Dear Reviewer,

Thank you again for providing a thorough review, which helped once gain to greatly improve this paper. We have made most of your suggested changes and you can find replies to each of your detailed comments below. We had several people reading over to provide corrections to the English language prior to the last resubmission and were confident this would suffice. However, since some errors made it through last time, this time we obtained professional proofreading.

Thank you again for your help with the manuscript.

Best regards,

Dyre Dammann

Detailed comments:

pan-Arctic?

Done

please check punctuation

Included a comma

I'm not sure about this sentence. Habitat for fauna? Then I don't see how it could evolve. If you mean humans - then the previous sentence has already introduced that.

Taken out

check punctuation.

This sentence was split (P1,L13): "This first comprehensive assessment of Arctic bottomfast sea ice extent has revealed that most of the bottomfast sea ice is situated around river mouths and coastal shallows. The Laptev and East Siberian Seas dominate the aerial extent, covering roughly 4.1 and 5.1 thousand km^2, respectively."

mapping scheme

Changed

for

Done

check punctuation

Done.

check the tenses throughout the manuscript. There is a mix between present and past tenses.

Done. Sentence simplified (P1,L19): "In a case study of the Nares Strait, we demonstrate that interferograms may reveal early-warning signals for the break-up of stationary sea ice."

is this part necessary? it makes the sentence too long and difficult to grasp. If you want to leave it, make it another sentence.

This has been changed (P1,L31): "It is further recognized that sea ice conditions for future Arctic marine operations will be challenging, and will require substantial monitoring and improved observations (Arctic Council, 2009). This improvement will require observations at a local and regional scale, in order to provide assessment of environmental hazards and effective emergency response (Eicken et al., 2011)."

this relates more to the introduction part on ice arches. Nothing to do with remote sensing.

Good catch. Moved

SAR backscatter

Done

typically does not give? let's not be so radical :)

Agree :) Changed

to the landfast ice stability

Took out the subsections in the results in response to other suggestion

with?

Changed

InSAR phase stability, referred to as InSAR coherence, largely depends on topography coupled with perpendicular baseline, and temporal stability of the scatterers on the ground surface. Coherence ranges between 0 (pure noise) and 1 (no noise), and serves as a measure of the quality of the interferogram.

Thank you for providing this. This has been included. All of this and info about coherence is moved to Section 2.1.

InSAR coherence has been successfully used to map the landfast ice edge through identifying areas of slow motion featuring high coherence?

Good sentence. This has been replaced, but the mention of coherence has been taken out since we now choose to introduce coherence first in Section 2.1.

local case studies

Included

this has also vague relation to the chapter's focus. Consider removing or find a better place for this part. The last sentence sounds like conclusion.

Agree. This has been moved to conclusions

In this study,..

Changed

information on ice stability which is relevant to

Included

their applicability?

Yes, changed

stability zones?

done

SAR

Yes, changed

Combine with the part on coherence in the previous chapter. Decide where it is better to introduce it.

Good point. All is placed in Section 2.1.

I think this should go to the data processing. You do not need to refer to interferograms here, just general S-1 data coverage used in this study etc...

Good point. This has been changed (P4,L19): "We acquired over one hundred SAR images, covering nearly the entire continental coastlines of the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas."

... that is why we focus on these coastlines?

Yes. This is now changed (P4,L21): "In this work, we focused on the Alaska and Russian marginal seas of the Arctic Ocean. These coastlines have high economic significance for the shipping and natural resource industries, and also feature dynamically diverse ice regimes."

check the order of words in the sentence

This has been changed (P4,L27): "In addition to images obtained for the large-scale mapping of stability zones, a series of six consecutive image pairs were acquired covering the Nares Strait and the break-up of an ice arch during spring 2017."

large-scale mapping?

Included

This should go Discussion

Agree. Done

break-up

Changed

this should go to Results

Moved to discussion as there is no mention of the ice arch in the results.

to visually identify ice features (...)

Done

Maybe add more details on backscatter processing. All acquired images were processed to backscatter or only some?

Done (P4,L31): "All the complex Sentinel-1 data was processed to obtain backscatter, in order to visually interpret features (e.g., landfast ice edge, fracturing, ice roughness and types)."

ice thinning?

Done

how do you make sure that the melt onset did not happen yet?

We can't really. We have moderated this sentence to (P5,3): "In this work, we obtained images as close to late April as possible. This timeframe was found to be ideal for our purpose, as ice thickness is near its maximum, leading to maximum stability and minimizing impacts from the onset of melt."

We also discuss the impacts of melt now further above in Section 2.3 (P4,L38): "This was likely predominately due to surface melt, as air temperature reached above freezing between SAR acquisitions. Other possible contributing reasons for coherence loss in this region could include ice motion, subsurface ice thinning from river runoff, and low signal-to-noise ratio."

(i.e. different time period)?

Done

Did you also use Gamma for backscatter processing?

Yes, included.

And here you can add that at all 52 interferograms were produced etc

Included (P5,L14): "The result was fifty-two interferograms, covering almost the entire coastline between the Canadian Archipelago and the Barents Sea."

stability zones?

Included

Do you mean here within one interferogram? why largely the same conditions? They are the same.

Yes. We argue not completely the same as forcing conditions will vary within one scene. This has been further clarified by including (P5,L17): "This allows us to identify variations within an area imaged under largely the same conditions (e.g., close to the same wind and ocean forcing)."

not clear to me

Changed to (P5,L19): "Therefore, interferograms can provide information related to the spatial variations in stability."

This sentence is difficult to understand. Do you start here with difficult cases, opposite to the Fig. 3a? Then introduce the coastline mask, that it can match poorly to the actual position of the coast, then that to overcome this you use backscatter. Provide more details on the work with backscatter.

This is now further clarified (P5,L27): "The shoreward boundary of bottomfast ice is difficult to obtain from the interferogram alone, since the phase signatures over bottomfast ice and low-laying coastal areas are similar. The use of the landmask (Wessel and Smith, 1996) is not ideal, since subtle coastal features such as sediment bars are often not captured. We therefore delineate the coastline (i.e., shoreward boundary of bottomfast ice) using the backscatter signature in a composite image with backscatter and phase (Figure 3b). Plotting bottomfast ice with the landmask can thus give the wrongful appearance that (1) areas of near-zero phase should have been mapped as bottomfast and (2) bottomfast ice appears in sporadic areas along the coast separated by floating ice."

make a better separation between parts on mapping of different classes. Maybe new paragraph?

Done

Where are examples on them? Before you use examples without identifying their geographic locations, be consistent.

Changed

I don't understand this sentence. why suddenly freshwater lakes?

Taken that part out as it was unnecessary

Why to use passive voice (here, before and after)? You mapped the zones!

Changed

what means remaining here?

This is now rephrased (P4,L38): "Non-stabilized ice is identified as landfast ice (i.e., areas featuring relatively high interferometric coherence) otherwise not marked as bottomfast or stabilized ice. Non-stabilized ice commonly features clear fringe patterns (Figure 3e).

it can never be 0 in reality. It is always above zero, and areas of low coherence can feature values of say 0.2. Just say "relatively high".

Good point. Changed

I understand what you mean here but it might be very confusing for a new reader and not necessary in my opinion.

Good point. Especially with rephrasing the sentence (see second to last comments above) this is already explained. Took this out.

I think this can be moved from Methods, sounds like Discussion, and I'm sure in Discussion you talk about that.

Good idea. This has been moved to Section 4.1.

Landfast

done

Results

done

Landfast ice stability zones?

done

consistent with the location of grounded ridges? Keep it simple. But also question - how do you know about ground ridges here?

We explain this further in the discussion. However, all we are intending to state here is that these patterns resemble a pattern we would expect near grounded ridges. This is now better clarified (P6,L21): "The line of discontinuity features several seaward points, an expected pattern surrounding grounded ridges. This is because grounded ridges

result in a shoreward increase in stability that does not extend to areas immediately to the side of the ridges (the along-shore direction). Examples of likely grounding points are indicated with white arrows in Figure 4b, and similar patterns are also apparent near the Mackenzie Delta (Figure 4c)."

what arrow exactly?grounding points?

This is now better described (see last comment).

?

Taken out

mark it on the figure. is it Bering Strait?

Changed.

why consistent?

Taken out

follows?

Changed

?

Taken out

Laptev Sea

Changed

Pyasina

Changed

not clear what you define as "around archipelago" and "confined by the islands". Mark non-stab. ice in Figure 8c.

Clarified (P7,L13): "In these archipelagos, the ice confined by islands is largely stabilized (Figure 8c)."

Areal analysis? Maybe you don't need a separate section for this...Think about it.

Agree. Good idea. We took that section out.

I would combine Fig. 9 with previous figures that the reader can directly compare interferograms and your mapped zones without need to turn pages back and forth.

Not a bad suggestion. However, we are concerned the figures would not fit on a page. The stability maps would therefore also be enlarged and take up more space than what they strictly need to. We think it works best like this, but are open to exact suggestions for how to rearrange this if need be.

calculated the area of each stability zone

Changed

the area calculations are not complete

Changed

part of this is in the section before. Also, if you use the table, why to mention every number then in text?

Shortened this considerably and took out redundancy. Also, took away numbers as you suggest.

InSAR technique?

Done

map?

Done

Other

Changed

The backscatter exhibits a visible discontinuity...(I don't see it sharp everywhere)

Changed to (P8,L31): "These images exhibit, in certain locations, a sharp discontinuity…"

areas of known stabilisation points?

