Dear reviewer,

Thank you so much for providing yet another very thorough review. The comments you have provided are very insightful. We agree with all of them and acknowledge that by following all of your suggestion have led to a substantially improved manuscript. We are very grateful for this.

The main improvements have been:

1) More structured method section, which now includes examples of the mapping of different zones. We agree that this was needed.
2) Expanded result section by splitting the interferogram figure into 5 separate figures. This has greatly helped providing much more insight into the mapping and mapping strategy.
3) Improved mapping of different areas. Here we realize that some areas were not optimally mapped. In other areas the decision to map certain areas were not clear. Here, we included example areas for each region, which has provided much more clarity to the mapping process.
4) We realize that mapping perfectly all areas on this scale is implausible and would also require local knowledge and other datasets for certain areas. We have now made it clearer that what we produce here is not a complete and perfect map of ice stability, but rather demonstrate the approach and application that potentially has to be complimented by other data products.

Please see detailed responses below. Thank you so much again!

With best regards,

Dyre Oliver Dammann

Dear authors,

Thanks for incorporating my comments and suggestions from the first round. The manuscript has already been improved. However, there is still some work to do in my opinion. I commented the manuscript with suggestions and questions. Main points are:

Still not clear how you classify fringe patterns. Many areas which look very similar are classified differently in different regions. See my comments in the manuscript to the Laptev Sea, for example. Therefore, I suggest to describe the manual procedure and add representative examples in Methods, as well as in the Results.

Structure of the paper can be improved. The entire chapter on the ice arch can be split and parts could be moved to the Introduction, Methods, Results and Discussion accordingly. The chapter on the comparison of your results with previous studies should be a part of Discussion. Your very results could be presented in a more detailed way, again with examples.

Furthermore, I insist on a professional proofreading to make the writing clearer and smoother. Many sentences could be simplified and shortened. I hope to see the updated version of your manuscript soon!

Best regards,

Your reviewer

Detailed comments:

landfast sea ice

Done

I'm not sure this information is important here. What does it really tell to the reader? Besides, you might reconsider Laptev Sea and East Siberian Sea zones as commented below. Better provide the information where is the largest area of stabilised and non-stabilised ice.

I absolutely agree. That is much better. I have now replaced with (P1,L16): "These seas also contain the largest extent of stabilized (East Siberian) and non-stabilized (Laptev) landfast ice."

not sure this was in the paper?

Great point. Taken out

I think this is included in the previous sentence

Agree. Taken out

this sentence seems to be not in place, also I would expand on what do you mean by "internally" and processes influencing this deformation

Absolutely, this was out of place. Now moved further down and changed to (P2,L6): "Although the landfast ice is stationary, it does deform 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)."

probably you should add which regions are you referring to here, or pan-Arctic? what about area decline?

This has been further clarified by changing to (P2,L1): "Similar to the drifting pack ice, landfast ice has declined significantly during the last few decades, in particular in terms of delayed freeze up in the Beaufort (Mahoney et al., 2014) and Laptev (Selyuzhenok et al., 2015) Seas as well as significantly reduced extent in the Chukchi Sea (Mahoney et al., 2014)."

choose one

Good point. Done

can you explain more detailed?

This has been further explained (P2,L3): "Later freeze up critically impacts stakeholders through reduced stability of the landfast ice in response to fewer grounded ridges that can withstand wind, ocean, or ice forcing (Dammann, 2017)".

Are these your own categories you are using in this study? Or they are common? In the latter case you should give some references and not say that you suggest these categories.

We are not aware of literature that utilize these categories, which is something we came up with based on this work. The categories have now been included in the text.

I would also list the categories in the text

Done

what properties?

Taken out

what means substantial here?

Taken out

it is not clear to me what different products are there, because you mention later backscatter change detection. So I would understand that the backscatter is the only product.

This has been changed to “different techniques”, which includes backscatter gradient differencing (SAR), boxcar image cross correlation (SAR), mean-value temporal compositing (MODIS).

maybe add how exactly, because it is not obvious from the previous sentence - no motion, no topography is involved

I like that idea. Now included much more (P3,L16): “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 map the boundary of landfast ice (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.”

using Sentinel-1 interferometry

Included

I don't understand what is meant here. What and how do you evaluate? Please be very clear in the objectives what are you doing in the paper

Largely taken out and now states (P3,L39): “We further explore limitations of the technology and possible applications.”

I think this section lacks some clear structure. I propose to have 3-4 sub-chapters: 1) InSAR principles; 2) Sentinel-1 data you used; 3) data processing; 4) mapping of zones with examples. Maybe additional chapter with "validation" datasets (Mahoney et al., 2014 and potentially Selyuzhenok et al., 2015)-in this case you would not need to describe these in details in Results.

Also, the work with backscatter is missing totally in Methods and data.

Great suggestion. These subchapters have been included and the methods section restructured accordingly. Backscatter is now mentioned in the processing section (P4,L35): “The complex Sentinel-1 data was processed to obtain the backscatter in order to interpret features that sometimes can be visibly identified such as the landfast ice edge, fracturing, and ice roughness and types. The data was further processed for interferometry.”

not sure you should mention study area in the header - it is pan-Arctic?

Good point. Taken out

comparison with what?

This has been changed to “validation” and this paragraph has now been moved to the new validation subsection of methods, which is now expanded upon and further helps clarify this.

I would maybe move this section to the first place

Done

not sure if you need this if you do not perform unwrapping

Taken out

according to the formula you should get a half of wavelength which is appr. 3 cm for the line-of-sight displacement. If you refer to lateral (horizontal), provide another formula with the incidence angle.

Taken out in response to previous comment

I would include this into the next sub-chapter where I would describe the approach you are using in more details.

Done

what was the time interval for interferograms? You have it on Fig.3 but it also needs to be in the text.

This has been included (P5,L6): “In this work we predominately utilize acquisitions with a temporal lag of either 12 or 24 days depending on data availability. For this timespan, the coherence over landfast ice was found to be generally high due to its stationary nature.”

what about Sentinel-1 debursting?

This has been included (P5,L12): “The IW images initially consist of independent bursts and swaths which we combined to utilize the full extent of the acquisition. We further coregistered multiple acquisitions to ensure that the images cover exactly the same area with sub-pixel accuracy.”

in Gamma software

Included

it would be nice to have representative and detailed examples on mapping of each class.

This has now been included

not clear to me what do you mean by that

Changed to: “including changing wind and ocean currents”

not clear what is absolute stability

This has been further clarified (P6,L3): “The zones themselves 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 to determine from fringe density alone since 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., 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).”

please simplify this sentence, it is enough to say that the near-zero phase change represents bottomfast ice.

This has been simplified and split (P5,L25): "Furthermore, Dammann et al. (2018c) showed that bottomfast ice can be mapped based on a near-zero phase change (since highly stable) where the ice is frozen to the seafloor. We here build 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)."

why to consider 4 classes at all? Again, is it established classification or yours? To my mind, having 4 classes and then reducing them to 3 is a bit confusing. It is not possible in this study to distinguish two types of stabilised ice - so just mention in the very beginning that the stabilised class in your study can be attributed to two mechanisms of formation

Agree. This is a good point. This has been taken out and the classes merged.

some words about this class for completeness.

This has been taken out and more was included about this in the introduction (P2,L10): "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)"

please merge this paragraph with 2.1. See also my general comment to the Methods section

Good suggestion. Done

please find a better title - you use the same one in the Methods (and it sounds as a method). I would expand this section - these are your main results and you dedicate them 0.5 page. Include more areas in the description and describe them more deliberately.

Agree. In response to a comment further down, what was Section 3.2 has now been moved to the discussion section. The results now consist of two sections "Evaluating landfast ice stability" and "Large-scale mapping of stability zones"

this sounds to me as Conclusions.

Good point. This has been moved to conclusions

I would add detailed examples (figures) for some key regions.

This has now been included

introduce the areal calculation of ice classes - it appears out of sudden. Also specify that the area calculations are not complete because of some data gaps.

Good idea. This has been included to introduce:

Section 3.1 (P6,L23): "We constructed a series of Sentinel-1 interferograms along the coastlines of five marginal seas of 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 landfast sea ice varies substantially between the seas in terms of the extent and interferometric fringe density."

And Section 3.2 (P7,L24): "Interferograms 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 the 2017 area extent of each stability zone and marginal sea in Table 2. However, it is important to note that this list is not complete since this analysis omitted some island groups and included some data gaps."

specify that you are talking about the area

Done

I thought all classes are based on that -including bottomfast ice. Maybe this class is the least ambiguous but still it is subjective.

Absolutely. Good catch. This has been included and rephrased (see two comments up)

Why "" on classes?

Removed.

explain why and provide examples

This is now been further clarified by including (P7,L7): “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 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.“

And

(P7,L15): “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). These areas, we also consider to be stabilized (Figure 7c), but possibly as a result of different ice type or thickness rather than through grounding or sheltering.”

I would say that in Kara Sea it is not vast areas, i.e. very comparable with Beaufort and Chukchi Sea

Agree. This has been rephrased

Chukchi Sea also belongs partly to Russian coast. I would remove this comparison

Done

please mark the archipelago on the map.

Done

But you classified most of this area as stabilised although big part of it doesn't look like this.

Some areas may have a significant fringe response, but when looking in contrast to the surrounding ice marked non-stabilized, the difference is apparent. This is now more visible with the introduced Figure 8c.

Also the region around Pyasina River seems to be partly incorrect.

To us, this seems to be correct. The interferogram over this area has been enlarged in Figure 8d.

