2008) such as the one considered here. It is expensive and logistically not feasible to achieve these recommended measurement intervals; instead, auger hole spacings of 3–4 km are common along the Kotzebue-Kiana ice road. However, such auger hole spacings may overlook significant thickness variability and areas of thin ice.

A common practice in such cases has been to apply a compensation factor (Γ), raising the minimum thickness requirement from h_0 to h, to account for thickness variability and factors that may reduce the bearing capacity of ice below its calculated measure:

$$h = \left(\sqrt{\frac{P}{A}}\right)\Gamma \tag{3}$$

Γ typically ranges between 1.15 (W. Crowell, pers. comm. 2016) and 2–2.25 (USAAF, 1968), depending on the constant A, temperature, salinity, and ice conditions, but does not take into account substantial thickness variability between auger holes in cases of large auger-hole spacing.

Here we make an effort to calculate Γ from a thickness compensation offset, Z:

$$Z \equiv h_0\left(\Gamma - 1\right) \qquad (4)$$

Z represents the difference between minimum thickness measured in an auger survey and the actual minimum thickness measured along the same survey stretch. Continuous (1 m interval) thickness data from GPR allows for simulated surveys that can estimate the minimum thickness that would be sampled with auger holes on the basis of hypothetical auger-hole spacings and survey starting points. Multiple surveys were simulated for auger-hole spacings ranging from 1 m to 3 km, and each simulated survey resulted in an offset between the actual minimum thickness and the sampled minimum. Assuming a normal distribution of offset values, Z is found as two standard deviations away from the mean. This definition ensures that when Z is subtracted from the minimum value in an auger survey, the new lower value falls below the actual minimum ice thickness value in 97.5% of surveys.

Assessing Trafficability Based on Ice Roughness

Synthetic aperture radar (SAR) is a valuable tool for assessing trafficability because of the signal's sensitivity to surface roughness, unmatched large-scale coverage and data availability, independence of weather conditions, and m-scale resolution. Different SAR-derived products can provide unique insight into the type of roughness. The radar backscatter cross section can indicate the roughness of the terrain; SAR polarimetry (PolSAR) can to some extent reveal what type of roughness features are present; and SAR interferometry (InSAR) can show the elevation of the rough features (Dammann et al., 2017).

Each remote sensing product (PALSAR L-band and TanDEM-X/TerraSAR-X X-band) was used in combination with GPS surveys of Utqiaġvik ice trails (Fig. 3c) during spring 2015 to determine to what extent individual trails favor different values or classes of ice types and roughness derived from SAR data. A trafficability index ranging from zero (large ridges not crossed by trails) to ~0.5 (smooth ice crossed extensively by trails) was created on the basis of how frequently trails crossed different roughness types, using an approach outlined in Dammann et al. (2017).

On the basis of the trafficability index, a cost factor conversion was applied to represent differences between roughness types in the cost equivalent of trail construction (i.e., the extent of unfavorable conditions in relation to stakeholder needs and resources, including financial cost, time, and safety). The cost conversion differs depending on the particular case. For instance, roughness features have a high cost for the Utqiaġvik ice trails since the work to level the ice or cut trail through such ice with pick axes is substantial. The same roughness features would have a lower cost for an industry ice road for which heavy equipment is available to level the ice. In essence, the relative cost between rough and smooth ice is lower for industry ice roads because of the high baseline costs of necessary road maintenance, such as artificial thickening and extensive use of the road throughout the season, making a straight path more economical. The cost conversion allows for the derivation of optimal trail routes and is described in detail in Dammann et al. (2017).

Determining Fracture Potential from Sea Ice Deformation

SAR interferometry (InSAR) is a technique that is gaining traction in sea ice research (Meyer et al., 2011; Berg et al., 2015; Dammann et al., 2016; Dierking et al., 2017; Marbouti et al., 2017); it is capable of determining sub-pixel deformation in the landfast sea ice cover down to the mm scale on the basis of phase displacement in the SAR signal. Determining small-scale displacements in the landfast ice over large areas has been difficult in the past and results could be obtained only by using much more costly point-based in-situ measurements. InSAR is dependent on the surface scattering elements remaining largely unchanged over time; hence, it can be used to effectively distinguish landfast ice from drifting ice or even from a rough water surface (Meyer et al., 2011). Interpretation of raw InSAR data is not straightforward since displacement is determined only in the line-of-sight direction of the SAR antenna. However, through the development of an inverse model, we are now able to reconstruct the deformation mode and magnitude (Dammann et al., 2016, 2018). This reconstruction enables us to assess the internal stress buildup and especially the primary tensile stress as the key driver of fracturing within sea ice. The stress and associated fracture potential can be derived from the deformation rate assuming an elasto-brittle rheology for the ice, which can lead to identifying areas particularly prone to fracturing and failure. More details on this approach can be found in Dammann et al. (2018). Here, we have evaluated PALSAR L-band interferometric data in the vicinity of Northstar Island, an offshore oil production platform, and an associated ice road near Prudhoe Bay, Alaska (Fig. 3d).