Done

backscatter mosaic from three images (8, 15, 17 April)

Done

shorten the sentence. And move it to the later part where you talk again about backscatter.

Done

identified by backscatter

Done

is

Done

?

Changed to (P9,L3): "Certain sections of the border between stabilized and non-stabilized ice extend relatively far from the coast (see black arrows in Figure 10d)."

I would make a new paragraph

Done

mapping discriminated?smth is wrong here

Changed (P9,L7): "Although the landfast ice edge can in some instances be mapped using a single backscatter image, stabilized ice cannot easily be discriminated from non-stabilized ice."

you could mark borders and dates of interferograms on this figure as well.

Done

established?

Changed to "determined"

surrounding what?adjacent?

Changed to "one interferogram"

I guess it is a tautology

Good point. Taken out

earlier than where?

Changed to: "earlier ice formation than surrounding areas"

as I said before, this needs to be explained in more details in Methods and/or Results

This is now clarified further in response to earlier comment

can you expand what exactly are the differences? forming of polynya?

Included (P9,L37): "This generally results in reduced ice forcing and landfast ice strain in contrast to the western Arctic."

this should go to Results

This has been moved to results and a new section, Section 3.2. The remaining of this subchapter was cut down and split where a small part made it into the conclusions and a part into the introduction.

please add scale bar

Done

this needs better phrasing. Can you show backscatter-derived landmask vs "official" landmask? Is the white outlined areas indeed ice or land, I'm confused.

This has been further clarified: "Phase/backscatter composite near a delta. This example exhibits a poor match between the landmask (transparent black shading) and low-laying coastal areas. Here, bottomfast ice (white outline) had to be mapped against the coastline, as identified in the backscatter data."

It would be difficult to delineate a landmask based on the SAR imagery alone and this is part of what causes the potential bias. We are now explaining this further in the discussion where we have included (P9,L24): "We have reduced such errors by not mapping areas that appears to be low-laying land in the SAR backscatter images. However, discriminating between ice and low-laying land can be difficult based on strictly SAR. Here, other remote sensing systems such as optical could be applied to further reduce biases from coastline errors. In areas where the landmask does not appear to fit the coastline due to errors or coastline changes, mapping intricate coastal morphology can be a time-consuming task—hence mapping on a pan-Arctic scale will inevitably contain inaccuracies. It is also worth mentioning that the other stability zones are mapped against the landmask, also likely resulting in errors. However, as the extent of these zones are larger, the relative contribution of such errors will be much smaller."

please mark b),c), and d) on a) for the orientation, here and on the following figures

Done

why not to give legend as on Figure before?

Done

mark dates of images on the figure

Done

Mapping ~~with~~pan-Arctic landfast sea ice stability ~~with~~using Sentinel-1 interferometry

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Abstract. Arctic landfast sea ice has undergone substantial changes in recent decades, affecting ice stability ~~with~~, and including potential impacts on ice travel by coastal populations and on industry ice roads. ~~The role of landfast ice as an important habitat has also evolved.~~ We present a novel approach ~~to evaluate~~for evaluating landfast sea ice stability on a pan-Arctic scale using Synthetic Aperture Radar Interferometry (InSAR). Using Sentinel-1 images from spring 2017, we discriminate between bottomfast, stabilized, and non-stabilized landfast ice over the main marginal seas of the Arctic Ocean (Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas). ~~The~~This approach draws on the evaluation of relative changes in interferometric fringe patterns. This first comprehensive assessment of Arctic bottomfast sea ice extent has revealed that ~~by area,~~most of the bottomfast sea ice is situated around river mouths and coastal shallows ~~in the~~. The Laptev and East Siberian Seas dominate the aerial extent, covering roughly 4.1 and 5.1 thousand km^2, respectively. These seas also contain the largest extent of stabilized and non-stabilized landfast ice, but are subject to the largest uncertainties surrounding the ~~classification~~mapping scheme. Even so, we demonstrate the potential for using InSAR ~~in~~for assessing the stability of landfast ice in several key regions around the Arctic, providing a new understanding of how stability may vary between regions. InSAR-derived stability may serve ~~as a~~for strategic planning and tactical decision- support ~~tool~~for different uses of coastal ice. In a case study~~, we examined an ice arch situated in~~ of the Nares Strait ~~demonstrating~~, we demonstrate that interferograms may reveal early-warning signals for the break-up of stationary sea ice.

1 Introduction

1.1 Landfast sea ice stability and stakeholder dependence

Sea ice is an important component of Arctic ecosystems and provides important ~~services~~functions as a climate regulator (Screen and Simmonds, 2010), habitat for marine biota (Thomas, 2017), and a platform for coastal populations (Krupnik et al., 2010). During the last century, an expansion of transportation and resource extraction have led to increased human presence

in the Arctic and further diversification of ice use (Eicken et al., 2009). The recent retreat of sea ice observed ~~throughout~~over the past several decades (Stroeve et al., 2012; Comiso and Hall, 2014; Meier et al., 2014) has already resulted in widespread consequences for ice users (ACIA, 2004; Aporta and Higgs, 2005; Fienup-Riordan and Rearden, 2010; Orviku et al., 2011; Druckenmiller et al., 2013) ~~and~~, as well as increasing hazards (Ford et al., 2008; Eicken and Mahoney, 2015). At the same

5   time, the related increased accessibility to Arctic waters (Stephenson et al., 2011) is leading to more ship traffic and resource exploration (Lovecraft and Eicken, 2011; Eguíluz et al., 2016). It is further recognized that ~~the~~ sea ice conditions for future Arctic marine operations will be challenging, and will require substantial monitoring and improved ~~regional~~ observations (Arctic Council, 2009) ~~at the scale necessary for assessing~~. This improvement will require observations at a local and regional scale, in order to provide assessment of environmental hazards and effective emergency response (Eicken et al., 2011).

10   Most of the Arctic Ocean is dominated by drifting pack ice, whereas stationary landfast ice occupies much of the Arctic coastlines between roughly ~~between~~ November and June, depending on location (Figure 1)~~;~~ ~~(~~Yu et al., 2014). Sections of landfast ice, often from several km ~~to up~~ to hundreds of km wide, are held in place by grounded ridges, islands, or coastline morphology, such as embayments or fjords. Similar to ~~the~~ drifting pack ice, landfast ice has declined significantly during the last few decades, ~~in particular~~particularly in terms of delayed freeze~~-~~up in the Beaufort (Mahoney et al., 2014) and Laptev

15   (Selyuzhenok et al., 2015) Seas, as well as significantly reduced extent in the Chukchi Sea (Mahoney et al., 2014). Later freeze-up critically impacts stakeholders through reduced stability of ~~the~~ landfast ice in response to fewer grounded ridges ~~that can withstand~~capable of withstanding wind, ocean, or ice forcing (Dammann, 2017). Previous research suggests that landfast ice stability can be expressed in terms of ~~the~~ combined frictional resistance provided by relevant grounding or attachment points (e.g., islands and grounded ridges)~~;~~ ~~(~~Mahoney et al., 2007; Druckenmiller, 2011). Although ~~the~~ landfast ice is stationary, it

20   deforms at the cm- to m-scale, on timescales of days to months, due to forcing from wind, currents, and drifting ice (Dammann et al., 2016). ~~The~~Its stability in part determines the rate at which the ice deforms, and ultimately, the severity of break-out events or magnitude of structural defects. We suggest that landfast sea ice can be further categorized into three regimes, defined through their respective stability~~. These categories include~~: (1) bottomfast ice~~;~~: (2) floating ice enclosed in lagoons or fjords, or sheltered by point features such as grounded ridges or islands~~;~~: and (3) floating ice extensions (Table 1). A typical landfast

25   ice regime is illustrated in Figure 2, where the stability of the landfast ice area decreases from the coast ~~towards~~toward the open ocean (Dammann et al., 2016).

Bottomfast sea ice can grow laterally to the km-scale during winter, depending on local bathymetry (Solomon et al., 2008; Stevens et al., 2010). ~~The~~This bottomfast ice allows for heat loss from the sea floor, and is therefore an integral part of aggregating and maintaining subsea permafrost (Solomon et al., 2008; Stevens et al., 2008; Stevens et al., 2010; Stevens, 2011) ~~and~~, as well as

30   controlling coastal stability/morphology (Are and Reimnitz, 2000; Eicken et al., 2005). Bottomfast ice is also relevant for fish, as it reduces habitable shallow waters during winter (Hirose et al., 2008)~~. Bottomfast ice is also of importance~~, and for on-ice operations, as it can support a much larger load than floating ice. High to moderately stable landfast ice is of relevance to industrial (Potter et al., 1981) and subsistence ice use (Druckenmiller et al., 2013), as well as for habitats (Tibbles et al., 2018). ~~For~~Ringed seals, for instance, ~~ringed seals~~ are dependent on stable landfast ice for denning (Smith, 1980). Low-stability ice is

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potentially relevant for ocean-based operations, such as shipping through trans-Arctic passages close to the coast, where patches of landfast ice occasionally break off and drift into nearby shipping lanes, potentially causing hazards. Even areas hundreds of km from landfast ice can be impacted through the failure of ice arches.

