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Assessing small-scale deformation and stability of landfast sea ice on seasonal timescales through L-band SAR interferometry and inverse modeling

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ABSTRACT

Rapid environmental change and increases in use of shorefast ice by industry and coastal communities highlight the need for an approach to accurately assess landfast sea-ice stability on seasonal timescales. While stability can sometimes be inferred from field measurements, current methods are lacking robustness and the ability to be automated and applied over large areas and long time scales to ensure safety and document change in the context of transportation, indigenous ice uses and industrial development. This paper introduces an inverse model capable of reconstructing three-dimensional deformation fields from one-dimensional interferometric L-band Synthetic Aperture Radar (SAR) phase patterns. We apply this method at three landfast ice locations on the Alaska Beaufort Sea coast near Barrow and Prudhoe Bay. We find the small-scale displacements estimated from the model consistent with regional patterns of ice motion. Our study suggests that interferometry can provide planning and decision-support information for ice road development and structures operating within ice. Moreover, InSAR can potentially increase our understanding of sea ice on a fundamental level in terms of large-scale stability and long-term changes in ice dynamics.

1. Introduction

Arctic sea ice has undergone major rapid change in recent decades (Comiso and Hall, 2014; Meier et al., 2014; Stroeve et al., 2012) with potentially widespread, global consequences. Direct impacts of a changing sea-ice cover are expected along circumpolar coastlines where both communities and industry depend on coastal and landfast sea ice as a platform vital to indigenous cultures, subsistence, transportation, and industrial development (Eicken et al., 2009). In Alaska, much of the landfast ice extent has also rapidly declined during the past decades (Fienup-Riordan and Rearden, 2010; Mahoney et al., 2014).

A major concern for ice users from both communities and industry is ice movement, which can eventually lead to reduced load bearing capacity through fracturing or even destabilization of landfast ice (BP, 2013; Eicken et al., 2011; George et al., 2004; Potter et al., 1981). The use of ice by the oil and gas industry for transportation and as a platform for exploration and staging of equipment requires clear identification of potential hazards (Eicken and Mahoney, 2015; Eicken et al., 2011) derived from small-scale displacements that may lead to cracks, wider openings or foster development of hazardous features such as strudel scour through later drainage through cracks (Dickins et al., 2011).

Evaluations of ice safety based on simple threshold criteria, e.g., with respect to minimum thickness (Finucane and Scher, 1983; USACE, 2002) are not applicable with respect to ice stability. However, it is clearly recognized that ice roads should try to avoid areas of ice movement and rely on routes over stable ice (Bashaw et al., 2013; Potter et al., 1981). The challenge for industrial use of sea ice as a platform is to make accurate measurements evaluating suitability and safety of the ice in a cost-effective and timely manner (Mesher et al., 2008). Moreover, information related to stability is often difficult to acquire and, due to the many factors that govern ice stability, typically requires measurements of the actual movement and deformation of the ice. Recent technological advances in satellite remote sensing set the stage for more thorough, quantitative and cost-effective alternatives to aerial reconnaissance often used to detect critical ice features (Potter et al., 1981).

Synthetic aperture radar interferometry (InSAR) has shown promise as a technique to detect differential displacement in the landfast sea ice (Dammert et al., 1998; Meyer et al., 2011; Morris et al., 1999; Vincent et al., 2004) down to the millimeter-scale in areas with small-scale deformation (mm- to m-scale) and no active ridging deformation, wet precipitation, or significant melt or desalination processes, which will

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change the scattering processes. These prior InSAR studies over sea ice have all demonstrated the potential value of SAR interferometry in understanding ice dynamics with potential implications for stakeholders. However, there are clear limitations to interpreting the exact 3-d deformation due to preexisting ambiguities resulting from the 1-d phase information (Li et al., 1996).This study – to our knowledge the first to analyze interferogram fringe patterns over sea ice in a rigorous manner – aims to develop a method drawing on InSAR data that can be used to evaluate large-scale deformation patterns of the landfast ice and the source of the deformation. Although the application of InSAR may eventually be used to study deformation of mobile pack ice (e.g. Mahoney et al. (2016)) or identify precursors to hazardous events such as ice pile-ups or breakouts, we will here focus on long temporal baseline InSAR to identify regionally persistent deformation processes in landfast ice related to thermal changes, due to ice growth, and external factors such as regional sustained pack ice forcing.

The goal is to develop an approach that can be used to establish a climatology of ice deformation that can be used during planning and execution of on-ice operations, capable of providing guidance on (i) the type of deformation occurring in different regions, (ii) the point in time when the ice is sufficiently stable to significantly reduce risk, and (iii) areas experiencing deformation large enough for substantial cracking and requiring thorough risk assessment on the ground. This method would also create the foundation for a large-scale comparison between models and observations of landfast ice dynamics, a crucial step in validating landfast ice numerical models.