RESULTS

Applying PATH for the Kotzebue Ice Road

The Kotzebue-Kiana ice road is a seasonal ice road extending roughly 100 km that connects Kotzebue with two communities, Noorvik and Kiana, on the Kobuk River (Fig. 3b). The road has been constructed annually over the last several years by the Northwest Arctic Borough (NAB) and remains open for periods between February and May, depending on ice and snow conditions in a given year. The road extends across brackish ice at Kotzebue into fresh ice across the estuary known locally as Kobuk Lake (Hotham Inlet) before continuing on river ice along the Kobuk River.

Here, the Kotzebue-Kiana ice road serves as one end-member of three case studies illustrating the application of the PATH framework. The suite of parameters relevant for over-ice travel has already been identified (Step 1a) and will be narrowed down further to a small set of critical parameters. In this process, information from NAB personnel, and in particular Fred Smith and Wendie Schaeffer, was critical. The inner Kotzebue Sound and Kobuk Lake are sheltered, so ice forms relatively early and persists around the Baldwin Peninsula throughout winter, ruling out landfast ice extent and stability as relevant parameters. The fact that the ice road is not constructed until spring, when small-scale deformation is minimal in this region of stable ice, reduces the relevance of the fracture potential (Step 1b). A salinity core we extracted by the ice road on the western side of Lockhart Point (on the first stretch of the ice road) in April 2014 revealed low salinity (maximum 1.0 ppt). Little ocean water influx into the estuary may indicate low salinity variability along most of the ice road, eliminating the potential significance of altered bearing capacity as a result of variable salinity and microstructure, but this issue needs to be addressed in more depth. Roughness is also often less of a concern because the typically calm fall freeze-up of the Kobuk Lake region results in mostly smooth, level ice surfaces (Step 1c). Pre-existing defects can be mitigated through reinforcement of the ice by road construction staff, and snow can be plowed away from the road within a set financial budget (W. Schaeffer, pers. comm. 2015) (Step 1d).

This evaluation leaves only two relevant ice parameters: thickness and ice duration. Thickness, which is one of the zero-order trafficability terms, is critical (Fig. 4). The ice road is also sensitive to timing and duration of the landfast ice season since there is often only a very short time span when the ice is thick enough (76 cm) for road construction (W. Schaeffer, pers. comm. 2015). Reduced freezing degree-days or above-average temperatures may therefore preclude ice road construction altogether. The ice road is used to transport goods and construction materials, lowering the price of products in rural communities. A further key purpose of the road is to increase the connectivity of rural communities within the Northwest Arctic Borough (NAB, 2011). Since these aims and services are not considered critical from an operations perspective, the NAB focuses on road safety if an ice road is constructed at all. With safety being the primary concern (W. Schaeffer, pers. comm. 2015), ice thickness is the most critical parameter to consider (Fig. 4). Ice thickness is particularly relevant in the Kotzebue region, where it has been reduced from the historical 1.5 – 1.8 m (5 – 6 ft) to the current 0.8 – 0.9 m (2.5 – 3 ft) (Schaeffer, 2014). NAB survey data from 2013 – 14 indicate that currently the borough assesses ice thickness about every 3 km to determine adequate ice thickness. However, it is uncertain whether this large auger-hole spacing may cause the assessors to overlook thinner sections, resulting in a potential safety hazard (Smith, 2014).

Given the need for high-resolution tracking of ice thickness, the most promising technique is GPR, which is employed in this work, but is both expensive and difficult to operate and interpret without proper training. Considering the modest road construction budget (NAB, 2011), we sought to develop an assessment strategy based on continuous thickness data without the need to repeat continuous measurements every year. This goal can be achieved by implementing a compensation factor that corresponds solely to the expected thickness variability.