Bely Island seems to have some bottomfast ice from the west and south.

You are right, the southern part should be marked as bottomfast. However, along the western part seems to be due to an inadequate landmask. The southern part has now been mapped.

Sharapov Shar Bay (west Yamal peninsula) seems to have stabilised ice.

Absolutely, this has been changed

just largest by area?

Yes, changed

C is classified as non-stabilised on Fig. 4. Mistake?

Yes, not sure why this was suddenly gone. Made sure this area appears as stabilized now.

to my mind this section belongs to Discussion

This has been moved to the discussion

not the stability zones but your mapping of them

Rephrased

but this area is identified based on the April interferogram? Say that the February interferogram was not helpful in mapping because likely it is too early for stabilising...From here also that the area D is likely larger than shown. the current wording about triangular area is confusing.

This has been changed (P9,L4): “The full area extent of the stabilized ice cannot be established due to limited data availability in the region and thus the surrounding interferogram had to be acquired as early as February before this region had stabilized.”

the island is quite far away from the area of stabilised ice, i would not connect them in the sentence.

Taken out

could you map the shoals (they are several) on your figures using the bathymetry information?

This has now been done and added to a new figure (Figure 11).

I actually thought about some similar analysis here as in Beaufort Sea, with multiyear fast ice edge position available from this study

I don't understand what do you want to say here in addition to what already has been said

Taken out

why future tense? please make the using of tenses consistent

Changed

it is not identified on the map - either insert the node A in the text or put the name on the map.

Included on the map. This sentence has also been moved to the methods section in response to other suggestion.

why do you need this sentence here? it should be clear from the methods already.

This context has been changed by moving the section to the discussion. The sentence is also changed to (P8,L22): “We examine three acquisitions from 8-17 Apr along the Beaufort Sea coast..”

why? consistent to what? please elaborate

This has been changed. Please see next comment.

what types? here you are talking only about landfast ice edge - so the contrast should be between fast ice and water/pack ice? also this I don't understand. In general you should provide a reference to this sentence.

This has been changed and a reference provided (P8,L24): “It is worth noting that relying backscatter to discriminate landfast or drifting ice only works in cases where there are noticeable differences in backscatter between the landfast and drifting ice or a severely deformed landfast ice edge as a result of shear interaction with the pack ice (Druckenmiller et al., 2013).”

this paragraph seems to break the flow between the previous and the following paragraphs. Please consider restructuring. Also, I don't really understand why do you need to use the term "discontinuities", because you have already mapped/classified fast ice zones for all regions in the same way. You can just refer to these zones instead of introducing discontinuities and then concluding that they correspond to the stability zones.

This has been totally restructured in what is now Section 4.1. We also now refer to the zones as you suggest.

as I said in the first review, I don't see it with the node B - the border between stabilised and non-stabilised does not coincide with this node. And actually the node is more pronounced to the east of your current marking -and there is no coincidence there as well. In case of the node A - the stabilised zone

almost coincides with the overall fast ice extent, so it is not representative to my mind. Node C - maybe yes.

We have totally restructured this section (now 4.1) and now discuss the similarity with the landfast ice edge and also the mismatch with node B.

this should be merged with the paragraph on the lines 17-23, as you say already there about ridges.

Done

it is still not clear to me, sorry. If it is an important message, please provide examples on the figure and clarify the sentences again. I would also not expect to have a straight line anyway, you don't need to specify it.

We have taken out the mention of a straight line, further clarified the sentence and provided examples in the figure.

this we know already - the analysis is done for all regions in the same way.

Taken out

what about distinguishing stabilised and non-stabilised zones from backscatter? You should mention this and discuss the differences you see on backscatter and interferometry. And also this sentence seems to be not in place.

The sentence has been moved and we have now introduced arrows in Figure 10a which indicates locations of grounding points on the backscatter image as obtained from InSAR. This demonstrates the lack of features that signify the change in stability.

if it is a finding of this study you should not include this reference. Otherwise, say that another study already reported on this problem.

This is now stated (P9,L12): "Dammann et al. (2018c) 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.”

this should be highlighted in Methods with examples

Done

what is the source of the coast mask?

The global, self-consistent, hierarchical, high-resolution shoreline database (GSHHG). This has now been referenced earlier, which we think helps clarify the source of the landmask throughout

does this sentence belong to the pre-previous one? Or using backscatter leads to this effect? Please clarify and provide a figure with an example.

This has now been moved to the methods section with an example (P5,L30): "Bottomfast sea ice appears with near identical phase values to low-lying coastal areas, but is discriminated from land by identifying the coastline using the backscatter signature in a composite image with backscatter and phase (Figure 3b). Subtle coastal features such as sediment bars are often not captured by the landmask (Wessel and Smith, 1996), which can give the wrongful appearance that (1) areas of near-zero phase should have been mapped as bottomfast and (2) bottomfast ice appear in sporadic areas along the coast separated by floating ice."

please provide more information on the origin of the landmask. Is it the same coast mask you are talking about before?

We have here introduced the landmask now in the method section with reference, which clarifies the origin of the landmask.

because it changed since 1996 or because of errors?

Both: "…coastline due to errors or coastline changes…"

I might disagree because the area of the bottomfast ice is very small compared to the area of the whole fast ice and errors in mapping could actually lead to significant variations in the areal estimations.

This has been changed: "…hence mapping on a pan-Arctic scale will inevitably contain inaccuracies that are likely to impact our findings."

examples?

Included now: Figure 6c and 7c

different from western Arctic? or what is meant here? please expand here.

Yes, included.

How can you tell that the ice is non-stable there? I don't see actually an example of "landfast ice seaward of offshore islands". Please provide examples.

This is now clarified with examples (P9,L35): "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 Figure 4d and 6d)."

spectrum of stability for sure, it is clear that stabilised/non-stabilised is way too broad (although much better than nothing, I agree), but is it really possible to identify more areas with this method? Maybe better say that it might be necessary to evaluate fringe density differently in different regions, also using additional information, i.e. bathymetry, etc

Expanded upon this (P9,L26): "Expanding upon the classes presented here would likely require a different set of evaluation criteria for fringes in depending on regions. Additional data such as bathymetry would also likely strengthen such analysis."

Add an introducing sentence before - "We focused on some examples of possibly erroneous classification...

Added this (P10,L5): “We focused on some examples with possibly suboptimal classification.”

but there are clearly some regions of lower fringe densities, why do you ignore them?

We agree a couple of areas here should (and now have been) be identified as stabilized following our consistent scheme. We have now further clarified (P9,L34): “We 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 predominately high fringe densities (Figure 7a) and was hence identified largely as non-stabilized despite being nearly landlocked (Figure 9).”

again, I think that the introducing of additional zones is not really possible (or not even needed) but just to use additional information (coastal set up) for reclassifying / cautious mapping

This has now been clarified (P9,L39): “Such additional classification would depend on other datasets such as a landmask or bathymetry to identify level of restricted ice movement in response to likely forcing conditions.”

I disagree with classifying all the area as non-stabilised. How does the fringe density on interferogram 10-22 differ from the density on interferogram 12-24? Also, there is clearly an area of different fringe density in the middle of 12-24 as well as the eastern part of 8-2 which is classified as non-stabilised. Also, why the Buor-Khaya Bay is non-stabilised?

We initially did not mark these areas as stabilized based on our criteria of needing a visible fringe gradient or having fringes difficult to determine. However, we agree it may be worth outlining the areas you indicate since they quite significantly distinguish themselves from the surrounding ice. We have therefore included the areas you specify in the stabilized category. Their location is largely now also explained by the validation in what is now Figure 11.

In the East Siberian Sea the entire Chaunskaya Bay is classified as stabilised although a significant part of it features dense fringes. Whereas in the Laptev Sea areas of much wider fringes are classified as non-stabilised.

We moderated to (P10,L4): “…we classify much of the landfast ice in this region as non-stabilized”. We have also changed the high fringe density in Chaunskaya Bay to non-stabilized

again, I don't see how can you compare the "stable" from Eicken and "stable" from your study. Maybe their definition of stable can well fit to your non-stabilised criterion? Therefore, I don't think there is an apparent contradiction to Eicken. We simply don't know what exactly they call "highly stable", right? Or provide more information on Eicken's stability

This has been changed to (P10,L5): “this suggests that the criteria for stabilized ice as used here is different than in Eicken et al. (2005) and can provide new information related to stability in the region.”

see the previous comment. Maybe just say that your study may provide some new insights into ice stability in this region.

Done. See previous comment

and the other part? based on what do you suggest it?

This sentence has been slightly moved and changed to incorporate this (P10,L6): “Based on the overall fringe counts and patterns, the majority of the phase response 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.)

reconfirm the one month please. or generalise to the entire winter period to make it relevant to your study. Maybe refer to break out events, possible in the region?

This has been expanded upon (P10,L9): "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 landfast ice formation, but could possibly result in more dynamic ice throughout spring due to reduced ice thickness."

how do you know that?

We found this in our 2016 work. The citation is now included

February?