Ice arches may be considered an additional zone of "temporarily stabilized pack ice." Ice arches form when ice moving through a narrow passage experiences flow stoppage as a result of confining pressure and begins to behave like landfast ice, though potentially without cohesive strength between individual floes (Hibler et al., 2006). Ice arches typically form between November and March (Moore and McNeil, 2018), and can block the export of ice through straits as wide as 100 km (Melling, 2002). When formed, such arches represent a significant obstacle to marine traffic, due to the high confining pressures that make icebreaking impossible for all but the most powerful vessels. Arches can in some locations prevail into the following season (Melling, 2002), but typically collapse in July–August (Kwok, 2005). Conversely, their break-up can lead to the advection of large amounts of thick multiyear ice into high-traffic shipping routes (Barber et al., 2018), creating a well-known hazard (Bailey, 1957; Wilson et al., 2004; Howell et al., 2013). Recent and ongoing sea ice decline is leading to an increasing presence of thinner ice in the Canadian Archipelago (Haas and Howell, 2015), and weaker ice due to warmer temperatures (Melling, 2002) may lead to earlier breaching of ice arches. This could result in a larger amount of advected ice with potentially longer travel paths, increasing the severity of such events (Melling, 2002; Barber et al., 2018). One location of particular interest is the Nares Strait, situated between Greenland and Ellesmere Island, featuring a seasonal ice arch (Kwok, 2005; Kwok et al., 2010) with important implications for the multiyear ice budget of the Arctic Ocean (Kwok et al., 2010). This stability is also relevant for destinational cargo shipping in the Arctic, as less stable, thinner ice is easier to break through, resulting in opportunities for docking in areas of landfast ice. For navigating through landfast ice, stabilization through ridging is also important to identify, as ridges can be problematic to navigate and are often associated with hazards (Hui et al., 2017).

1.2 Remote sensing of landfast ice stability

Satellite remote sensing is an important tool for measuring ice conditions in the Arctic, including the mapping of landfast ice (Muckenhuber and Sandven, 2017). Optical/thermal satellite data, such as from the Advanced Very High Resolution Radiometer (AVHRR), were used to produce operational ice charts until the early 1990s, when SAR was introduced into the charting production (Yu et al., 2014) as a superior data set, thanks to its independence from light and weather conditions and its higher (~100 m) resolution—both advantageous to stakeholders (Eicken et al., 2011). Different techniques exist to map the boundaries of landfast sea ice, typically derived by evaluating unchanged sections of ice between consecutive SAR backscatter scenes (Johannessen et al., 2006; Giles et al., 2008; Mahoney et al., 2014). In addition to its use in the mapping of landfast ice, SAR backscatter can also discriminate between multiyear and first-year ice (Onstott, 1992) and identify different roughness regimes (Dammann et al., 2017). SAR has also been used to estimate the advection of ice through

straits in the Canadian Archipelago (Melling, 2002; Kwok, 2006; Howell et al., 2013). ~~One location of particular interest is the Nares Strait situated in between Greenland and Ellesmere Island, which features a seasonal ice arch (Kwok, 2005;Kwok et al., 2010) with important implications on the multiyear ice budget of the Arctic Ocean (Kwok et al., 2010). However, backscatter does not give information pertaining to ice stability of the.~~ However, SAR backscatter typically does not give information pertaining to the stability of landfast ice or "temporarily stabilized pack ice" since the internal movement of the landfast ice is too small (mm/day) to be identified with change detection.

SAR interferometry (InSAR) is a signal processing technique, which extracts the phase difference between two SAR images acquired ~~from~~with similar viewing geometries. This phase difference (typically referred to as interferometric phase) can either signify topography if acquisitions are separated in space (i.e., non-zero perpendicular baseline~~)~~), or ~~measures~~measure the line-of-sight motion if acquisitions are separated in time (non-zero temporal baseline~~);~~ (Bamler and Hartl, 1998; Ferretti et al., 2007). ~~InSAR is dependent on similar acquisition geometry, scatterers, and atmospheric conditions at the time of the two acquisitions to retain a non-zero interferometric coherence, which ranges between 0 and 1.~~ InSAR has been ~~used to~~successfully used to map ~~the boundary of~~ landfast ice edges by identifying areas of slow motion (Meyer et al., 2011) ~~through identifying the ice that has not shifted more than a few meters over weeks and hence retain interferometric coherence.~~. InSAR has also provided information pertaining to landfast ice dynamics (Li et al., 1996; Morris et al., 1999; Vincent et al., 2004; Marbouti et al., 2017) and topography (Dammann et al., 2017;Dierking et al., 2017) by evaluating the phase change between acquisitions. InSAR has also been shown to reveal plausible rheologies for landfast ice ~~–~~(Dammert et al., 1998), and has been used to determine the origin of internal ice stresses (Berg et al., 2015). Combined with inverse modeling, InSAR ~~also allows~~enables us to determine ice deformation modes (Dammann et al., 2016), rates, and the associated stress and fracture potentials (Dammann et al., 2018b).

These studies have demonstrated (1) the potential of InSAR as a tool ~~to assess~~for assessing landfast ice dynamics and stability through local case studies and (2) its utility as a planning tool for on-ice operations (Dammann et al., 2018a; Dammann et al., 2018b). They have also laid the foundation for applying InSAR on a larger scale, potentially as a ~~mean to generate~~means for generating operational information products and ~~evaluate~~evaluating long-term trends. ~~We argue the utility of InSAR and potential applications also extend to maritime activities and shipping. In regards to the latter, vessel traffic typically does not traverse landfast ice.~~ However, the assessment of landfast ice stability and spatio-temporal extent can potentially aid management of conflicting ice uses such as in the case of the access route to the Voisey's Bay mine in the Canadian Arctic which cuts through landfast ice that is part of a traditional Nunatsiavummiut use area (Bell et al., 2014). ~~For vessel traffic through ice-covered straits or archipelagos, the approach outlined here can also possibly help identify and evaluate hazards associated with ice arches.~~

The coverage and access to InSAR-compatible SAR scenes has been an obstacle in the past, but has improved significantly since the launch of Sentinel-1. ~~The~~ (the suitability of Sentinel-1 for automatic SAR processing has been shown, e.g., in Meyer et al.~~.~~ (., 2015). ~~Hence~~In this study, we explore InSAR as a tool ~~to provide~~for providing pan-Arctic information on ice stability, which is relevant to subsea permafrost, biological habitats, and sea ice use. The goal of this work is to determine ~~the~~ Sentinel-

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1 interferometric data availability along substantial parts of the circumpolar coastlines, and ~~to~~ explore ~~applications to~~their applicability for consistently ~~map~~mapping landfast sea ice stability zones in different geographic regions. We further explore limitations of the technology and possible applications.

2 Data and methods

5 ### 2.1 InSAR principles

The interferometric phase may be related to ~~the~~ lateral (e.g., thermal contraction or displacement due to compressional or shear forces) or vertical (e.g., through buckling or tidal displacement) sea ice motion ~~occurring~~that occurs in between the acquisition times ~~of~~for the two ~~InSAR~~SAR images. A phase signature can sometimes also be attributed to factors not related to surface motion, such as atmospheric phase delay. Of the phase change attributed to motion, only displacement in line-of-sight direction

10 (Δr_{LOS}) results in a phase change $\Delta \Phi_{disp}$, according to $\Delta \Phi_{disp} = 4\pi \Delta r_{LOS}/\lambda$~~.~~. The observed phase is measured within the wrapped interval of $[0; 2\pi]$. The interferogram is a series of fringes representing the projection of the true three-dimensional ice motion onto the line-of-sight vector. The orientation of ~~the~~ fringes can be used to interpret the direction of the three-dimensional motion field~~. The~~, and fringe spacing is an indicator of the deformation rate. The interpretation of observed fringe patterns is, however, not straightforward, and it typically requires the use of an inverse model (Dammann et al., 2016). The

15 interferometric phase values will only be useful if scattering elements remain largely unchanged throughout the time interval bracketed by the image pairs used in processing. InSAR phase stability, referred to as InSAR coherence, depends largely on topography coupled with perpendicular baseline, as well as the temporal stability of the scatterers on the ground surface. Coherence ~~is~~ranges between 0 (pure noise) and 1 (no noise), and serves as a measure of the quality of the interferogram. Coherence is ~~in general~~generally high if scatterers remain unchanged, and low if there is significant change in the scattering

20 medium (Meyer et al., 2011).

2.2 Sentinel-1 data

This study ~~utilizes~~uses Sentinel-1, a constellation of two C-band SAR systems (Sentinel-1A and B) ~~operating~~in operation since 2014 and 2016, respectively, with a repeat-pass interval of ~~6~~six to ~~12~~twelve days, depending on ~~if~~whether both or just one of the satellites acquire data~~or only one of them. Owing~~. Thanks to ~~the~~a free-and-open data policy and large spatial coverage,

25 we obtained Sentinel-1 acquisitions ~~were obtained~~ for five marginal seas of the Arctic Ocean, enabling mapping of landfast sea ice on a pan-Arctic scale. All images used were captured in interferometric wideswath (IW) mode, with a single-look resolution of roughly 3 m ~~x~~ $\times$ 22 m in slant range and azimuth, respectively, and a ~250 km swath width. Images were acquired almost exclusively ~~acquired~~ between March and May 2017 (see supplementary data for full list of images used). ~~We generated a total of 52 interferograms that cover almost~~We acquired over one hundred SAR images, covering nearly the entire continental

30 coastlines of the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas. To reduce computational costs, we omitted

Greenland, some island groups, and the Canadian Archipelago, which are characterized by extensive coastline lengths. ~~The Alaskan~~In this work, we focused on the Alaska and Russian marginal seas of the Arctic Ocean. These coastlines have high economic significance for the shipping and natural resource industries~~. They~~, and also feature dynamically diverse ice regimes ~~and large~~. Large areas of bottomfast ice are expected in these regions. Except for one approximately 50 km-long section of

5   coast in the Kara Sea and the eastern Laptev Sea, multiple InSAR compatible pairs were available for the specified time frame. This allowed us to select interferograms centered around the end of April, when most Arctic landfast ice is at its maximum extent and thickness.