The Kotzebue-Kiana ice road crosses smooth ice that is interrupted only by small cm-scale roughness along the Baldwin Peninsula before crossing Kobuk Lake towards the Kobuk River Delta (Fig. 5a). The collected GPR data closely match the auger hole measurements collected for validation (red dots in Fig. 6a) and in the last segment, the crossing of Kobuk Lake, the data exhibit particularly high thickness variability (differences of 40 cm in as little as 20 m intervals) confirmed by auger holes (Fig. 6b). This significant thickness variability indicates that auger holes cannot be expected to yield a representative thickness within the limitations of a practical sampling interval. It can therefore be concluded that it is critical to apply a compensation factor in nearly all cases where local ice thickness variability is not known.

The GPR data, excluding areas of bottomfast ice, were analyzed to determine Z as the discrepancy between auger hole measurements and actual ice thickness. The nonlinear relationship between Z and the sampling intervals from 0 to 3 km is illustrated in Figure 7 with Z close to 40 cm at the sampling interval of 3 km—a typical sampling interval for this ice road. The Northwest Arctic Borough typically seeks a minimum ice thickness, h_0, of 76 cm or more (W. Schaeffer, pers. comm. 2015), a value based on the maximum estimated load of equipment transported across the road. According to this analysis, measurements every 3 km should therefore exceed 116 cm (h_0 + Z) to ensure that the entire ice road meets adequate thickness requirements with 97.5% confidence. Adding Z to the minimum thickness corresponds to $\Gamma = 1.5$, which is higher than the compensation factors typically used by Hilcorp for the Northstar ice road (1.15) and would result in a substantial increase of the compensation factor suggested by the U.S. Army (2.0 – 2.25), which does not account for thickness variability.

Applying PATH for Utqiaġvik Ice Trails

We now explore how PATH can be applied in a different ice regime at Utqiaġvik, Alaska. The landfast ice near Utqiaġvik is subject to significant pack ice interaction throughout the season, which often leads to rough ice conditions. A large fraction of the Iñupiat population takes part in constructing trails extending from shore to the landfast ice edge, which serve as access and transportation routes for annual spring hunting activities (Druckenmiller et al., 2013).