Yes, due to the new interferogram introduced. Changed.

this paragraph contains many different aspects which are not related to each other. Try to make a smoother flow

Good point. This paragraph is now made much smoother and consistent (P10,L24):

"Sentinel-1 IW imagery are predominately acquired over land, hence it is likely not possible to construct interferograms away from the coast to cover extensive landfast ice approaching the 250 km IW swath such as that in the East Siberian Sea. The data availability of these images further restricts the temporal baseline between images to a minimum of 12 days, shorter than past work to identify 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), the mapping of the seaward landfast ice edge may incorporate stationary pack ice. A longer baseline will result in lower interferometric coherence. With a 12-day baseline, some regions already feature consistent coherence loss such as the Kotzebue Sound region. Such regions can most often be identified through a spatially gradual progression from high coherence to a complete loss of coherence, where an exact map of landfast ice type boundaries is not possible. It is worth mentioning that this technique can only be used before the onset of melt when widespread coherence loss occurs, hence it is not possible to evaluate the retreat of bottomfast ice or reduction of ice stability in response to melt."

maybe you also should mention that future studies should investigate the effect of varying temporal baseline on the stability mapping?

Done (see above)

maybe better mark the entire Bay and not the town? It took me a while to understand that you are talking about the southern part of the Bay and not about the point with arrow

Good point. Done

I'm not sure it is gradual but the boundary is hard to see, true

Changed to "spatially inconsistent progression"

to my mind you should split this whole chapter between Introduction, Methods, Results and Discussion. In the beginning you are talking about importance of ice arches, previous studies on them etc. Then you provided clear results of your analysis.

This is a good idea. This has been done

this chapter sounds like Conclusions and should be merged with them

This has been done

is "and" missing here?

No, but changed the sentence to make it more readable (P12,L15): “Bottomfast ice is important because it helps aggregating subsea permafrost, which serves to constrain the location of permafrost-rich shorelines”

i don't get the connection

Taken out

"appears to be meaningful in most regions"? I don't think it was proven

Taken out

sea ice

Done

ice stability

Done

see my comment on that above. I'm not convinced that the nodes of Mahoney et al. 2014 correspond to your classes boundary. I would describe it more cautiously.

We have now described this better. See response to earlier comment

there are no islands as I see

There are a number of islands stabilizing the ice cover especially in the form of barrier islands enclosing lagoons.

as also previously said, I think that not the additional zones would help but adaptation of the method to the different regions and additional sources of information. Indeed, more zones could be distinguished based on the fringe rates but you argue that you want to keep the approach simple. In this case I don't think you can come up with more zones than you have already.

We agree. We have changed this to (P11,L31): “This makes it challenging to directly adapt the proposed scheme to the East Siberian and Laptev Sea without further incorporating an InSAR time series analysis and local knowledge of the region. Introducing other data pertaining to coastal morphology, bathymetry, and regional wind and ocean forcing climatology would also further strengthen the stability analysis.”

is it anticipated from your study or from the referred one? either move to Discussion or remove the reference.

Removed

consider removing references from Conclusions

Taken out all

I would remove d) or combine it with c)

Done

this caption is a little messy

Cleaned up now

where do the rates come from?

These came from assessing the interferograms in this work, but this column has been removed since we found it somewhat misleading that the zones are based on the rate values.

what is this?

Specified to: “Area fraction: non-stabilized / stabilized”

Ice

~~Landfast~~Mapping Arctic landfast sea ice stability ~~– mapping pan-Arctic ice regimes~~ with ~~implications for ice use, subsea permafrost and marine habitats~~ Sentinel-1 interferometry

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Abstract. Arctic landfast sea ice has undergone substantial changes in recent decades affecting ice stability with 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 landfast sea ice stability on a pan-Arctic scale using Synthetic Aperture Radar Interferometry (InSAR). Using Sentinel-1 images from spring 2017, ~~the approach discriminates~~we discriminate between bottomfast, ~~with critical relevance for subsea permafrost, as well as~~ stabilized, and non-stabilized ~~floating~~ landfast ice over the main marginal seas of the Arctic Ocean (Beaufort, Chukchi, East Siberian, Laptev and Kara Seas). The ~~analysis~~approach draws on evaluation of ~~small-scale lateral motion derived from~~ relative changes in interferometric fringe patterns. This first comprehensive assessment of Arctic bottomfast sea ice extent revealed that by area, most of the bottomfast sea ice is situated around river mouths and coastal shallows in the Laptev and East Siberian Seas, covering roughly 4.1 and 5.1 thousand km^2 respectively. ~~The fraction between~~ These seas also contain the largest extent of stabilized and non-stabilized ~~and stabilized ice is lowest in the Beaufort at almost unity, and highest in~~ landfast ice, but are subject to the ~~adjacent Chukchi Sea. Beyond~~largest uncertainties surrounding the ~~simple mapping of~~ classification scheme. Even so, we demonstrate the potential for using InSAR in assessing the stability of landfast ice ~~zones, this work provides~~in several key regions around the Arctic, providing a new understanding of how stability ~~zones~~ may vary between regions ~~and over time.~~. InSAR-derived stability ~~data~~ may serve as a strategic planning and tactical decision-support tool for different uses of coastal ice. ~~Such information may also inform assessments of important sea ice habitats.~~ In a case study, we examined an ice arch situated in Nares Strait demonstrating 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 as a climate regulator ~~(Screen and Simmonds, 2010)~~(Screen and Simmonds, 2010), habitat for marine biota (Thomas, 2017), ~~as well as~~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 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 (~~Druckenmiller et al., 2013~~ACIA, 2004;Aporta and Higgs, 2005;Fienup-Riordan and Rearden, 2010;Orviku et al., 2011;~~ACIA, 2004~~Druckenmiller et al., 2013) and increasing hazards ~~(Eicken and Mahoney, 2015;Ford et al., 2008).~~(Ford et al., 2008;Eicken and Mahoney, 2015). At the same time, the related increased accessibility to

Arctic waters (Stephenson et al., 2011) is leading to ~~increasing~~more ship traffic and resource exploration (Lovecraft and Eicken, 2011;Eguíluz et al., 2016). It is recognized that the sea ice conditions for future Arctic marine operations will be challenging and will require substantial monitoring and improved regional observations ~~(Ellis and Brigham, 2009)~~(Arctic Council, 2009) at the scale necessary for assessing environmental hazards and effective emergency response (Eicken et al., 2011).

Most of the Arctic ~~ocean~~Ocean is dominated by drifting pack ice, whereas stationary landfast ice occupies much of the Arctic coastlines roughly between November and June depending on location (Figure 1) (Yu et al., 2014). ~~Although the landfast ice is stationary, it does deform internally at the cm- to m-scale on timescales of days to months (Dammann et al., 2016). The often several km to up to hundreds of km wide sections of landfast ice~~Sections of landfast ice, often 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 in terms of delayed freeze up in the Beaufort (Mahoney et al., 2014~~;Selyuzhenok et al., 2015~~)~~. Later freeze up critically impacts stakeholders through increased mobility (reduced stability) of the landfast ice in response to~~ and Laptev (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 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~~;Mahoney et al., 2007b~~)~~.~~. Although the landfast ice is stationary, it 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 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~~ therefore~~ suggest that landfast sea ice can be further categorized into ~~four~~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 ice regime is illustrated in Figure 2, where the stability of the landfast ice area decreases from the coast towards 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).~~(Solomon et al., 2008;Stevens et al., 2010). The bottomfast ice allows for heat loss from the sea floor and is therefore an integral part of aggregating and maintaining subsea permafrost (~~Stevens~~Solomon et al., 2008;Stevens et al., 2008;Stevens et al., 2010;Stevens, 2011)~~,~~, and controlling coastal stability/morphology ~~(Eicken et al., 2005;Are and Reimnitz, 2000), and sediment properties (Solomon et al., 2008).~~(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)~~(Hirose et al., 2008). Bottomfast ice is also of importance 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), ~~but also for habitats (Tibbles et al., In press).~~as well as for habitats (Tibbles et al., 2018). For instance, ringed seals are dependent on stable landfast ice for denning ~~(Smith, 1980).~~(Smith, 1980). Low-stability ice is 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 as an additional zone of “temporarily stabilized pack ice”. Ice arches form when ice passing through a narrow passage experiences flow stoppage as a result of confining pressure and behaves 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 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. ~~Ice arches consist of stationary ice forming between islands during freeze-up and when collapsing in the spring can send hazardous old ice into shipping routes (Bailey, 1957;Wilson et al., 2004;Barber et al., 2018).~~The 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 advection of large amounts of thick multiyear ice into high-traffic shipping routes (Barber et al., 2018) which is a well-known hazard for shipping (Bailey, 1957;Wilson et al., 2004;Howell et al., 2013). Stability is also of relevance 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 ~~substantial~~ landfast ice. For navigating through landfast ice, stabilization through ridging is also important to identify since 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 mapping of landfast ice ~~(Muckenhuber and Sandven, 2017).~~(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 due its independence of light and weather conditions and due to its higher (~100 m) resolution, both advantageous to stakeholders (Eicken et al., 2011). Different ~~information products~~techniques exist to map the boundary 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~~;Giles et al., 2008~~). ~~Beside~~In addition to its use in mapping of landfast ice, SAR backscatter can also ~~has the ability to help~~ discriminate between multiyear and first-year ice (Onstott, 1992) and identify different roughness regimes (Dammann et al., 2017). ~~However, backscatter does not give information pertaining to ice stability~~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 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 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 the line-of-sight motion ~~of an observed feature~~ if acquisitions are separated in time (non-zero temporal baseline) ~~(Ferretti et al., 2007;Bamler and Hartl, 1998). InSAR has been used to successfully map landfast ice~~ (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 map the boundary of landfast ice (Meyer et al., 2011) ~~as well as to provide~~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 (~~Marbouti et al., 2017;~~Li et al., 1996;Morris et al., 1999;Vincent et al., 2004;~~Morris~~Marbouti et al., ~~1999~~2017) and topography (Dammann et al., 2017;Dierking et al., 2017)~~. In recent studies,~~ 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 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 the potential of InSAR as a tool to assess landfast ice dynamics and stability through localized case studies.~~These studies have demonstrated the potential of InSAR as a tool to assess landfast ice dynamics and stability through case studies and utility as a planning tool for on-ice operations (Dammann et al., 2018a;Dammann et al., 2018b). They also laid the foundation for applying InSAR on a larger scale, potentially as a mean to generate operational information products and evaluate 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 suitability of Sentinel-1 for automatic SAR processing ~~was~~has been shown, e.g., in ~~Meyer et al. (2015).~~Meyer et al. (2015). Hence, we explore InSAR as a tool to provide pan-Arctic information ~~pertaining to stability~~ relevant to subsea permafrost, biological habitats, and sea ice use. The goal of this work is to determine the Sentinel-1 interferometric data availability along substantial parts of the circumpolar coastlines, and explore ~~whether the different ice stability regimes can~~applications to consistently ~~be analyzed and mapped~~ map landfast sea ice stability in different geographic regions. We further explore limitations of the technology and ~~the utility for long-term assessments of change. We also evaluate the kind of sea ice information that can be extracted directly from InSAR with operational relevance in terms of tactical and strategic decision making, without costly or complex algorithms.~~ possible applications.