~~In addition to images obtained for mapping of stability zones, a series of six consecutive image pairs were acquired covering the breakup of an ice arch in Nares Strait during spring 2017. This failure event occurred relatively early as compared with~~

10   ~~past events (Kwok, 2005) partly in response to thinner ice conditions and northerly winds (Moore and McNeil, 2018). The image sequence featured a 6-day temporal baseline covering a timespan of 36 days. The resulting interferograms revealed the ice deformation around the location of fracture up until the failure event.~~

In addition to images obtained for the large-scale mapping of stability zones, a series of six consecutive image pairs were acquired covering the Nares Strait and the break-up of an ice arch during spring 2017. This image sequence featured a six-day

15   temporal baseline covering a timespan of thirty-six days.

2.3 Data processing

~~The~~All the complex Sentinel-1 data was processed to obtain ~~the~~ backscatter, in order to visually interpret features ~~that sometimes can be visibly identified~~ (e.g.~~ the~~, landfast ice edge, fracturing, ~~and~~ ice roughness and types). ~~The data~~Data was further processed for interferometry. Depending on the perpendicular baseline, sea ice topography can have a modest impact

20   on the phase difference. Due to ~~the~~ tight baseline limits (<50 m standard deviation) ~~of~~for the Sentinel-1 constellation, and ~~as~~since sea ice topography rarely exceeds 10 m, impacts ~~on the~~for interferogram interpretation are minimal for the data shown here. In this work we predominately ~~utilize~~employed acquisitions with a temporal lag of either ~~12~~twelve or ~~24~~twenty-four days, depending on data availability. For this timespan, the coherence over landfast ice was found to be generally high, due to its stationary nature. However, coherence loss was evident in some areas~~,~~ in particular in the Chukchi Sea, such as in the

25   Kotzebue Sound. This was likely ~~partly~~predominately due to surface melt, as air temperature reached above freezing between SAR acquisitions. Other possible contributing reasons for coherence loss in this region could include ice motion, subsurface ice thinning from river runoff, and low signal-to-noise ratio. Significant decorrelation can also occur in late spring, as the onset of melt ~~at that time~~ causes substantial changes in the scattering medium. In this work, we obtained images as close to late April as possible. This timeframe was found to be ideal for our purpose, as ice thickness is near its maximum, leading to maximum

30   stability ~~without risking~~and minimizing impacts from the onset of melt. To ensure a realistic representation of ~~what~~ an operationally-produced synoptic, contiguous pan-Arctic interferogram ~~would look like~~, we did not attempt to derive alternative interferograms (i.e., different time periods) in cases of low coherence.

All backscatter images and interferograms in this work were produced using a standard Sentinel-1 workflow in Gamma software (Werner et al., 2000). The IW images initially consist of independent bursts and swaths, which we combined to utilize full extent of the acquisition. We further coregistered pairs of acquisitions, to ensure images cover exactly the same area with sub-pixel accuracy. Images were then multi-looked, averaging 10 px in range and 2 px in azimuth, resulting in reduced speckle and a final pixel spacing of roughly 23×28 m. Next, spectral filtering was performed to ensure both images comprise the same spectral range, reducing phase noise in the final interferogram. The interferometric phase was calculated for each pixel of the coregistered and filtered images. Furthermore, the expected phase ramp in cross-track direction from a stationary flat earth surface was removed. The phase noise of the final interferogram was reduced using an adaptive phase filter (Goldstein and Werner, 1998). The result was fifty-two interferograms, covering almost the entire coastline between the Canadian Archipelago and the Barents Sea.

2.4 Mapping landfast ice stability zones

In this work, we evaluated relative ice stability based on fringe spacings within individual interferograms. This allowed us to identify variations within an area imaged under largely the same conditions (e.g., close to the same wind and ocean forcing). Trends from higher to lower fringe density will likely correspond to increasing ice stability. Therefore, interferograms can provide information related to the spatial variations in stability. Meyer et al. (2011) demonstrated that interferometry can be used to map the landfast ice based on a coherent phase response. Their work also suggested that fringe patterns are significantly impacted by grounded ridges and reduced fringe density. Dammann et al. (2018c) further showed that bottomfast ice can be mapped based on a near-zero phase change where ice is frozen to the seafloor. We built on this work by suggesting that InSAR can be used to map three different zones of relative stability: bottomfast ice, stabilized ice, and non-stabilized ice (Table 1). These three zones are subjectively and manually mapped without the use of specific threshold values.

Bottomfast ice is identified with near-zero phase change in the interferogram. It can often be distinguished from adjacent floating ice commonly featuring a non-zero phase change or low coherence (Figure 3a). The shoreward boundary of bottomfast ice is difficult to obtain from the interferogram alone, since the phase signatures over bottomfast ice and low-laying coastal areas are similar. The use of the landmask (Wessel and Smith, 1996) is not ideal, since subtle coastal features such as sediment bars are often not captured. We therefore delineated the coastline (i.e., shoreward boundary of bottomfast ice) using the backscatter signature in a composite image with backscatter and phase (Figure 3b). Plotting bottomfast ice with the landmask can thus give the wrongful appearance that (1) areas of near-zero phase should have been mapped as bottomfast and (2) bottomfast ice appears in sporadic areas along the coast separated by floating ice.

We ~~can~~could often identify stabilized ice by a stark fringe discontinuity between different fringe densities (Figure 3c). However, in some regions ~~such as the Laptev and East Siberian Seas~~, changes in stability are more gradual between zones ~~(Figure 6c and 7c)~~. Mapping of such regions are therefore more subjective and possibly less exact. In ~~the case of~~cases lacking stark fringe discontinuities, stabilized ice is also mapped in regions featuring a very slight phase response with no clear fringe

5   patterns ~~similar to a pattern on freshwater lakes with thick ice (Figure 3d). Non-stabilized ice is mapped as the remaining ice featuring non-zero interferometric coherence and clear fringe patterns (Figure 3e). Only the outer margin of the stabilized and non-stabilized ice is mapped and the coastal boundary represents either the boundary of another stability zone or the coastline as represented by the landmask.~~ (Figure 3d).

~~The zones themselves are based on relative stability in terms of whether the ice is anchored or sheltered. Determining absolute~~

10 ~~stability (i.e. whether an area is stable enough for a specific use, such as ice roads) would be problematic to determine from fringe density alone. This is because there are many factors that affect fringe density in addition to stability, including changing wind and ocean currents,~~ Non-stabilized ice is identified as landfast ice (i.e., areas featuring relatively high interferometric coherence) otherwise not marked as bottomfast or stabilized ice. Non-stabilized ice commonly features clear fringe patterns (Figure 3e).

15 ~~satellite viewing geometry, and the prevalent mode of ice deformation (Dammann et al., 2016). A measure of whether the ice is stable would also depend on the specific stakeholders and their dependence on stability. As an example, on shorter time scales, industry ice roads would be able to accommodate less strain than community ice trails due to different mode of transportation and user specific needs. Further steps to identify such thresholds are outlined in Dammann et al. (2018a).~~

2.5 Validation areas and data

20 The Beaufort Sea coast of Alaska was used for validation, as ~~the~~landfast sea ice in this area includes all three ~~landfast ice regimes~~stability zones (bottomfast ~~ice~~, stabilized ~~ice,~~ and non-stabilized ~~ice~~), and ample validation data is available from previous ~~landfast sea ice~~ studies. Alaska's Beaufort Sea coast is of major interest in the context of local and indigenous ice use, as well as industry resource exploration and extraction. Some areas along this coastline feature similar landfast ice extent over time scales from months to years. It was found that these regions ("nodes") of consistent landfast ice extent are often tied

25 to the location of the 20-m isobath, a water depth associated with the grounding of pressure ridges stabilizing the landfast ice (Mahoney et al., 2014). Indigenous knowledge and a field study also indicate persistent grounded ridges in the location of the node closest to Utqiaġvik, Alaska (Meyer et al., 2011). We also evaluated our ~~approach~~results near Stolbovoy Island in the Laptev Sea. This area features a shoal of <-10-m water depth, leading to earlier formation of fast ice than the surrounding areas (Selyuzhenok et al., 2015), likely due to the formation of grounded ridges on the shoal and resulting in increased stability.

3 Results

3.1 Evaluating landfast ice stability zones

We constructed a series of Sentinel-1 interferograms along the coastlines of five marginal seas ~~of~~in the Arctic Ocean during 2017: the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas. As seen in the in the interferograms (Figures 4-8), ~~the~~
5   landfast sea ice varies substantially between the seas in terms of the extent and interferometric fringe density.

The landfast sea ice extent in the Beaufort Sea ranges from almost zero up ~~towards~~toward 100 km (Figure 4a). River outlets such as the Colville and Mackenzie Deltas feature extensive regions of bottomfast ice several kilometers wide (Figure 4b, c). Bottomfast ice is also prominent in many lagoons along the coast. Much of the floating ice along the ~~western~~ coast ~~of the Beaufort Sea~~ from ~~Foggy Island Bay (east of~~ Prudhoe Bay~~)~~ to Point Barrow ~~by Utqiaġvik~~ is stabilized. ~~The floating~~This

10   stabilized ice can be identified by ~~ice shoreward of~~ a stark fringe discontinuity separating regions of different fringe density and stability (Figure 4a, b). The line of discontinuity features several seaward points ~~(see arrow in Figure 4b) consistent with the~~, an expected ~~stabilization of the ice cover immediately shoreward of~~pattern surrounding grounded ridges. ~~Similar~~This is because grounded ridges result in a shoreward increase in stability that does not extend to areas immediately to the side of the ridges (the along-shore direction). Examples of likely grounding points are indicated with white arrows in Figure 4b, and

15   similar patterns are also apparent near the Mackenzie Delta (Figure 4c). The landfast ice in the eastern part of the Beaufort Sea also consists of large areas of stabilized ice. Here, the landfast ice is noticeably sheltered by land features, resulting in lower density fringes ~~directly downstream from land~~ (Figure 4d).