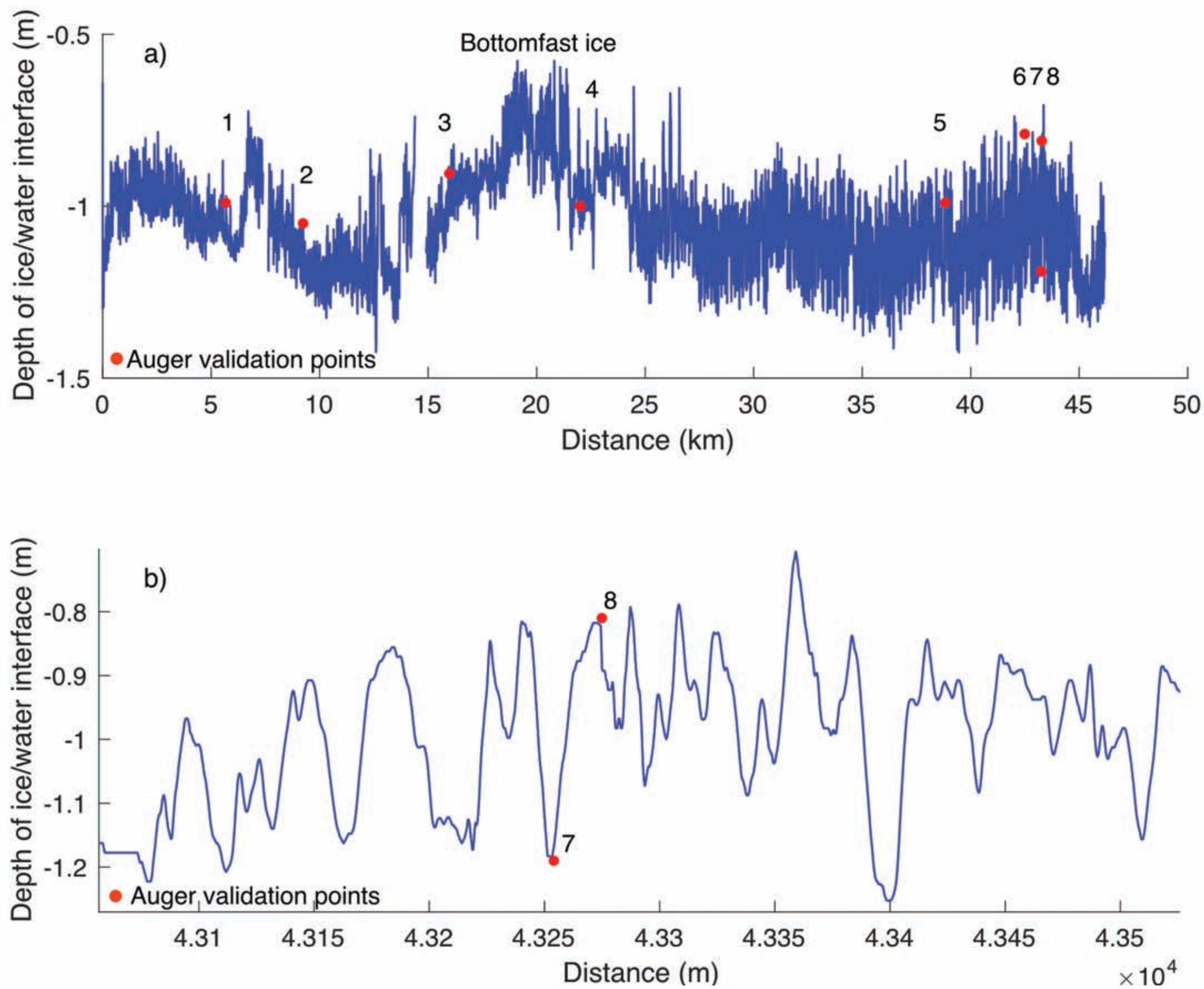

FIG. 6. a) Ice thickness across the Kotzebue ice road from Kotzebue to Kobuk Delta. b) High-frequency thickness variability on the Kobuk Lake crossing around validation points 7 and 8.

Following through stage 1 of PATH, ice roughness is a key parameter of concern since rough ice increases the time needed for trail construction and its cost, possibly to the point where poor efficiency makes trail construction prohibitive. Ice roughness also affects safety since trails meandering through rubble fields increase evacuation time in case of an emergency such as a landfast ice breakout event (Druckenmiller et al., 2013). Roughness is also linked to stability, which is itself a key parameter affecting trail safety. Timing and duration are also relevant, but have a lesser impact on trail construction. Snow cover affects over-ice travel by smoothing over roughness. Bearing capacity (left column in Fig. 4) is generally less of a concern because ice is thicker at Utqiaġvik than in the Kotzebue region. However, ice thickness does play an important role when it comes to subsistence whaling activities that take place at the landfast ice edge, where ice of sufficient bearing capacity is needed to haul a whale onto the ice for butchering (not considered in this analysis). The relevance of different ice parameters for ice trail use at Utqiaġvik is summarized in Figure 4.

Applying stage 2 of PATH, we define a key stakeholder need as the ability to travel from a point on the coast to a point at the ice edge following a route that requires minimal trail construction effort without compromising safety. On the basis of this need, we single out ice roughness as a key parameter. As part of stage 3, we determine that large spatial coverage is necessary for an assessment strategy to be able to guide ice use over the several tens of square kilometers used for trail construction near Utqiaġvik. SAR is a good candidate for obtaining relevant information on ice roughness because it can provide sufficient spatial coverage at the relevant spatial resolution. Also, in this particular case, there is a reduced need for in situ surveys since a strategy assessing efficiency rather than safety is less concerned with accuracy. However, little effort has

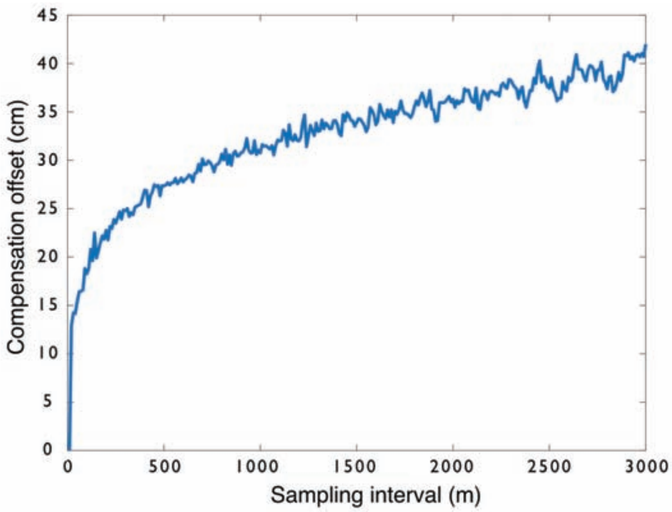

FIG. 7. Compensation offset for different sampling intervals.

been made to develop techniques to assess ice roughness from a trafficability perspective; we therefore explored several promising SAR techniques, which formed the basis for a combined trafficability index.