2 Data and methods

2.1 ~~Satellite data and study area~~

~~This study utilizes Sentinel-1, a constellation of two C-band SAR systems (Sentinel-1A and B) operating since 2014 and 2016, respectively, with a repeat-pass interval of 6 to 12 days depending on if both satellites acquire data or only one of them. Owing to the free-and-open data policy and large spatial coverage, Sentinel-1 acquisitions were obtained for five marginal seas of the Arctic ocean including the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas, 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 22 m in slant range and azimuth respectively and a ~250 km swath width. Images were almost exclusively acquired between March and May 2017 (see supplementary data for full list of images used). The Beaufort Sea coast of Alaska was used for comparison, as the sea ice in this area includes all four landfast ice regimes (bottomfast ice, semi-enclosed lagoon ice, ice stabilized by grounded ridges and islands, and areas with floating extensions of ice; Table 1), and as ample validation data is available from previous landfast sea ice studies. Alaska's Beaufort Sea coast is also of major interest in the context of local and indigenous ice use as well as industry resource exploration and extraction.~~

~~2.2~~ InSAR~~-based detection of landfast ice~~ 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 in between the acquisition times of the two InSAR images. A phase signature can sometimes also be attributed to factors not related to surface motion ~~or topography such~~

~~as atmospheric phase delay and coregistration errors, but these effects are small compared to ice motion and can often be corrected (Scharroo and Visser, 1998).~~such as atmospheric phase delay.~~ Depending on the perpendicular baseline, sea ice topography can have a modest impact on the phase difference. Due to the tight baseline limits (<50 m standard deviation) of the Sentinel-1 constellation and as sea ice topography rarely exceeds 10 m, impacts on the interferogram interpretation are minimal for the data shown here (Dammann et al., 2016).~~ Of the phase change attributed to motion, only displacement in line-of-sight direction (Δr_{LOS}) results in a phase change $\Delta\Phi_{disp}$ according to $\Delta\Phi_{disp} = 4\pi\,\Delta r_{LOS}/\lambda$ ~~and the~~. The observed phase is measured within the wrapped interval of $[0; 2\pi]$.~~ For Sentinel-1, the sensor wavelength λ is 5.66 cm, such that ice lateral displacement has to exceed $\Delta r_{LOS} \approx 5cm$ for the $\Delta\Phi_{disp}$ phase values to result in more than one fringe and ambiguous phase values.~~ 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~~ while the~~. The fringe spacing is an indicator of the deformation rate. The interpretation of observed fringe patterns is, however, not straightforward, and it typically ~~requiring~~requires the use of an inverse model (Dammann et al., 2016). The 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. Coherence is a measure of the quality of the interferogram. Coherence is in general high if scatterers remain unchanged and low if there is significant change in the scattering medium (Meyer et al., 2011).

2.2 Sentinel-1 data

This study utilizes Sentinel-1, a constellation of two C-band SAR systems (Sentinel-1A and B) operating since 2014 and 2016, respectively, with a repeat-pass interval of 6 to 12 days depending on if both satellites acquire data or only one of them. Owing to the free-and-open data policy and large spatial coverage, 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 22 m in slant range and azimuth respectively and a ~250 km swath width. Images were almost exclusively acquired between March and May 2017 (see supplementary data for full list of images used). We generated~~The 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. Coherence (ranging between 0 and 1) is~~ a ~~measure~~total of ~~the quality~~52 interferograms that cover almost the entire continental coastlines of the ~~interferogram~~Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas. To reduce computational costs, we omitted Greenland, some island groups, and the Canadian Archipelago, which ~~in general is~~are characterized by extensive coastline lengths. The Alaskan and Russian coastlines have high economic significance for the shipping and natural resource industries. They feature dynamically diverse ice regimes and large areas of bottomfast ice are expected in these regions. Except for one approximately 50 km-long section of 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~~if scatterers remain unchanged and low if there is significant change~~ 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 ~~the scattering medium~~Nares Strait during spring 2017. This failure event occurred relatively early as compared with past events ~~(Meyer et al., 2011). For the~~(Kwok, 2005) partly in response to thinner ice conditions and northerly winds (Moore and McNeil, 2018). The image sequence featured a 6~~ or 12~~-day ~~repeat cycle supported by~~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.

2.3 Data processing

The complex Sentinel-1 data was processed to obtain the backscatter in order to interpret features that sometimes can be visibly identified (e.g. the landfast ice edge, fracturing, and ice roughness and types). The data was further processed for interferometry. Depending on the perpendicular baseline, sea ice topography can have a modest impact on the phase difference. Due to the tight baseline limits (<50 m standard deviation) of the Sentinel-1 constellation, and as sea ice topography rarely exceeds 10 m, impacts on the interferogram interpretation are minimal for the data shown here. In this work we predominately utilize acquisitions with a temporal lag of either 12 or 24 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 Kotzebue Sound. This was likely partly due to ice motion, subsurface thinning from river runoff, and low signal-to-noise ratio. Significant decorrelation can ~~however~~also occur in late spring as the onset of melt at that time causes substantial changes in the scattering medium. In this work, we ~~have~~ obtained images as close to late April as possible. This ~~time frame~~timeframe was found to be ideal for our purpose as ice thickness is near its maximum leading to maximum stability without risking impacts from the onset of melt. ~~All interferograms in this work were produced using a standard Sentinel-1 workflow. The images were first geometrically coregistered~~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 in cases of low coherence.

All interferograms in this work were produced using a standard Sentinel-1 workflow in the Gamma~~to ensure that the images cover exactly the same area with sub-pixel accuracy. The images were then multi-looked by averaging 10 pixels in range and 2 pixels in azimuth, resulting in reduced speckle and a final pixel spacing of roughly 23x28 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). All of these steps were completed for each interferogram using the GAMMA RS~~ software (Werner et al., 2000). The IW images initially consist of independent bursts and swaths which we combined to utilize the full extent of the acquisition. We further coregistered pairs of acquisitions to ensure that the images cover exactly the same area with sub-pixel accuracy. The images were then multi-looked by averaging 10 pixels in range and 2 pixels in azimuth, resulting in reduced speckle and a final pixel spacing of roughly 23x28 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

~~**2.3 Mapping of landfast ice zones**~~

~~In this work, we are looking at the fringe spacing to roughly determine relative ice stability. There are many factors that affect fringe density in addition to stability, including the atmospheric and ocean forcing conditions, satellite viewing geometry, and the prevalent mode of ice deformation (Dammann et al., 2016), making it problematic to evaluate absolute stability from fringe density alone. Instead, we focus on abrupt changes in fringe spacing within individual interferograms that allow~~(Goldstein and Werner, 1998).

2.4 Mapping of landfast ice zones

In this work, we evaluate relative ice stability based on fringe spacings within individual interferograms. This allows us to identify variations within an area imaged under largely the same conditions. Trends from higher to lower fringe density will~~, in such cases,~~ likely correspond to increasing ice stability. ~~We hypothesize~~Therefore, interferograms can provide information related to the relative ice spatial variations. 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 by reduced density ~~can reveal~~ of the fringes. Furthermore, Dammann et al. (2018c) showed that bottomfast ice can be mapped based on a near-zero phase change where the ice is frozen to the seafloor. We build on this work by suggesting that InSAR can be used to map three different zones of relative stability ~~zones~~: bottomfast ice, stabilized ice, and non-stabilized ice (Table 1). ~~The often-strong fringe gradient leading to an area of near-zero phase change has been shown to represent the boundary of where the ice is frozen to the sea floor and can subsequently be used to map bottomfast ice (Dammann et al., 2018c). In Table 1, the two sheltered regimes will both lead to reduced fringe density and can be difficult to discriminate based on InSAR data alone.~~

These ~~regimes are therefore assigned to the zone "stabilized ice". The~~ three zones ~~(i.e. bottomfast ice, stabilized ice, non-stabilized ice)~~ are subjectively and manually mapped without the use of specific threshold values. Here, bottomfast ice is identified with near-zero phase change in the interferogram. It can often be distinguished from the adjacent floating ice commonly featuring a non-zero phase change or low coherence (Figure 3a). Bottomfast sea ice appears with near identical phase values to low-lying coastal areas, but is discriminated from land by identifying the coastline using the backscatter signature in a composite image with backscatter and phase (Figure 3b). Subtle coastal features such as sediment bars are often not captured by the landmask (Wessel and Smith, 1996). This can give the wrongful appearance that (1) areas of near-zero phase should have been mapped as bottomfast and (2) bottomfast ice appear in sporadic areas along the coast separated by floating ice. We can 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. Mapping of such regions are therefore more subjective and possibly less exact. In the case of lacking stark fringe discontinuities, stabilized ice is also mapped in regions featuring a very slight phase response with no clear fringe 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.