~~The landfast~~Landfast sea ice in the Chukchi Sea is generally less extensive than in the Beaufort Sea, particularly along the Russian coast (Figure 5a). Bottomfast ice in the Chukchi ~~Sea~~ is constrained mostly to lagoons. Some of ~~the~~these lagoons, such

20   as the Kasegaluk, consist almost exclusively of bottomfast ice (Figure 5b). Only a few areas ~~in the~~of landfast ice appear to be stabilized, including the northern coast of Alaska near Peard Bay (Figure 5c~~)~~), and the ~~Bearing Strait~~southern Chukchi Sea near Shishmaref (Figure 5d). The Chukchi Sea consists predominantly of non-stabilized ice, with the most extensive region of landfast ice situated off shore from the village of Shishmaref (Figure 5d). The Chukchi Sea features ~~consistent~~ coherence loss in several regions such as the Kotzebue Sound (Figure 5a).

25   The landfast ice in the East Siberian Sea is more extensive than in the Chukchi and Beaufort Seas and can extend over 100 km from shore (Figure 6a). Bottomfast ice is also more extensive than in the Beaufort and Chukchi Seas. The bottomfast ice in the East Siberian Sea ~~follow~~follows several sections of coastline even tens of km away from major rivers~~. Even so,~~, though most of the bottomfast ice is situated near the Kolyma and Indigirka Deltas (Figure 6b). In contrast to the Beaufort and Chukchi Seas, stabilized ice extends several tens of km offshore without being sheltered by coastline morphology or islands (Figure

30   6c). These large areas also lack clear indications of the presence of grounded ridges ~~as found by smaller areas of stabilized ice (Figure 6d) and in the Beaufort Sea.~~ (Figure 6d).

~~The landfast~~Landfast ice in the Laptev Sea, similar to the East Siberian Sea, extends upwards of 100 km from shore (Figure 7a). ~~In the Laptev~~Here, most of the bottomfast ice is situated around river outlets and in particular near the Lena Delta,

9

extending tens of km from shore (Figure 7b). ~~The~~This delta features a large amount of small, low-~~laying~~lying land areas (e.g~~-~~., gravel islands) only partly covered by the landmask. This has made it problematic to delineate all areas of bottomfast ice, and led to more approximate delineations than in the other deltas mapped. On the east side of the Lena Delta and south of the Great Lyakhovsky Island, there are extensive sections of stabilized ice (Figure 7c). Some regions of the eastern Laptev Sea lack a clear discontinuity, but at the same time feature locally reduced fringe density, indicative of stabilized ice (Figure 7c). We also ~~consider~~considered these areas to be stabilized (Figure 7c), ~~but~~though possibly as a result of different ice type or thickness, rather than through grounding or sheltering. However, one offshore area is clearly identified as stable by a lack of consistent fringe patterns and a clear discontinuity, likely due to grounded ridges (Figure 7d).

~~The landfast~~Landfast ice in the Kara Sea features much smaller ~~landfast~~ ice extent than the other Russian Seas (Figure 8a). Bottomfast ice is also much less prevalent and largely situated ~~by~~near the ~~Payasina~~Pyasina River (Figure 8b). The landfast ice extends tens of km from shore, predominately in areas supported by offshore islands and archipelagos (Figure 8c and d). ~~The ice surrounding the~~In these archipelagos ~~is largely non-stabilized, but,~~ the ice confined by ~~the~~ islands is ~~predominately stable~~largely stabilized (Figure 8c).

~~3.2 Large-scale mapping of stability zones~~

Interferograms have enabled the mapping of landfast ice stability zones based on subjective interpretation of interferometric fringes (Figure 9). The resulting stability map allows for a large-scale comparison and analysis of bottomfast, stabilized, and non-stabilized landfast ice, within and between the different seas. For this comparison, we have ~~listed~~calculated the ~~2017~~ area ~~extent~~ of each stability zone ~~and marginal sea in~~ (Table 2~~.~~). However, it is important to note ~~that this list is~~these area calculations are not complete ~~because~~, as the analysis omitted some island groups and included some data gaps.

Most areas with extensive bottomfast ice reaching several km from shore are located either in the vicinity of river deltas or within lagoons ~~(Figure 9). However, a prominent exception is the coastline of the western East Siberian Sea, where our analysis shows substantial area extent of bottomfast ice even tens of kilometers away from any major rivers.~~. The East Siberian Sea ~~with~~and its three large river systems (the Indigirka, Bogdashkina, and Kolyma Rivers) ~~contains~~contain the most bottomfast ice of the regions considered here ~~with 5.1x10³ km².~~. The Laptev Sea also contains a large ~~fraction~~area of ~~the Arctic~~ bottomfast sea ice ~~with 4.1x10³ km², largely concentrated around the Lena and Yana Deltas. The~~. Together, the Laptev and East Siberian Seas contain over half (~57 %) of the total areal extent of bottomfast ice calculated, while the Chukchi Sea features ~~extensive~~ the lowest extent of bottomfast ice ~~(1.8x10³ km²), but almost exclusively within large lagoons such as~~of the ~~Kasegaluk Lagoon. The bottomfast~~regions considered here. Bottomfast ice is predominately situated in ~~the Beaufort Sea coast (2.5x10³ km²) can be found in lagoons and around the Colville and Mackenzie Deltas. The Kara Sea contains a bottomfast ice extent comparable with the Beaufort Sea with 2.6x10³ km².~~lagoons.

Stabilized ice was found in all marginal seas (Figure 9), though ~~their~~its relative contributions to overall landfast ice extent varied widely. The largest extent of stabilized landfast ice in our study region ~~are~~was found in the Laptev and East Siberian Seas ~~featuring a total areal extent of 74x10³ km² and 45x10³ km² respectively~~. These regions feature particularly large

continuous areas of stabilized ice labeled A-F in Figure 9. Even so, as we ~~delineate~~delineated here, the Beaufort Sea is the only sea that features more stabilized ice than non-stabilized ice ~~featuring an areal fraction (stabilized ice / non-stabilized ice) of 0.86.~~. This is likely attributed to the large grounded sections, as well as areas sheltered by coastal morphology ~~resulting in 35x10³ km² stabilized ice~~. The Laptev Sea also features large areas confined by coastlines. However, in the Laptev sea, these

5   regions also commonly feature non-stabilized ice. ~~A~~Meanwhile a large part of the landfast ice in the Kara Sea is mapped as stabilized ~~(16x10³ km²),~~, largely due to the fraction of landfast ice situated between islands and archipelagos. With a relatively narrow landfast ice extent as compared to other seas and absence of regions of sheltered ice, the Chukchi Sea contains the lowest total extent of stabilized ice ~~with 4.6 x10³ km²~~.

In the Chukchi Sea, we identified the vast majority of ~~the~~ landfast ice as non-stabilized ~~with 29 x10³ km²~~ (Figure 9~~)~~). resulting

10   in ~~the~~our largest areal fraction (~~stabilized ice /~~ non-stabilized ice~~)~~ ~~with 5.4. However~~, / stabilized ice). Though the largest total areas of non-stabilized ice can be found in the Laptev ~~Sea (127x10³ km²)~~ and ~~the~~ East Siberian ~~Sea (80x10³ km²).~~Seas. Here, the distinction between stabilized and non-stabilized landfast ice is not as straightforward as in the Beaufort and Chukchi Seas, due to a lack of clear boundaries between areas of different fringe densities. Even so, it is clear that landfast ice extent in the East Siberian and Laptev Seas is dominated by vast areas of non-stabilized ice. However, unlike the Chukchi Sea, we also

15   identified significant areas of stabilized landfast ice along these two seas. The Kara Sea features predominately non-stabilized ice ~~(37x10³ km²)~~ along the coast and along the outer margins of archipelagos.

3.2 Evaluating stability of temporarily stabilized pack ice

Sentinel-1 SAR backscatter imagery captured the location and break-up of the ice arch in Nares Strait in 2017 (Figure 12). This break-up event occurred relatively early as compared with past events (Kwok, 2005), partly in response to thinner ice

20   conditions and northerly winds (Moore and McNeil, 2018). The arch appeared stable on 6 May (Figure 12b), before eventually failing sometime before 12 May (Figure 12c) as seen in the SAR backscatter images. The interferograms revealed the ice deformation around the location of fracture up until the failure event. As seen in the interferograms, the ice arch features various levels of cm- to m-scale deformation and fractures prior to break-up, resulting in fringe discontinuities (Figure 13a) most pronounced near the arch terminus to the south. Near the failure line, there was no sign of a fringe discontinuity up until

25   12 April (Figure 13a), when the interferogram displays near cross-track parallel fringes, indicating compression towards the terminus (Figure 13b). There is a significant contrast in fringe density on either side of the line, which may be indicative of a fracture, where the ice to the west is being compressed more rapidly than the ice close to the coast. The interferogram between 18 and 24 April features widespread coherence loss, possibly due to continued compression (Figure 13c). Deformation is less severe from 24 April on, when fringe density is significantly reduced. However, we did notice a fringe discontinuity to the east

30   of the failure line, featuring perpendicular intermediate fringe patterns following to late April (see arrows in Figure 13d). These patterns develop further into circular patterns often associated with vertical lifts and depressions (Figure 13e), before the whole arch appears to fail through shear motion along this same fault (Figure 13f).