The trafficability index is displayed in Figure 8a for the vicinity of two trails (A and B) shown as black lines. It is clear that these trails favor areas of high trafficability and are attempting to minimize use of low-trafficability areas. Trail A followed a smooth refrozen lead before heading into less trafficable ridged ice. Trail B headed almost straight out from the coast, crossing a large ridge (dashed line in Fig. 8a) before following a high-trafficability refrozen lead. The cost function from the starting point of trail A to all other pixels aids identification of preferred routes and further enables the determination of lowest-cost paths from the starting point to where the trail stops or leaves the study area (Fig. 8b). The lowest-cost trails (green) follow the actual trails (black) with impressive accuracy taking advantage of multiple highly trafficable areas (Fig. 8). Some discrepancies exist and may be due to insufficient information from SAR data or inaccurate cost functions. Another possibility is that trail crews were not able to assess ice conditions fully, resulting in less cost-effective trails. Further details of this approach are provided by Dammann et al. (2017).

Applying PATH to an Industry Ice Road near Prudhoe Bay

For this case study, initially we had less access to local knowledge than in the other two case studies. However, we were able to draw upon findings from the other two case studies, which serve as end members in terms of sensitivity to ice surface conditions, bearing capacity, and stability. In contrast with operations at Kotzebue, planning, construction, and maintenance of the Northstar ice road is less dependent on the ice cover's initial bearing capacity. Industry resources in the form of heavy equipment and personnel are such that ice thickness can be sufficiently monitored and artificially increased through sequential flooding of the road early in the season (W. Crowell, pers. comm. 2016). At the same time, the Northstar ice road is much more affected by detection and management of surface roughness features and fracture potential than the Kotzebue ice road since it traverses an area more exposed to ice deformation. Although the ice road is more sheltered than the ice trails at Utqiaġvik, which makes a break-out event unlikely, Northstar is more exposed to deformation than the ice at Kotzebue as a result of interactions between shorefast ice and pack ice. By using the PATH framework, we have identified the relevance of critical parameters, and in particular the fracture potential (Fig. 4), on the basis of the setting and exposure of the ice road.

SAR was again used for its cost-effectiveness and ability to survey large areas. Deformation mode and rate were evaluated through inverse modeling of InSAR data (Dammann et al., 2016) and used to derive fracture potential using an elasto-brittle rheology (Dammann et al., 2018). The backscatter image and associated fracture potential (Fig. 9a, b) clearly indicate less severe fracturing shoreward of Northstar Island due to the stabilizing effect of the island. Also, we identify an increase in fracture potential (up to roughly 40 fracture events per 300 m × 300 m pixel during 1.5 months) in the vicinity of the ice road and in particular in areas prone to fracturing according to field observations by ice road engineers (W. Crowell, pers. comm. 2016), validating the approach taken here.

Displacements may lead to cracks that penetrate all the way to the ice/water interface and reduce load-bearing capacity; therefore, it is recognized that ice roads should try to avoid areas of ice movement and rely on routes across stable ice (Potter et al., 1981; Bashaw et al., 2013) with reduced fracture potential. A key stakeholder need identified for the Northstar site is the need for continuous and extensive use of the ice road (Fig. 9a) throughout the 2.5-month operating season (Krieger et al., 2003), with minimal exposure to fractures or cracks that affect load-bearing capacity. This aim can be achieved either by routing the road through ice that has minimal occurrence of cracks and limited exposure to processes that generate cracks, or by placing the road on ice with confined occurrences of cracks that can be closely monitored and repaired as needed. The approach outlined here can potentially be used as a monitoring tool throughout the season, but also as a planning too. It can inform the routing of ice roads through areas less prone to deformation by creating a climatology of deformation based on past interferograms. More details and a broader discussion can be found in Dammann et al. (2018).