The zones themselves are ~~therefore~~ 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 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, 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

The Beaufort Sea coast of Alaska was used for validation, as the sea ice in this area includes all three landfast ice regimes (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 to the location of the 20-m isobath, a water depth associated with grounding of pressure ridges stabilizing the landfast ice (Mahoney et al., 2014). ~~The approach we present here, opens up the possibility of mapping landfast sea ice zones on a pan-Arctic scale. To demonstrate, we used Sentinel-1 data acquired March through May 2017 and generated 52 interferograms that cover almost the entire continental coastlines of the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas. To reduce computational costs, we omitted Greenland, some island groups and in particular the Canadian Archipelago, which are characterized by extensive coastline lengths. The Alaskan and Russian coastlines have high economic significance for the shipping and natural resource industries and feature dynamically diverse ice regimes and large areas of bottomfast ice are expected in these regions.~~ 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 near Stolbovoy Island in the Laptev Sea. This~~Except for one approximately 50 km-long section of 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.~~ ~~Coherence loss was evident in some areas, in particular in the Chukchi Sea, such as in the Kotzebue Sound likely partly due to ice motion, subsurface thinning from river runoff, and low signal-to-noise ratio. However, 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 in these cases.~~

~~3 Results~~

~~3.1 Mapping pan-Arctic ice stability zones~~

~~The interferograms produced in this work (Figure 3) allowed for a detailed map of landfast ice including the identification of three landfast ice stability zones: bottomfast ice, stabilized landfast ice, and non-stabilized landfast ice. To our knowledge, our results (Figure 4) represent 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. Subject to the considerations included in the discussions, it is clear that most areas with extensive bottomfast ice reaching several km from shore are located either in the vicinity of river deltas or within lagoons. However, a prominent exception is the coastline of the western East Siberian Sea, where our analysis shows substantial amounts of bottomfast ice even tens of kilometers away from any major rivers. The East Siberian Sea with its three large river systems (the Indigirka, Bogdashkina, and Kolyma Rivers) contains the most bottomfast ice of the regions considered here (Table 2). The Laptev Sea also contains a large fraction of the Arctic bottomfast sea ice mostly concentrated around the Lena and Yana Deltas.~~

~~The map of “stabilized” and “non-stabilized” landfast ice is based on subjective interpretation of the interferograms. Both stabilized and non-stabilized landfast ice zones were found in all marginal seas (Table 2), though their relative contributions to overall landfast ice extent varied widely. For example, in the Chukchi Sea, we identified the vast majority of the landfast ice as non-stabilized, with stabilized landfast ice occupying less area than the bottomfast ice. Conversely, the greatest area of stabilized landfast ice was found in the adjacent Beaufort Sea, with a larger extent of stabilized than non-stabilized landfast ice.~~

~~In the East Siberian, Laptev and Kara Seas, the distinction between stabilized and non-stabilized landfast ice is not as straightforward as in the Beaufort and Chukchi Seas. Even so, it is clear that landfast ice extent in the East Siberian, Laptev and Kara Seas is dominated by vast areas of non-stabilized ice. Unlike the Chukchi Sea, we still identified significant areas of stabilized landfast ice along the Russian Arctic coast. In the Kara Sea, these are primarily found between the islands of the Nordenskiöld~~

~~Archipelago in the east, but the most extensive regions of stabilized landfast ice in our study region (those that extend furthest from the coast) are found in the Laptev and East Siberian Seas (areas labeled A, B, and C in Figure 4).~~

~~3.2 Comparing stability zones with areas of known ice stability~~

~~To investigate whether the stability zones are reasonable, we compare our delineations to two areas (i.e. the Laptev and Beaufort Seas) where the landfast sea ice has been tracked over several years resulting in information pertaining to landfast sea ice stability. Due to limited SAR data availability in the central part of the Laptev Sea, the interferogram of the ice surrounding the Stolbovoy Island had to be acquired as early as February before the time of maximum ice stability (Figure 3). Even so, it is clear that the area to the northwest of the island features stabilized ice (see "D" in Figure 4). The stabilized ice area appears triangular due to the much earlier acquisition date of the surrounding interferogram. This exact~~ 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 resulting in increased stability. ~~The ability of interferometry to identify stabilized ice in this region lends support to our approach.~~

3 Results

3.1 Evaluating landfast ice stability

We constructed a series of Sentinel-1 interferograms along the coastlines of five marginal seas of 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 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 100 km (Figure 4a). River outlets such as the Colville and Mackenzie Deltas feature extensive regions of bottomfast ice several kilometers wide (Figure 4b). 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 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 expected stabilization of the ice cover immediately shoreward of grounded ridges. 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 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 lagoons, such as the Kasegaluk, consist almost exclusively of bottomfast ice (Figure 5b). Only a few areas in the landfast ice appear to be stabilized, including the northern coast of Alaska near Peard Bay (Figure 5c) and the Bearing Strait (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).

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 several sections of coastline even tens of km away from major rivers. Even so, 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 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. The landfast ice in the Laptev Sea, similar to the East Siberian Sea, extends upwards of 100 km from shore (Figure 7a). In the Laptev, most of the bottomfast ice is situated around river outlets and in particular near the Lena Delta extending tens of km from shore (Figure 7b). The delta features a large amount of small low-laying land areas (e.g. gravel islands) only partly covered by the landmask. This 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 these areas to be stabilized (Figure 7c), but 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 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 the Payasina 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 archipelagos is largely non-stabilized, but the ice confined by the islands is predominately stable (Figure 8c).

3.2 Large-scale mapping of stability zones

Interferograms 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 the 2017 area extent of each stability zone and marginal sea in Table 2. However, it is important to note that this list is not complete because 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 its three large river systems (the Indigirka, Bogdashkina, and Kolyma Rivers) contains the most bottomfast ice of the regions considered here with $5.1x10^3$ km^2. The Laptev Sea also contains a large fraction of the Arctic bottomfast sea ice with $4.1x10^3$ km^2, largely concentrated around the Lena and Yana Deltas. The Chukchi Sea features extensive bottomfast ice ($1.8x10^3$ km^2), but almost exclusively within large lagoons such as the Kasegaluk Lagoon. The bottomfast ice in the Beaufort Sea coast ($2.5x10^3$ km^2) 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 $2.6x10^3$ km^2.

Stabilized ice was found in all marginal seas (Figure 9), though their relative contributions to overall landfast ice extent varied widely. The largest extent of stabilized landfast ice in our study region are found in the Laptev and East Siberian Seas featuring a total areal extent of $74x10^3$ km^2 and $45x10^3$ km^2 respectively. These regions feature particularly large continuous areas of stabilized ice labeled A-F in Figure 9. Even so, as we delineate 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 $35x10^3$ km^2 stabilized ice. The Laptev Sea also features large areas confined by coastlines. However, in the Laptev sea, these regions also commonly feature non-stabilized ice. A large part of the landfast ice in the Kara Sea is mapped as stabilized ($16x10^3$ km^2), 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 $x10^3$ km^2.

In the Chukchi Sea, we identified the vast majority of the landfast ice as non-stabilized with 29 $x10^3$ km^2 (Figure 9) resulting in the largest areal fraction (stabilized ice / non-stabilized ice) with 5.4. However, the largest areas of non-stabilized ice can be found in the Laptev Sea ($127x10^3$ km^2) and the East Siberian Sea ($80x10^3$ km^2). 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 identified significant areas of stabilized landfast ice along these two seas. The Kara Sea features predominately non-stabilized ice ($37x10^3$ km^2) along the coast and along the outer margins of archipelagos.

4 Discussion

~~We will also consider the landfast ice along the Alaska Beaufort Sea coastline, which has been extensively researched and tracked in terms of its annual cycle and decadal variability (Mahoney et al., 2007a;Mahoney et al., 2004). The resulting stack of all landfast ice edges for all months between 1996 and 2008 (Mahoney et al., 2014) is plotted in Figure 5a. From this figure, it is clear that in certain regions, the ice extent is similar over time scales from months to years (see areas highlighted in the figure). It was found that these regions ("nodes") of consistent landfast ice extent are often tied to the location of the 20 m isobath, a water depth associated with grounding of pressure ridges (Mahoney et al., 2014) (Figure 5a). A field study and indigenous knowledge also indicate persistent grounded ridges in the location of the node closest to Utqiaġvik, Alaska (Meyer et al., 2011).~~

~~We created three interferograms acquired during the period April 8 – May 9 to cover the same stretch of coastline. The respective master images exhibit a sharp discontinuity in backscatter (see arrows in Figure 5b) along the general location of the landfast ice edge from Figure 5a and can be assumed to be the landfast ice edge. Determining the landfast ice edge can in some instances be achieved by evaluating a single amplitude image as here, but is not consistent and only works in cases where there are stark discontinuities in backscatter due to different ice types or a severely deformed landfast ice edge. The interferograms indicate in this case a similar landfast ice edge by a complete loss of coherence seaward of the discontinuity apparent in Figure 5b (Figure 5c). These interferograms reveal a wide range of fringe densities, ranging from near constant phase for areas close to the coast to the point where fringes are dense enough to almost merge near the landfast ice edge. It is also apparent that the fringe density does not linearly increase with distance from the coast, but rather changes along two distinct discontinuities.~~