4 Discussion

4.1 Validating stability zones with areas of known ice stability

The InSAR technique to evaluatemap bottomfast sea ice was thoroughly validated in several regions by Dammann et al.

5 (2018c). The high stability of these regions can be inferred from the ice resting on the sea floor. However, other stability zones (i.e., stabilized and non-stabilized ice) are based on relative stability, in terms of whether the ice is anchored or sheltered. Determining absolute stability (i.e., whether an area is stable enough for a specific use, such as ice roads) would be problematic using fringe density alone. This is because there are many factors that affect fringe density in addition to stability, including changing wind and ocean currents, satellite viewing geometry, and the prevalent mode of ice deformation (Dammann et al.,

10 2016). A measure of whether ice is practically stable would also depend on specific stakeholders and their dependence on stability. For example, on shorter time scales, industry ice roads would be able to accommodate less strain than community ice trails, due to different modes of transportation and user-specific needs. Further steps to identify such thresholds are outlined in Dammann et al. (2018a).

There is limited information that can be used to validate furtherthese stability classes, —namely, the separation between

15 stabilized- and non-stabilized ice. Even so, we comparecompared our mapping approach here with one region in the Beaufort and one in the Laptev Sea with areas of known stabilized icestabilization points. We examineexamined a backscatter mosaic from three acquisitions from images (8-, 15, and 17 Apr) along the Beaufort Sea coast. These images exhibit, in certain locations, a sharp discontinuity in backscatter, which in this case can be used to identify the location of the landfast ice edge (see white arrows in Figure 10a).

20 The landfast ice edge identified using backscatter is consistent with the three "nodes" (A-C) identified by Mahoney et al. (2007a; 2014; our Figure 10b). These nodes signify a persistent landfast ice edge, believed to be a result of reoccurring grounded ice features (Mahoney et al., 2014). The ice shoreward of these three nodes is expected as stabilized, because grounded ridges are known to stabilize landfast ice, leading to reduced strain shoreward of the grounding points (Mahoney et al., 2007; Druckenmiller, 2011). Interferograms exhibit a phase response, suggesting stabilized ice directly shoreward of node

25 A and C (Figure 10c). Here, node A is known to correspond to the location of large grounded ridges, offering stability to the ice cover (Meyer et al., 2011). Nodes B and C are also expected to be regions of persistent grounded ridges since the nodes coincide roughly with the 20-m isobath (Mahoney et al., 2014). However, ice directly shoreward of node B appears non-stabilized, with stabilization only further in. This may be due to the reduced keel depth of ridges in 2017, or possibly reduced grounding strength of ridges present in B. Certain sections of the border between stabilized and non-stabilized ice extend

30 relatively far from the coast (see black arrows in Figure 10d). At these points, the stability is higher than adjacent areas with the same distance from shore. This is consistent with increased stability behind grounded ridges. It is

Although the landfast ice edge can in some instances be mapped using a single backscatter image, stabilized ice cannot easily be discriminated from non-stabilized ice. This is apparent when comparing grounding locations as obtained with InSAR with backscatter images (see black arrows in Figure 10a). It is also worth noting that relying on backscatter to discriminate landfast or drifting ice only works in some cases ~~where there are~~. There must be noticeable differences in backscatter between ~~the~~

5 landfast and drifting ice, or ~~when there is~~ a severely deformed landfast ice edge as a result of shear interaction with the pack ice (Druckenmiller et al., 2013).

~~The landfast ice edge in this analysis is consistent with the three "nodes" (A-C) identified by Mahoney et al. [2007a; 2014] (Figure 10b). The nodes signify a persistent landfast ice edge. This is believed to be a result of reoccurring grounded ice features (Mahoney et al., 2014). The ice shoreward of these three nodes are expected to be stabilized because grounded ridges~~

10 ~~are known to stabilize the landfast ice leading to reduced strain shoreward of the grounding points (Mahoney et al., 2007;Druckenmiller, 2011). The interferograms exhibit a phase response suggesting stabilized ice directly shoreward of node A and C (Figure 10c). Here, node A is known to correspond to the location of large grounded ridges~~ ~~offering stability to the ice cover (Meyer et al., 2011).~~ ~~Node B and C are also expected to be regions of persistent grounded ridges since the nodes coincide roughly with the 20 m isobath (Mahoney et al., 2014). However, the ice directly shoreward of B appears non-stabilized~~

15 ~~and the stabilization occurs further in. This may be due to reduced keel depth of ridges in 2017 or possibly reduced grounding strength of ridges present in B. The border between stabilized and non-stabilized ice feature multiple curves towards land ending in seaward points (see black arrows in Figure 10d).~~ ~~At these points, the stability is higher than adjacent areas with the same distance from shore. This is consistent with increased stability behind grounded ridges.~~ ~~Although the landfast ice edge can in some instances be mapped using a single backscatter image, the mapping of stabilized ice cannot easily be discriminated.~~

20 ~~This is apparent when comparing grounding locations as obtained with InSAR with the backscatter images (see black arrows in Figure 10a).~~

Similar patterns indicating grounded ridges were found in the Laptev Sea, where an April interferogram ~~exhibits~~shows a section of stabilized ice roughly 100 km ~~off shore~~offshore (see "A" in Figure 11). The full area extent of the stabilized ice cannot be ~~established~~determined due to limited data availability in the region, and ~~thus the surrounding~~one interferogram had

25 to be acquired as early as February, before this region had stabilized. Stabilized ice is expected in this region, which features a large ~~shallow~~ shoal, earlier ice formation than surrounding areas, and grounded ridges (Selyuzhenok et al., 2015). The location of this large shoal, along with smaller ones, are obtained from Jakobsson et al. (2012) and displayed in Figure 11b. Here, it is apparent that even some of the smaller shoals are associated with stabilized ice (see "B" and "C" in Figure 11b). It is also clear that the extensive stabilized ice that stretches out halfway between Great Lakhovsky Island and Stolbovoy Island

30 is potentially anchored between the coast and the shallow areas (see "D" in Figure 11b).

4.2 Methodological limitations for mapping stability zones

There are a number of sources of uncertainty that affect our map of landfast ice and its relative stability. Dammann et al. (2018c) have determined that in some instances, bottomfast ice has to be approximated on the sub-km-scale due to ambiguities

associated with low fringe density or fringes parallel to the bottomfast ice edge. We also acknowledge that small islands or sandbars not represented by our landmask may be erroneously identified as bottomfast ice. However, we greatlyWe have reduced such errors by not mapping areas that appears to be low-laying land in the SAR backscatter images. However, discriminating between ice and low-laying land can be difficult based on strictly SAR. Here, other remote sensing systems

5 such as optical could be applied to further reduce biases from coastline errors. In areas where the landmask does not appear to fit the coastline due to errors or coastline changes, mapping the intricate coastal morphology can be a time-consuming task, —hence mapping on a pan-Arctic scale will inevitably contain inaccuracies. It is also worth mentioning that the other stability zones are mapped against the landmask, also likely resulting in errors. However, as the extent of these zones are larger, the relative contribution of such errors will be much smaller.

10 In this work, we did not apply strict mapping thresholds to distinguish between stabilized and non-stabilized ice, but rather made subjective determinations based on fringe patterns. This approach works well in the Chukchi and Beaufort Seas, where regions of low fringe density lie adjacent to the coast or bottomfast ice and can be easily distinguished from regions of higher fringe density. However, in some regions, especially in the Russian Arctic, there is often a lack of distinct boundaries between regions of different fringe spacing, introducing ambiguities between stabilized and non-stabilized ice on scales from km to

15 even tens of km (FigureFigures 6c and 7c). The difficulty distinguishing in these two zones may result from reduced pack ice interaction along the Russian shelf, given the predominately divergent ice regimeregimes (Reimnitz et al., 1994; Alexandrov et al., 2000; Jones et al., 2016). This generally results in reduced ice forcing and landfast ice strain in contrast to the western Arctic. Such ice regime is expected to feature reduced dynamically-induced strain (and therefore fewer interferometric fringes) in non-stabilized ice, making it appear more stable. This is visible in the different fringe densities of the non-stabilized ice in

20 FigureFigures 4d and 6d). Additionally, the greater extent of landfast ice on the shoreward side of the grounding points provides a greater fetch, which may cause stabilized ice on the Russian Shelf to exhibit higher fringe densities than in the Chukchi or Beaufort Seas. This suggests, that there is likely a spectrum of landfast ice stability. Additional zones may be necessary to fully characterize the landfast ice regimes in different regions for different ice uses or research aims. Expanding uponon the classes presented here would likely require a different set of evaluation criteria for fringes, depending on regions. Additional

25 data such as bathymetry would also likely strengthen such analysis.