DISCUSSION

In these three case studies, PATH helped translate specific user-defined needs into quantitative assessment strategies. However, effective application of PATH in operational settings requires further work. First, decision

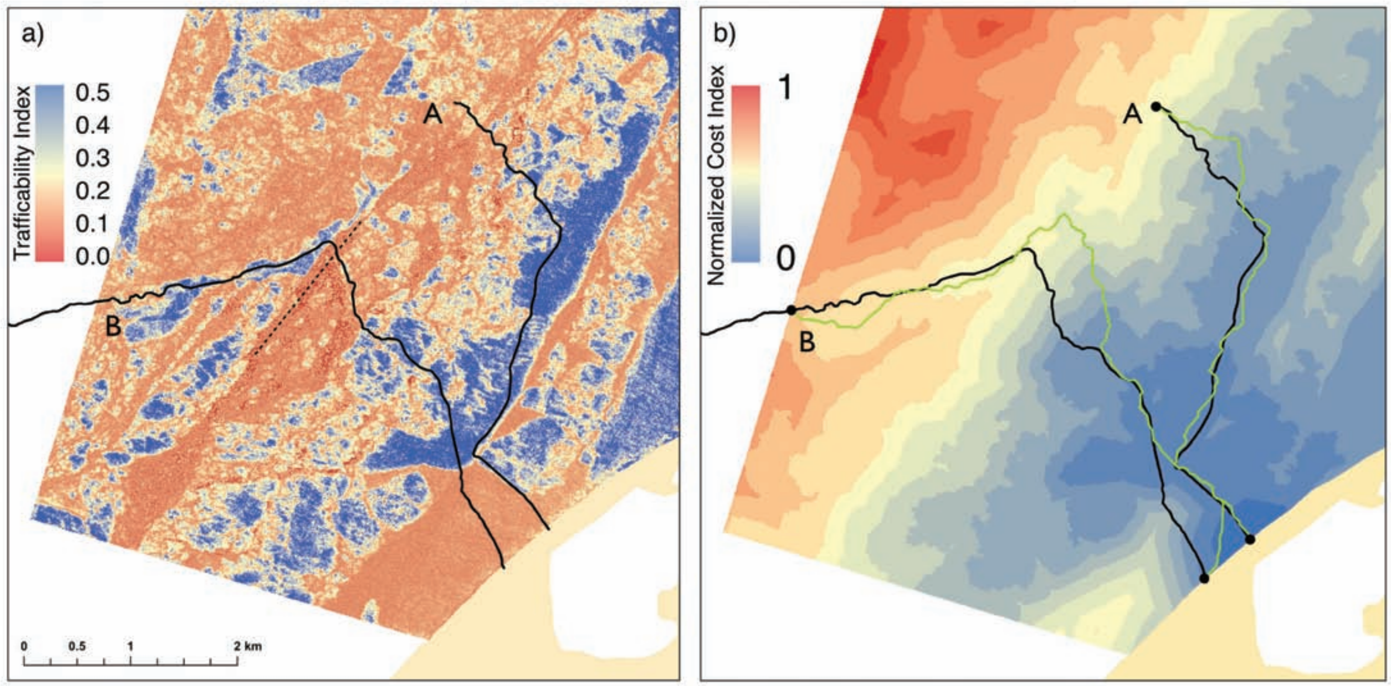

FIG. 8. a) Trafficability index calculated for the sea ice surrounding two ice trails (black) extending out from shore roughly 5 km northeast of Utqiaġvik. Dashed line represents location of large ridge. b) Normalized cost of ice trail construction from starting point of trail A to any other location on the map. Green lines represent optimal trails. Trails were mapped in April and May 2015. Land is masked out in orange.