~~One discontinuity separates the area of near-zero phase change from an area with relatively low fringe density. This discontinuity indicates the boundary between bottomfast and floating ice as two of these interferograms were validated both on Elson Lagoon near Utqiaġvik and the Colville Delta (Dammann et al., 2018c). The second discontinuity appears to largely coincide with locations of the nodes identified by Mahoney et al. [2007a; 2014], which are thought to be associated with~~

4.1 Validating stability zones with areas of known ice stability

The technique to evaluate bottomfast sea ice was thoroughly validated in several regions by Dammann et al. (2018c). However, there is limited information that can be used to validate further stability classes, namely the separation between stabilized- and non-stabilized ice. Even so, we compare our mapping approach here with one region in the Beaufort and one in the Laptev Sea with known stabilized ice. We examine three acquisitions from 8-17 Apr along the Beaufort Sea coast. These images exhibit 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). It is worth noting that relying on backscatter to discriminate landfast or drifting ice only works in cases where there are noticeable differences in backscatter between the 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 ~~(Figure 5a)~~ (~~Meyer~~Mahoney et al., ~~2011~~2014). ~~This finding is~~The ice shoreward of these three nodes are expected ~~since~~to be stabilized because grounded ridges are known to stabilize the landfast ice leading to reduced strain shoreward of the grounding points (Mahoney et al., ~~2007b~~2007;Druckenmiller, 2011)~~.~~

~~The discontinuity is not a straight line, but features~~. 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 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 ~~similar to the expected~~. This is consistent with increased stability ~~directly shoreward of grounded ridges. We performed a subjective, manual mapping (i.e. without the use of a specific threshold) of the strong phase gradients in Figure 5d and concluded that the ice regions separated by these discontinuities consist of non-stabilized, stabilized, and bottomfast ice (Figure 5e).~~behind grounded ridges. Although the landfast ice edge can in some instances be mapped using a single backscatter image, the mapping of ~~bottomfast and~~ stabilized ice cannot easily be discriminated ~~as~~. This is apparent ~~by~~when comparing grounding locations as obtained with InSAR with the ~~map from~~backscatter images (see black arrows in Figure ~~5e with Figure 5b.~~ 10a).

~~4 Discussion~~

Similar patterns indicating grounded ridges were found in the Laptev Sea where an April interferogram exhibits a section of stabilized ice roughly 100 km off shore (see “A” in Figure 11). The full area extent of the stabilized ice cannot be established due to limited data availability in the region and thus the surrounding interferogram had 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, and grounded ridges (Selyuzhenok et al., 2015). The location of this 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 is potentially anchored between the coast and shallow areas (see “D” in Figure 11b).

4.~~1~~2 Methodological limitations for mapping stability zones

~~Although there~~There are a number of sources of uncertainty that affect our map of landfast ice and its relative stability~~, it is clear that not all landfast ice is equally stable and at least three different zones of stability have been identified. In some areas, the map of bottomfast ice has had~~. Dammann et al. (2018c) 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 ~~(Dammann et al., 2018c). We also acknowledge that small islands or sandbars not represented by our coast mask~~. We also acknowledge that small islands or sandbars not represented by our landmask may be erroneously identified as bottomfast ice. However, we greatly reduced such errors by not mapping areas that appears to be low-laying land ~~and sediment bars in the SAR backscatter images. This can lead to the appearance of sporadic areas of bottomfast ice, separated by areas with a phase resembling that of bottomfast ice, but which in reality is land. In areas where the landmask (Wessel and Smith, 1996) does not appear to fit the coastline~~in the SAR backscatter images. 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. ~~However, these uncertainties are unlikely to significantly affect our findings at regional and pan-Arctic scales.~~ 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 ~~mapped~~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 even tens of km~~.~~ (Figure 6c and 7c). The difficulty distinguishing these two zones ~~of landfast ice in the Russian Arctic~~ may result from ~~a~~ reduced ~~level of dynamic~~ pack ice interaction along the Russian shelf, given the predominately divergent ice regime (Reimnitz et al., 1994;~~Jones et al., 2016;~~Alexandrov et al., 2000;Jones et al., 2016)~~.~~ in contrast to the western Arctic. Such ice regime is expected to feature reduced dynamically-induced strain (and therefore fewer interferometric fringes) in ~~landfast ice seaward of offshore islands and grounded ridges~~ non-stabilized ice making it appear more stable. This is visible in the different fringe densities of the non-stabilized ice ~~appear more stable.~~in Figure 4d and 6d). Additionally, the greater extent of landfast ice on the shoreward side of 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~~ and additional~~. Additional zones may be necessary to fully characterize the landfast ice regimes in different regions ~~and~~ for different ice uses or research aims. Expanding upon the classes presented here would likely require a different set of evaluation criteria for fringes depending on regions. Additional data such as bathymetry would also likely strengthen such analysis.

We 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 predominately high fringe densities (Figure ~~3) and~~7a). Hence, the Khatanga Gulf was ~~hence~~ identified largely as non-stabilized despite being nearly landlocked (Figure ~~4~~9). Due to the shallow water in this region, it is likely that the high fringe 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 ~~zones~~zone of stability that allows higher fringe densities in coastally confined regions. Such additional classification would depend on other datasets such as a landmask or bathymetry to identify 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 ~~highly stable (Eicken et al., 2005).~~stable (Eicken et al., 2005). However, based on relatively high fringe density, in particularly offshore of the Lena Delta, we classify ~~landfast ice in this region as non-stabilized (Figure 4).~~

~~This suggests~~much of the landfast ice in this region as non-stabilized (Figure 9). This suggests that 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 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 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)~~(Selyuzhenok et al., 2017), which showed that areas identified as landfast ice in operational ice charts may actually contain pockets of partly mobile ice~~ over one ~~. This was shown for the month after initial landfast ice formation~~. Based on the overall fringe counts and patterns, only part of the phase response is likely attributed to tidal motion. The number of useful zones of landfast~~, but could possibly result in more dynamic ice ~~stability is limited by other inherent sources of uncertainty including sensitivity~~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 problematic 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 ~~early March. Fringe density tends to decrease over the winter as the ice thickens.~~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 consistent fringe patterns and discontinuities that identify temporal changes. ~~However, the temporal change will also~~Temporal changes result in ~~a~~ phase ~~gradient~~discontinuities at the image ~~stitching~~stitchings not related to different stability zones, which ~~may~~ further ~~complicate~~complicates the mapping process.

~~The~~ Sentinel-1 ~~interferograms considered here has a minimum~~ IW imagery is predominately acquired over land, so it is likely not possible to construct interferograms away from the coast to cover extensive landfast ice approaching the 250 km IW swath such as that in the East Siberian Sea. The data availability of these images further restricts the temporal baseline between images to a minimum of 12 days~~. Even if this baseline is~~, shorter than ~~what has been used in the past (Dammann et al., 2016;Mahoney et al., 2004), it is unlikely that~~past work to identify 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), the mapping of the seaward landfast ice edge ~~incorporates~~may incorporate stationary pack ice~~ (as could possibly be the case for~~. A longer baseline will result in lower interferometric coherence. With a ~~6~~12-day baseline~~). Some~~, some regions already feature consistent coherence loss such as the Kotzebue Sound region. Such regions can most often be identified through a spatially ~~gradual~~inconsistent progression from high ~~coherence~~ to a complete loss of coherence~~, where an exact map~~. In such cases, the mapping of landfast ice type boundaries is not possible. It is worth mentioning that this technique can only be used before the onset of melt when widespread coherence loss occurs~~, hence~~. Therefore, it is not possible to evaluate the retreat of bottomfast ice or reduction of ice stability in response to melt. ~~Furthermore, IW imagery are predominately acquired over land, hence it is likely not possible to construct interferograms away from the coast to cover extensive landfast ice approaching the 250 km IW swath such as that in the East Siberian Sea.~~

4.~~2~~3 Temporarily stabilized pack ice

~~Prior studies have demonstrated the utility of InSAR over landfast ice as a planning tool for on-ice operations (Dammann et al., 2018a;Dammann et al., 2018b) but we argue here that such utility and potential applications also extend to maritime activities and shipping.~~ 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 break-up resulting in fringe discontinuities (Figure 13a~~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 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 help identify and evaluate hazards associated with ice arches. Ice arches form when ice passing through a narrow passage experiences flow stoppage as a result of confining pressure and behaves 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 export of ice through straits as wide as 100 km (Melling, 2002).~~

~~Indeed, ice arches may be considered as an additional zone of "temporarily stabilized pack ice". 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. The 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 advection of large amounts of thick multiyear ice into high-traffic shipping routes (Barber et al., 2018) which is a well-known hazard for shipping (Bailey, 1957;Howell et al., 2013). SAR data have previously been used to estimate the advection of ice through straits in the Canadian Archipelago (Kwok, 2006;Melling, 2002;Howell et al., 2013). One location of particular interest is the Nares Strait situated in between Greenland and Ellesmere Island (Figure 6a), which features a seasonal ice arch (Kwok et al., 2010;Kwok, 2005) with important implications on the multiyear ice budget of the Arctic Ocean (Kwok et al., 2010). Here, we go beyond the detection of the presence of ice arches and explore the potential use of InSAR in assessing their stability and dynamic precursors to failure.~~

~~In 2017, Sentinel-1 SAR backscatter imagery captured the break-up of this arch. The arch was relatively stable on 6 May (Figure 6b) before eventually failing sometime before 12 May (Figure 6c). This failure event occurred relatively early as compared with past events (Kwok, 2005) partly in response to thinner ice conditions and northerly winds (Moore and McNeil, 2018). A sequence of six interferograms with a 6-day temporal baseline covering a timespan of 36 days indicates ice deformation around the failure line up until the failure event (Figure 7). The ice arch features various levels of cm- to m-scale deformation and fractures resulting in fringe discontinuities (Figure 7a~~) 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 ~~7a~~13a) when the interferogram displays near cross-track parallel fringes indicating compression towards the terminus (Figure ~~7b~~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 compression (Figure ~~7c~~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 ~~7d~~13d). These patterns develop further into circular patterns often associated with vertical lifts and depressions (Figure ~~7e~~13e) before the whole arch appears to fail through shear motion along this same fault (Figure ~~7f~~13f).