We have focused on some examples with possibly suboptimal classification. One potential candidate for reclassification is landfast ice in sheltered bays, such as the Khatanga Gulf in the western Laptev Sea, which exhibited predominatelypredominantly high fringe densities (Figure 7a). Hence, the Khatanga Gulf was identified largely as non-stabilized, despite being nearly landlocked (Figure 9). Due to the shallow water in this region, it is likely that the high fringe

30 density is caused in part by vertical motion associated with tides and coastal set up. Since vertical motion has less impact on stability in well-confined landfast ice, such examples suggest the potential need for an additional zone of stability that allows, allowing higher fringe densities in coastally confined regions. Such additional classification would depend on other datasets such as a landmask or bathymetry to identify the level of restricted ice movement in response to likely forcing conditions. Another, larger-scale example is the eastern Laptev sea, which is an area of landfast ice sheltered by the New Siberian Islands

and is typically considered stable (Eicken et al., 2005). However, based on relatively high fringe density, particularly offshore of the Lena Delta, we classified much of the landfast ice in this region as non-stabilized (Figure 9). This suggests the criteria for stabilized ice used in this analysis is different than in Eicken et al. (2005), and can provide new information related to stability in the region. Based on the overall fringe counts and patterns, the majority of the phase response

5   is due to lateral displacement and potentially only partially due to vertical displacement (circular fringe patterns with low density — see Dammann et al. (., 2016)) due to tidal motion. It is possible that landfast ice in this region may be less stable than previously thought, and that a "partially stabilized" zone may be appropriate. This would be consistent with a recent SAR backscatter analysis of landfast ice in the Laptev Sea (Selyuzhenok et al., 2017), which showed that areas identified as landfast ice in operational ice charts may actually contain pockets of partly mobile ice. This was shown for the month after initial

10   landfast ice formation, but could possibly result in more dynamic ice throughout spring due to reduced ice thickness.

Sensitivity to specific atmospheric and oceanographic conditions during the time period between SAR acquisitions may place a limitation on the number of stability zones that can be mapped. For example, in the absence of dynamic interaction with pack ice, there may be little difference in fringe spacing between landfast ice seaward and shoreward of stabilizing anchor points. Without evaluating the phase response for each area of interest in detail during different forcing scenarios, it may be

15   difficult to understand under what conditions the ice remains stable. Classification of stability based on relative differences in fringe density is also complicated by the use of non-simultaneous interferograms to provide complete coverage of a region. The interferograms used here were obtained as close to maximum ice extent and stability as possible (roughly late April), but sometimes had to be obtained as early as February. Fringe density tends to decrease over the winter as the ice thickens (Dammann et al., 2016). Hence, the use of interferograms based on different dates can aid interpretation by confirming

20   consistent fringe patterns and discontinuities that identify temporal changes. Temporal changes result in phase discontinuities at the image stitchings not related to different stability zones, which further complicates the mapping process.

Sentinel-1 IW imagery is predominantly acquired over land, so it is likely not possible to construct interferograms away from the coast, for extensive landfast ice approaching the 250 km IW swath, such as that in the East Siberian Sea. Data availability further restricts the temporal baseline between images to a

25   minimum of twelve days, though this now represents a shorter period than past work identifying landfast ice (Mahoney et al., 2004; Meyer et al., 2011; Dammann et al., 2016). Further studies should investigate the effect of different temporal baselines on the stability product. A shorter baseline will result in higher temporal resolution. However, with a shorter baseline (e.g., Sentinel-1 6-day baseline), mapping of the seaward landfast ice edge may incorporate stationary pack ice. A longer baseline will result in lower interferometric coherence. With a twelve-day baseline, some regions, such as the

30   Kotzebue Sound region, already feature consistent coherence loss. Such regions can most often be identified through a spatially inconsistent progression, from high to a complete loss of coherence. In such cases, the mapping of landfast ice type boundaries is not possible. It is worth mentioning this technique can only be used before the onset of melt, when widespread coherence loss occurs. Therefore, it is not possible to evaluate the retreat of bottomfast ice or the reduction of ice stability in response to melt.

4.3 Temporarily stabilized pack ice

Sentinel-1 SAR backscatter imagery captured the location and break-up of the ice arch in Nares Strait in 2017 (Figure 12). In this case, the arch appeared stable on 6 May (Figure 12b) before eventually failing sometime before 12 May (Figure 12c). As seen in the interferograms, however, the ice arch features various levels of cm- to m-scale deformation and fractures prior to

5 break-up resulting in fringe discontinuities (Figure 13a) most pronounced near the arch terminus to the south. Near the failure line, there is no sign of a fringe discontinuity up until 12 April (Figure 13a) when the interferogram displays near cross-track parallel fringes indicating compression towards the terminus (Figure 13b). There is a significant contrast in fringe density on either side of the line which may be indicative of a fracture where ice to the west is being compressed more rapidly than the ice close to the coast. The interferogram between 18 – 24 April features widespread coherence loss possibly due to continued

10 compression (Figure 13c). Deformation is less severe from 24 April when fringe density is significantly reduced. However, we notice a fringe discontinuity to the east of the failure line featuring perpendicular intermediate fringe patterns towards late April (see arrows in Figure 13d). These patterns develop further into circular patterns often associated with vertical lifts and depressions (Figure 13e) before the whole arch appears to fail through shear motion along this same fault (Figure 13f). This example demonstrates that it may be possible to detect precursors to break-out events without rigorous inverse model-

15 based interpretation of fringe patterns (e.g., Dammann et al., 2016;Dammann et al., 2018b), which does not easily lend itself to operational workflows. The evaluation of the interferograms leading up to the failure of the ice arch suggests that InSAR has the ability to inform stakeholders of changing stability and ice movement with potential value for an early warning system designed to alert ice users of hazards related to ice movement. Recent and ongoing sea ice decline is leading to an increasing presence of thinner ice in the Canadian Archipelago (Haas and Howell, 2015). Weaker ice due to warmer temperatures

20 (Melling, 2002) may lead to earlier breaching of ice arches. This could result in a larger quantity of advected ice with potentially longer travel paths increasing the severity of such events (Melling, 2002;Barber et al., 2018).

5 Conclusion

In a time of rapidly changing sea ice conditions and continued interest in the Arctic by from a range of stakeholders, we stress the need for new assessment strategies to enable safe and efficient use of sea ice. InSAR is gaining growing attention in the

25 sea ice scientific community, and here we demonstrate its value for identifying zones of landfast ice stability. We are also highlighting the application of InSAR in for the development of operational sea ice information products, for both long-term strategic planning as well as and short-term tactical decisions. Using interferograms generated by a standardized workflow, we show that three stability zones of landfast ice can be identified based on fringe density and continuity, which are indicative of differential ice motion occurring between SAR acquisitions. Along the Beaufort Sea coast of Alaska, we find that the landfast

30 ice regime can be well described with three stability zones: bottomfast ice, where the sea ice is frozen to or resting on the seabed; stabilized ice, which is floating but sheltered by coastlines or anchored by islands or grounded ridges; and non-stabilized ice, which represent floating extensions seaward of any anchoring points. This finding was These findings are

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supported by comparison with the location of stable "nodes"," identified through analysis of hundreds of landfast ice edge positions over the period 1996-2008. Not only does this provide some validation of our results, but it demonstrates the ability of InSAR to capture useful information in just two snapshots, compared to previously requiring analysis over many years. Based on our findings, it is likely that InSAR-derived maps could provide substantial value as a stand-alone product for some

5   regions such as the Beaufort Sea. With that said, the stability zones in the Beaufort Sea and the Russian Arctic appear to be qualitatively different. This makes it challenging to directly adapt the proposed scheme to the East Siberian and Laptev SeaSeas, which isare associated with substantial uncertainties. Even so, we have demonstrateddemonstrate the data availability and application of this InSAR-based approach, which can provide added value to ice charts and other products. In ice charting, multiple information products are evaluated with local knowledge to create final products. Similarly, the value of InSAR may

10   be greatly enhanced by complimentinglinking with other products (e.g., InSAR time series analysis, SAR-based and optical remote sensing products, local knowledge, coastal morphology and bathymetry, and atmospheric and ocean forcing data). The use of a standardized workflow facilitates large-scale application of this approach, which we demonstrateddemonstrate on a near-pan Arctic scale using 52fifty-two Sentinel-1 acquisition pairs during spring 2017. This has allowed us to map the same zones of landfast ice in the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas. To our knowledge, our results represent

15   the first mapping of bottomfast ice extent at this scale and the first attempt at any scale to map the extents of different landfast ice stability zones. It also enabled us to estimate and compare the total area covered by each stability zone in each marginal sea. However, we note that these comparisons are based on the assumptions that the landfast ice regimes in all these seas can be well described by the same three stability zones. Although the delineation of different zones can be subjective, in particular in the Russian Arctic, our results clearly show that not all landfast ice is equally stable. Here, InSAR is potentially able to

20   detect small-scale motions up to hundreds of km from shore that have previously been overlooked. In addition, there are uncertainties associated with the exact mapping of stability zones, in particular in terms of the exact delineation between stabilized and non-stabilized ice in the East Siberian and Laptev Seas. Here, the boundaries between stabilized and non-stabilized ice isare more difficult to discriminate, likely due to fewer pinning points where the ice is grounded or supported. Therefore, what we present here is not an operational ice chart, but we demonstrate the ability and application to discriminate

25   stability classes on a pan-Arctic scale using InSAR.

The method presented in this work has a broad set of potential applications for monitoring, including subsea permafrost, biological habitats both beneath and above the ice surface, and ice use by a range of stakeholders. Bottomfast ice is important because it helps for aggregating subsea permafrost, which serves to constrain the location of permafrost-rich shorelines. Utilizing InSAR, it is likely possible to monitor changes in bottomfast ice over time, with significant implications for erosion

30   and spring flooding and the release of methane hydrates. We argue the utility of InSAR and its potential applications also extend to maritime activities and shipping. In regards to the latter, vessel traffic typically does not traverse landfast ice. However, the assessment of landfast ice stability and spatio-temporal extent can potentially aid the management of conflicting ice uses such as in the case of the access route to the Voisey's Bay mine in the Canadian Arctic, which cuts through the landfast ice that is part of a traditional Nunatsiavummiut use area (Bell et al., 2014).