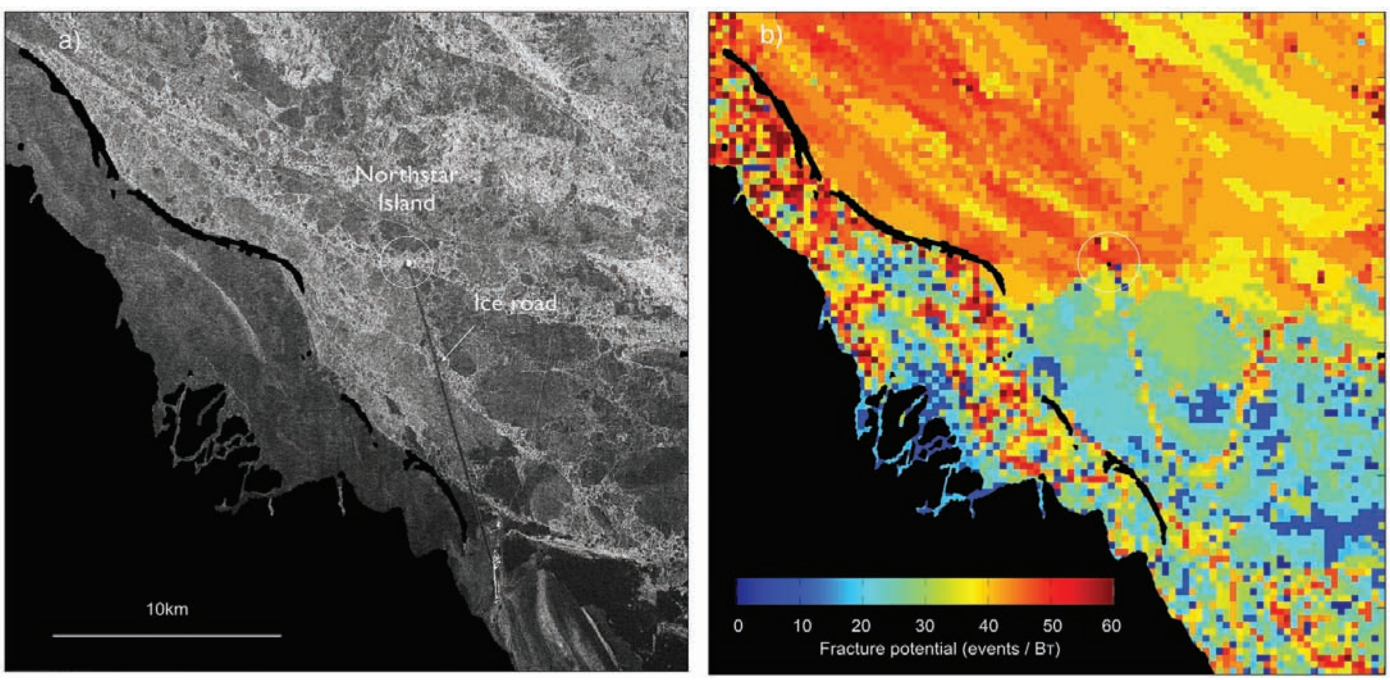

FIG. 9. a) ALOS-1 PALSAR amplitude image for the Northstar Island (circled) and Prudhoe Bay region, Alaska (21 March 2010). The arrow is pointing to the ice road connecting the island to the mainland. b) Apparent fracture potential for the 46-day time period (B_T) between 21 March and 6 May 2010 using an elasto-brittle rheology. Land is masked out in black.

makers such as ice-road engineers or government agencies need to implement quantitative guidelines for ice use based on the newly developed metrics. This task requires definition of operation thresholds that build on improved understanding of ice use and relevant ice properties and processes, such as (1) what degree of thickness variability can be tolerated in the thickness compensation factor approach, (2) what roughness scales can be negotiated by different modes of transportation, and (3) what level of fracturing will critically compromise over-ice transport on a local ice trail or an industry ice road.

Second, data accessibility needs to be improved. Techniques commonly used to assess sea ice on scales relevant to use depend heavily on satellite remote sensing such as SAR, altimetry, passive microwave, and optical sensors. However, in this work on landfast sea ice we identify high spatial variability of sea ice parameters and the need for cm-scale accuracy, resulting in more stringent requirements than what can be provided by some of these techniques. For instance, altimetry such as ICESat-1 (retired) and ICESat-2 (planned 2018 launch) can be used to estimate ice thickness and roughness, but with incomplete coverage at scales larger than the swath width of 3 km and with uncertainties reaching up to around 50 cm (Kwok and Cunningham, 2008). The Special Sensor Microwave Imager (SSM/I) and the Advanced Microwave Scanning Radiometer – EOS (AMSR-E) sensors can be used to estimate thickness of thin ice (< 20 cm) with high accuracy (~5 cm) (Tamura et al., 2007; Nihashi et al., 2009) or thicker ice (< 50 cm) using a lower frequency product from ESA's Soil Moisture and Ocean Salinity (SMOS) with dm-scale accuracy (Tian-Kunze et al., 2014), but both at a spatial resolution of tens of kilometres. Our work has focused predominately on SAR because of its unmatched combination of m-scale resolution and repeat-pass cycles on the order of days to weeks. However, SAR coverage is still sparse, particularly in terms of single pass bi-static interferometric products. The recent launches of Sentinel-1 and ALOS-2 and the anticipated launch of NISAR in 2020 will greatly increase data availability, enabling detailed analysis for both tactical and strategic decisions.