This example demonstrates that it may be possible to detect precursors to break-out events without rigorous inverse model-based interpretation of fringe patterns (e.g., Dammann et al., 2016;Dammann et al., 2018b), which does not easily lend itself to operational workflows. ~~Evaluating~~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) and weaker~~(Haas and Howell, 2015). Weaker ice due to warmer temperatures ~~(Melling, 2002)~~(Melling, 2002) may lead to earlier breaching of ice arches. This ~~may in turn~~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~~;Melling, 2002~~).

~~4.3 InSAR as a monitoring tool for landfast ice stability~~5 Conclusion

In a time of rapidly changing sea ice conditions and continued interest in the Arctic by 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 sea ice scientific community, and here we demonstrate its value for identifying zones of landfast ice stability. We are also highlighting application of InSAR in the development of operational sea ice information products for both long-term strategic planning as well as 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 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 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 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 Sea, which is associated with substantial uncertainties. Even so, we have demonstrated 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 be greatly enhanced by complimenting 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 demonstrated on a near-pan Arctic scale using 52 Sentinel-1 acquisition pairs during spring 2017. This 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 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 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 is 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 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 aggregating subsea permafrost~~ constraining~~, 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 and spring flooding ~~(Dammann et al., 2018c) and the release of methane hydrates (Brothers et al., 2012).~~and the release of methane hydrates. With respect to ice users, sea ice navigation near or through landfast sea ice is presently predominately supported by sea ice charts that map areas occupied by landfast ice~~, but~~. However, the sea ice charts do not provide information as to the relative stability of the ice. The information provided here would likely be useful in the context of navigation and supporting on-ice operations~~ and could be provided through the~~. 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.

~~In this work, no parameters were changed in the interferometric processing workflow between regions or image pairs emphasizing the possibility of producing these images in a cost-effective manner and by personnel with limited experience with InSAR, similar to semi-automated processing underlying SARVIEWS (http://sarviews-hazards.alaska.edu) and HyP3 (http://hyp3.asf.alaska.edu). The method of mapping landfast ice stability is further based on visual interpretation. We have based the analysis strictly on identifying areas of reduced phase response or a strong phase gradient without applying other datasets or advanced interpretation methods such as inverse modeling. Hence, the approach can potentially be adapted by organizations without the need for trained SAR experts. The subjective, manual image interpretation approach has proven useful in most regions due to the presence of both stabilized and non-stabilized landfast ice, but is subject to highlighted limitations.~~

~~5 Conclusion~~

~~In a time of rapidly changing ice conditions and continued interest in the Arctic by a range of stakeholders, we stress the need for new assessment strategies to support continued safe and efficient use of sea ice. InSAR is gaining growing attention in the sea ice scientific community and here we demonstrate its value for identifying and mapping newly defined zones of landfast ice. We are also highlighting the potentially substantial impact InSAR may have on the development of operational sea ice information products for both long-term strategic planning as well as 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 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 anchored by islands or grounded ridges; and non-stabilized ice, which represent floating extensions seaward of any anchoring points. This finding was supported by comparison with the location of stable "nodes" identified through analysis of hundreds of landfast ice edge positions over the period 1996-2008 (Mahoney et al., 2014). Not only does this provide some validation of our results, but it demonstrates the ability of InSAR to capture in two snapshots what otherwise requires analysis of data over many years. 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 Sea without including additional stability zones. This would allow for a more rigorous definition of landfast sea ice in different regions with implications for operational mapping.~~

~~The use of a standardized workflow facilitates large-scale application of this approach, which we demonstrated on a near-pan Arctic scale using 52 Sentinel-1 acquisition pairs during spring 2017. This allowed us to map the same zones of landfast ice in the Beaufort, Chukchi, East Siberian, Laptev, and Kara seas. 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 assumption that the landfast ice regimes in all these seas can be well described by the same three stability zones. Although we find evidence that other zones of landfast ice may exist in the Russian Arctic, our results clearly show that not all landfast ice is equally stable. Here, InSAR is potentially able to detect small-scale motions on scales reaching hundreds of km that have previously been overlooked.~~

We further demonstrate the scientific and operational value of InSAR over sea ice through the examination of interferograms of ice arches~~, which in~~. In this context, they can be considered ~~as~~part of an additional stability ~~zones~~zone of quasi-landfast ice (i.e.~~g.,~~ “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. ~~We also anticipate that inverse modeling of the interferograms of ice arches to estimate the small-scale strain field (Dammann et al., 2018b) may improve our ability to predict their formation. We also show how~~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 ~~the~~ development of operational guidelines in terms of what stability zones should be prioritized or avoided.

This work builds on previous applications of InSAR to ~~the~~ study ~~of~~ landfast ice ~~(Meyer et al., 2011;Berg et al., 2015;Dammert et al., 1998;Morris et al., 1999;Dammann et al., 2018b)~~ and demonstrates what can be achieved over large areas with a standardized ~~work flow~~workflow. 2017 was the first year Sentinel-1 covered the Arctic coast with 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~~, thereby allowing~~. This would allow improved prediction of formation and break-up. ~~This~~Not only will ~~not only~~this enhance operational sea ice information available to stakeholders, but it also allow us to better understand the response of coastal sea ice to a changing Arctic environment.

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Competing interests

The authors declare that they have no conflict of interest.

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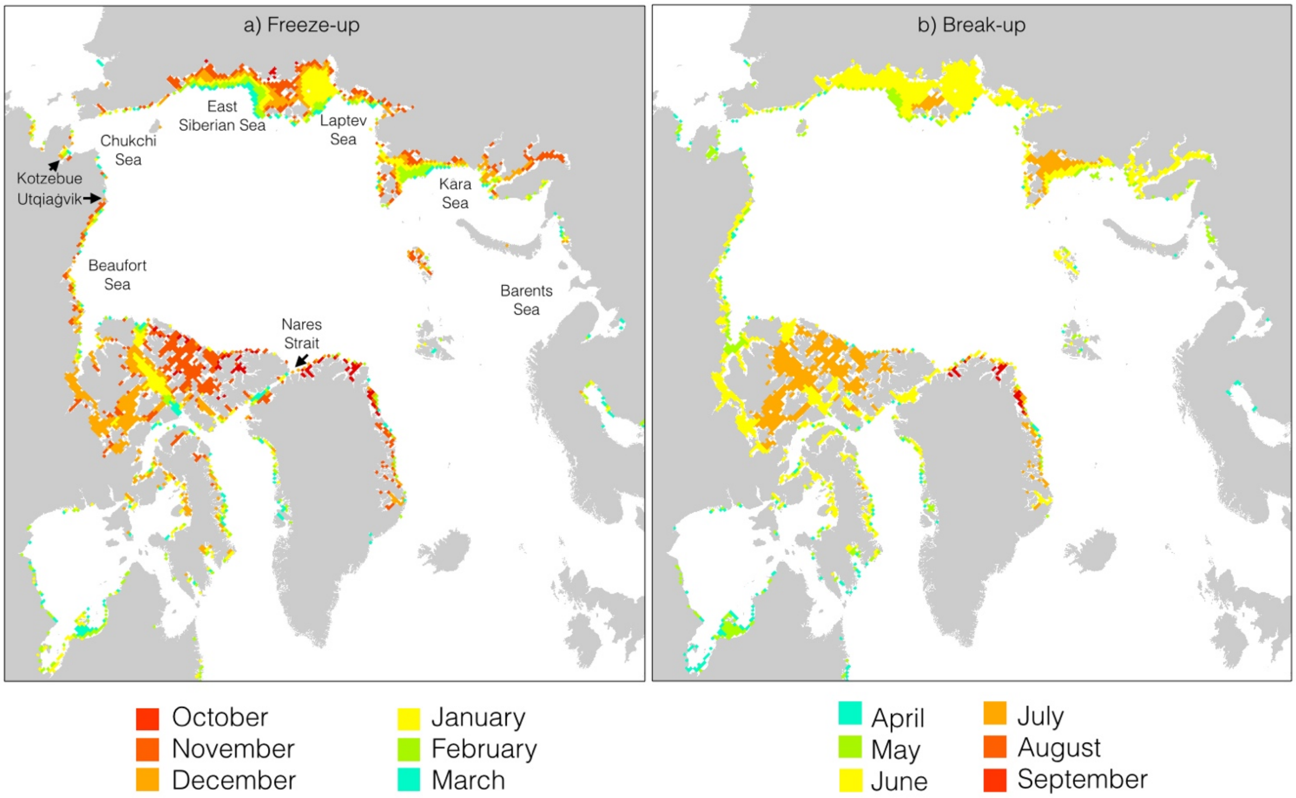


Figure 1: (a) Oct - Mar (Freeze-up) and (b) Apr - Sep (break-up) monthly mean landfast sea ice extent (1976 - 2007) derived from sea ice charts based on optical instruments and SAR. The data for this figure was obtained from the National Snow and Ice Data Center (Yu et al., 2014).