The ice regime evaluated in this study ranges from smooth to severely deformed during early to mid spring before the onset of melt. The absence of both melt and widespread severe deformation events (ridging or lateral deformation >~10 m) enables scatterers to stay intact enabling coherent interferogram formation. InSAR is first validated over sea ice as a technique capable of identifying small-scale displacement within the landfast ice (Section 2). Then, a two-dimensional deformation field is produced from the one-dimensional phase measurements using an inverse model constrained to a canonical set of realistic strain mechanisms (Section 3), a technique that is then tested and validated in northern Alaska (Section 4). Model ambiguities and limitations are further discussed in Section 5.

2. L-band InSAR data for landfast ice analysis

2.1. Data

Synthetic aperture radar interferometry (InSAR) is a technique that measures phase differences between two SAR scenes acquired from two coherent viewing geometries (Bamler and Hartl, 1998; Ferretti et al., 2007). The observed phase difference can originate from displacement of the scattering surface if measurements were acquired at different times (non-zero temporal baselines) and/or from surface topography if measurements originate from slightly different vantage points (non-zero spatial baselines).

This study utilizes L-band PALSAR-1 Synthetic Aperture Radar (SAR) images acquired by the Japanese Advanced Land Observing Satellite-1 (ALOS-1). PALSAR-1 operated from 2006 to 2011 with a 46-day repeat cycle and in a typical year provided almost complete coverage of the northern Alaska coastline in a four-month period during the landfast ice season (Fig. 1). Obtaining coherent interferograms is most likely during this time of year, when the surface of landfast ice is most stable and least affected by thermodynamic and dynamic processes. Interferograms can also often be obtained over landfast ice earlier and later in the spring as well, provided the ice remains stationary and there is no melting, flooding or other significant change at the surface. From all available data, this study selected a series of three interferograms for three areas along the North American Arctic coast including (1) the Alaska Beaufort Sea coast near Barrow, (2) the area surrounding Northstar Island near Prudhoe Bay, and (3) Foggy Island Bay (Fig. 1). Information about the SAR data used in this study is summarized in Table 1.

All three acquisitions are covering areas within the landfast sea ice regime (outlined with colored lines in Fig. 1). The likelihood of substantial movement (i.e., on the order of a few decimeters to several meters) leading to defects, destabilization or full-scale breakouts, depends on the overall stability of the ice cover. Typically, stability is defined as the ability of shorefast ice to remain immobile and undeformed under the action of atmosphere, ocean, or ice forcing. Depending on the region, ice stability depends on a combination of the anchoring strength imparted by grounded ridges and/or topographic features such as islands or promontories, as well as on ice thickness, structure, and the presence of defects such as pre-existing cracks (Mahoney et al., 2007).

A typical landfast sea ice regime is illustrated in Fig. 2 where the stability decreases going from left to right. The most stable ice is the ice frozen to the ground (bottomfast), which is nearly completely stationary. Small-scale non-elastic deformation of lagoon ice or ice sheltered by islands from dynamic forcing is dominated by thermal creep and cracking. Shoreward of grounded ridges, deformation is also governed largely by thermal forcing, but can also be impacted by ice dynamics. Oceanward of any grounding points, the ice is more susceptible to dynamic forcing and the propagating forces from pack ice interaction and is hence less stable (especially younger and thinner ice). Except for the bottomfast ice, even sheltered ice can move several centimeters during a month and therefore exhibits interferometric fringes.

This study focuses on deformation processes in the stable landfast ice zone, which are largely driven by thermal processes (e.g., ice growth, thermal contraction) or moderate dynamic deformation (e.g., wind-generated deformation behind grounding points, internal ice stress generated by pack ice interaction propagating into the stable ice zone) occurring over long time-scales and benefit from a large temporal InSAR baseline. By applying a shorter temporal baseline, the methods used in this study can potentially be extended to the pack ice, where the ice is susceptible to dynamic ridging and rafting events and wave propagation (Mahoney et al., 2016), but such analysis is beyond the scope of this study.

2.2. InSAR processing

Interferograms in this study are constructed using a general processing workflow outlined in Fig. 3. The multi-looked interferograms are sampled 2 and 4 pixels in slant range and azimuth respectively. Multi-looking results in pixel spacings of ~15.2 m and ~12.5 m in ground range and azimuth, respectively. All acquisitions are from ascending passes. Sea ice interferograms are complicated to interpret due to the many discrete floes that can move in multiple directions. This is also true for landfast ice where the floes are frozen together, but can still behave as mechanically discrete units. The spatial discontinuities occurring between acquisitions as well as noise can make phase unwrapping of sea ice difficult (Morris et al., 1999) and we choose to not focus on this processing step since we are mostly interested in the identification of relative displacement in this study. Terrain correction is typically superfluous since the highest ridge features rarely exceed 10 m. For example, for PALSAR-1 to receive a phase signal larger than the expected phase noise from a large ridge, the perpendicular baseline would have to be close to 2 km, far greater than the baselines that are used in this study and are listed in Table 1 (see Section 2.4 for more detailed information regarding topographic influence on fringes).

2.3. L-band SAR interferometry and coherence over sea ice

Derivation of image-pair coherence is an integral part of the InSAR processing flow and can provide valuable information about changes on the Earth surface such as those related to ice dynamics. An interferogram can be constructed successfully only if scattering between areas in the InSAR partners remains coherent. Complex coherence $|\gamma|$ for