Third, development of data products such as fracture potential and trafficability needs to be automated so that use of such data can transition from research to operations. Additional work is required to adapt the approaches developed here to different ice regimes throughout the Arctic. In the case of ice thickness compensation factors, the thickness variability will vary by region, hence further thickness surveys will have to be conducted, with potential difficulties in areas of saline ice and variable water salinity challenging both GPR and electromagnetic induction measurements. However, the region around Kotzebue, and in particular Kobuk Lake, is expected to have high thickness variability (Fig. 6) compared to other sheltered ice regimes because of the many river channel outlets resulting in subsurface currents and advection of water with above-freezing temperatures. While interannual variability remains to be evaluated, the findings illustrated in Figure 7 may therefore be of use in other areas as an upper compensation factor limit for thickness variability.

The trafficability index based on ice trails at Utqiaġvik needs to be expanded to other modes of transportation. The SAR products are also based primarily on roughness, while the trail routes are determined by multiple factors, including considerations of hunting preferences and safety. More data on ice use should be included so that the range of constraints on trail routing will be reflected in a more accurate index. Additionally, polarimetric classifications need to be standardized for the full range of ice types and roughness encountered in the Arctic, rather than simply based on individual scenes through maximum-likelihood approaches as practiced here.

We have already applied the model to determine fracture potential in multiple locations in Alaska, including Elson Lagoon, Prudhoe Bay, and Foggy Island Bay. We therefore expect this approach to work well in other ice regimes. However, InSAR has limited success in areas of very smooth ice because a low signal-to-noise ratio reduces coherence. Other conditions, such as higher tidal displacement than that observed in Arctic Alaska, may also result in limitations. Here, more work is required to understand the robustness of this approach.

CONCLUSION

Throughout the Arctic, a diverse set of stakeholders depends on services provided by the landfast sea ice. Arctic sea ice is undergoing rapid changes that may jeopardize or severely affect the benefits derived by these users from the ice cover. In the context of such changes, it is necessary to fully understand and quantify the links between sea ice and its use on the basis of key geophysical parameters and to monitor changing ice conditions through the lens of individual ice users or stakeholders. Here we identify nine largely independent geophysical parameters that govern the feasibility, safety, and efficiency of landfast sea ice travel and related uses. These nine can be constrained further into three independent categories of ice motion, bearing capacity, and surface conditions. We present the PATH framework as a means to link geophysical measurements and ice user and stakeholder information needs according to the relevance of different parameters to ice use.

More work is needed to arrive at operational information products applicable across all polar sea ice regimes. Such standardized products will also allow for a combination of the approaches outlined here. For instance, combining roughness analysis with estimates of fracture potential for the same area would enable a much broader trafficability assessment that accounts for both efficiency and safety. In such combined analysis, multiple assessment strategies could be integrated, including optical sensing for detection of surface melt and flooding (Webster et al., 2015) or presence of snow (Gesell, 1989). This process would greatly benefit from better access to ice use information through interviews or surveys of ice trails and roads, in particular in regard to constraints on industry operations.

Ice use information from expert local and Indigenous knowledge aids strategy development by linking geophysical parameters with user needs. In such locations, ice users likely already construct trails along favorable routes. However, calculated optimal routes may still differ from actual trails when operators lack critical information or cannot apply all relevant routing criteria. Discrepancies between calculated and actual routes can inform trafficability analysis and support route optimization based on additional ice user considerations. Trafficability analysis and maps will be particularly valuable in areas of limited local knowledge, such as in scenarios of escape, evacuation, and rescue (Barker et al., 2006). Also, in certain regions, elements of local and Indigenous knowledge no longer apply because of rapid change (AMAP, 2011), which may be even more prevalent in the future. In such cases, the PATH approach can support adaption to change.

Remote-sensing approaches to assess parameters related to ice use enable the use of archived SAR data to provide information relevant to stakeholders and decision makers, such as changes in trafficability on decadal scales. Model results have also been used to predict the future accessibility of the Arctic by land-based ice roads and shipping (Stephenson et al., 2011). Identification of relationships between ice use and geophysical sea ice parameters, as presented here, may help advance predictions of future landfast sea ice trafficability based on model results. Such advances require a landfast ice model that captures the relevant parameters presented in this work. Development of new landfast ice models (Hopkins, 2008) in turn may benefit from the deformation and roughness analysis presented here.

While this work focuses on landfast ice use in the context of PATH, the approach itself is not limited to the trafficability realm alone. Addressing geophysical properties through the lens of specific ice uses can offer substantial benefits to stakeholders depending on sea ice in a broader sense, such as the shipping industry. Here, new ice-associated parameters would have to be considered in the context of the PATH framework, such as ice strength or drift velocity. The approach presented here can also be applied to the use of sea ice by marine mammals that depend on different ice-associated parameters for travel, shelter, or denning and may also have potential far outside sea ice science.

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