With respect to ice users, sea ice navigation near or through landfast sea ice is presently predominately supported by sea ice charts ~~that~~used to map areas occupied by landfast ice. However, ~~the sea ice~~these charts do not provide information ~~as to~~about the relative stability of the ice. The information provided here would likely be useful in the context of navigation and ~~supporting~~support of on-ice operations. The InSAR-based approach described here can potentially provide support by identifying the following stability-related features:

1) Low-stability ice that may break off and drift into shipping lanes.
2) Grounded ridges that may be problematic for ice navigation, but at the same time may provide added stability for on-ice operations.
3) Stable areas to use for equipment staging by coastal community hunters and industry.
4) Bottomfast ice for development of ice roads for transportation of heavy loads.

We further demonstrate the scientific and operational value of InSAR over sea ice through the examination of interferograms of ice arches. In this context, they can be considered part of an additional stability zone of quasi-landfast ice (i.e~~.~~., "temporarily stabilized pack ice"). Preliminary analysis of the Nares Strait ice arch in 2017 suggests that interferograms may reveal ~~early warning signals of an imminent break-up.~~precursors to the failure of ice arches. We further speculate that InSAR tools can be developed to inform stakeholders of changing landfast ice stability and ice movement. Such applications would have potential value for an early warning system designed to alert ice users of hazards related to ice movement and break-out events. The use of inverse modeling may further help derive the small-scale strain field from interferograms, which may improve our ability to predict their failure. We expect that InSAR can provide valuable information for stakeholders, enabling tracking of ice dynamics and stability on seasonal timescales. The ability to provide stability information to stakeholders also opens up for development of operational guidelines in terms of what stability zones should be prioritized or avoided.

This work builds on previous applications of InSAR to study landfast ice and demonstrates what can be achieved over large areas with a standardized workflow. 2017 was the first year Sentinel-1 covered the Arctic coast with the IW images necessary for this analysis. If this coverage continues, there will be considerable opportunity for development beyond what is presented here, including development of automated methods for mapping and classifying landfast ice suitable for incorporation into operational ice charts. Furthermore, through additional analysis of landfast ice and ice arches subject to different forcing conditions, we anticipate improving our understanding of stabilizing and destabilizing mechanisms. This would allow the improved prediction of formation and break-up. Not only will this enhance the operational sea ice information available to stakeholders, but it also ~~allow~~allows us to better understand the response of coastal sea ice to a changing Arctic environment.

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Figure 1: (a) Oct~~—~~–Mar (Freeze-up) and **(b)** Apr~~—~~–Sep (break-up) monthly mean landfast sea ice extent (1976~~—~~–2007~~)~~), derived from sea ice charts based on optical instruments and SAR. The data for this figure was obtained from the National Snow and Ice Data Center (Yu et al., 2014).

Figure 2: Conceptual scheme of landfast sea ice, where different regimes possess different levels of stability.

Figure 3: (a) ~~example~~Example of interferometric phase response over bottomfast ice. **(b)** Phase/backscatter composite near a delta. This example ~~of~~exhibits a poor match between the landmask (transparent black shading) and low-laying coastal areas ~~near a delta hence.~~ Here, bottomfast ice (white outline) had to be mapped against the coastline, as identified in ~~a phase/~~the backscatter ~~composite~~data. **(c)** ~~example~~Example of stabilized ice as identified based on a phase discontinuity. **(d)** ~~example~~Example of stabilized ice as identified by low fringe density and non-consistent fringe patterns. **(e)** ~~example~~Example of non-stabilized ice as identified by high fringe density. Land is masked out in light gray in a, c, d, and e.

Figure 4: (a) Sentinel-1 interferograms derived from image pairs acquired over the Beaufort Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May, respectively. **(b)-(d)** ~~represent three~~Three enlarged areas identified in (a~~)~~), further discussed in the text.

Figure 5: (a) Sentinel-1 interferograms derived from image pairs acquired over the Chukchi Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May, respectively. **(b)-(d)** ~~represent three~~Three enlarged areas identified in (a~~)~~), further discussed in the text.

Figure 6: (a) Sentinel-1 interferograms derived from image pairs acquired over the East Siberian Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May, respectively. **(b)-(d)** ~~represent three~~Three enlarged areas identified in (a~~)~~), further discussed in the text.

Figure 7: (a) Sentinel-1 interferograms derived from image pairs acquired over the Laptev Sea between February and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May, respectively. **(b)-(d)** ~~represent three~~Three enlarged areas identified in (a~~)~~), further discussed in the text.

Figure 8: (a) Sentinel-1 interferograms derived from image pairs acquired over the Kara Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May, respectively. **(b)-(d)** ~~represent three~~Three enlarged areas identified in (a~~)~~), further discussed in the text.

Figure 9: InSAR-derived map of non-stabilized and stabilized landfast ice and bottomfast ice from Sentinel-1 image pairs, acquired ~~predominately~~predominantly between March and May, 2017. Letters "A~~"~~" ~~"~~- "G" mark areas discussed in the text. Land is masked out in light grey. This map of stability zones is subject to limitations and uncertainties outlined in the text.

Figure 10: (a) Sentinel-1 backscatter images over the western Beaufort Sea. White arrows signify the landfast ice edge as identified by contrasting backscatter. **(b)** ~~landfast~~Landfast ice edge occurrence mapped for the period 1996–2008 over the Alaska Beaufort Sea (Mahoney et al. 2014). Light red circles correspond to areas of frequent landfast ice edge formation, referred to as "nodes. **(c)** ~~interferograms~~Interferograms between mid~~—~~-April and mid~~—~~-May 2017. **(d)** ~~different~~Different stability zones derived from (c). Potential grounding points as identified in (d) are marked with black arrows in (d) and (a). Land is masked out in light gray.

Figure 11: (a) Sentinel-1 interferograms over Laptev Sea near Stolbovoy Island between February and May 2017. **(b)** ~~outlined~~Outlined non-stabilized (light orange) and stabilized (dark orange) ice. Shallow areas (<10 m~~)~~ ~~(~~; Jakobsson et al., 2012) are marked with gray cross hatching. Stabilized ice that is likely supported by grounding near shallow features are marked "A"-"D" and further discussed in the text. Land is masked out in light gray.

Figure 12: Map of Nares Strait (a), and Sentinel-1 backscatter images over the 2017 ice arch (blue line in a) before (b) and after (c) failure. The line of failure is identified in (c) and marked as a dashed line in both (b) and (c). Land is masked out in light gray.

Figure 13: Interferogram over the Nares Strait ice arch in 2017, covering the time period 6~~—~~-12 Apr~~.~~ (a). Smaller panels show consecutive interferograms within the box for 12 - 18 Apr (b~~),~~); 18 - 24 Apr (c~~),~~); 24 - 30 Apr (d~~),~~); 30 Apr - 6 May (e~~),~~); and 6 - 12

May (f). ~~The dashed~~Dashed line represents the line separating ~~the~~ fast and moving ice in Figure 12c. The black arrows in (d) indicate fringe patterns further discussed in the text. Land is masked out in light gray.

Table 1: Landfast sea ice stability regimes and assigned stability zones identified using InSAR

	Landfast ice regime	Stability	Stability zone	Identified by
1	Bottomfast sea ice (i.e., ice frozen to or in broad contact with the sea floor)	Completely stable. Ice is frozen to or resting on the sea floor, restricting lateral motion. Vertical tide jacking may occur as the ice thickens.	Bottomfast	No identifiable phase difference from the adjacent land
2	Floating ice sheltered by point features, such as grounded ridges or islands, or fully enclosed in lagoons or fjords	Moderate stability. Ice is supported by coastlines or point features, completely or largely inhibiting break out events. In addition to thermal creep, internal stress from more dynamic ice can propagate in between pinning points, resulting in dm- to m-scale non-elastic deformation.	Stabilized	Poorly defined, widely spaced fringes, or abruptly reduced fringe spacing compared to offshore ice
3	Floating ice extensions	Low stability. Dominated by m-scale deformation from ice, wind, and ocean forcing. Persistent inelastic deformation can lead to accumulated strain on the order of tens of meters on time-scales exceeding several weeks. ~~The ice~~Ice may remain attached (Mahoney et al., 2004) or can break-off from the stabilized ice.	Non-stabilized	Well-defined fringe orientation or patterns

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Table 2: Approximate area coverage of landfast ice (in thousand km^2).

Area	Bottomfast	Stabilized	Non-stabilized	Total area of landfast ice	Area fraction: non-stabilized / stabilized
Beaufort Sea	2.5	35	29	67	0.83
Chukchi Sea	1.8	4.6	25	31	5.43
East Siberian Sea	5.1	45	80	130	1.78
Laptev Sea	4.1	74	127	205	1.72
Kara Sea	2.6	16	37	56	2.3

The bottomfast ice zone is constrained between its outer extent (interpreted from the phase) and the coast (as interpreted from the backscatter scenes). The stabilized zone is constrained between its outer extent (as interpreted from the phase) and the bottomfast ice or the landmask (Wessel and Smith, 1996). The non-stabilized ice is constrained between the outer extent of non-zero coherence and the bottomfast ice, stabilized ice, or the landmask.

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