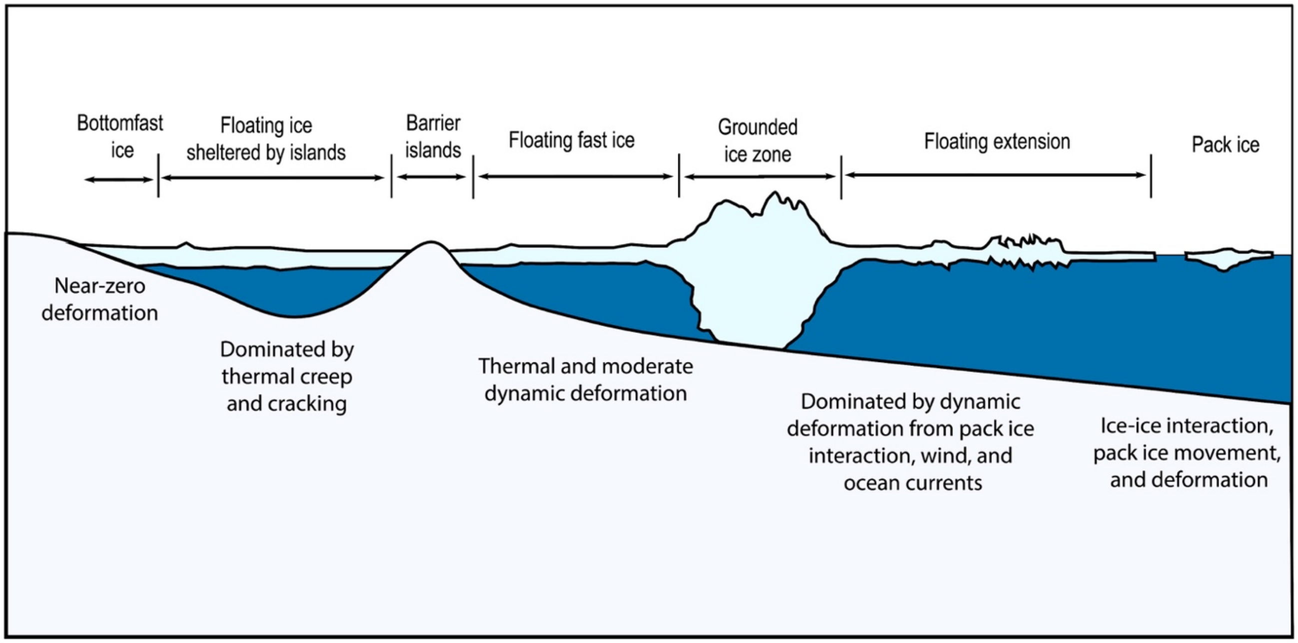


Figure 2: Conceptual scheme of landfast sea ice where different regimes possess different levels of stability.

~~Figure 3: 52 Sentinel-1 interferograms derived from image pairs acquired between February and May, 2017.~~

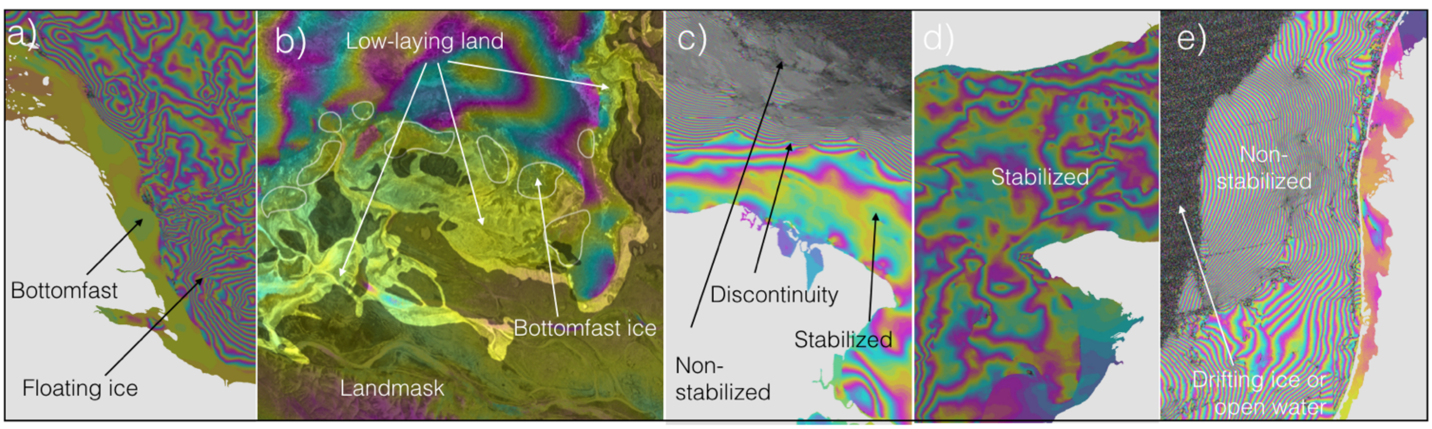


Figure 3: (a) example of interferometric phase response over bottomfast ice. (b) example of a poor match between the landmask (transparent black shading) and low-laying coastal areas near a delta hence bottomfast ice (white outline) had to be mapped against

the coastline as identified in a phase/backscatter composite. (c) example of stabilized ice as identified based on a phase discontinuity. (d) example of stabilized ice as identified by low fringe density and non-consistent fringe patterns. (e) example of non-stabilized ice as identified by high fringe density. Land is masked out in light gray in a,c,d, and e.

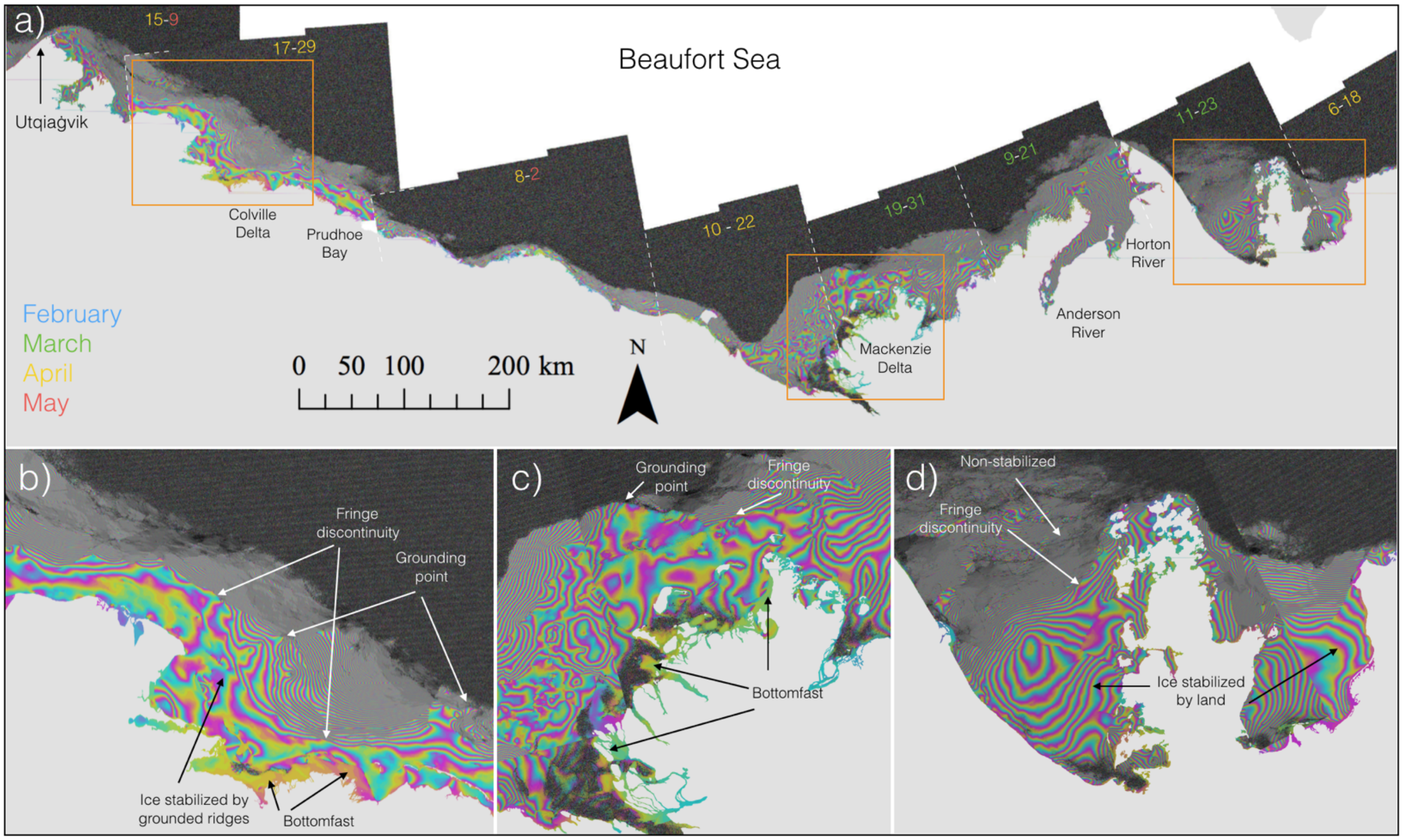
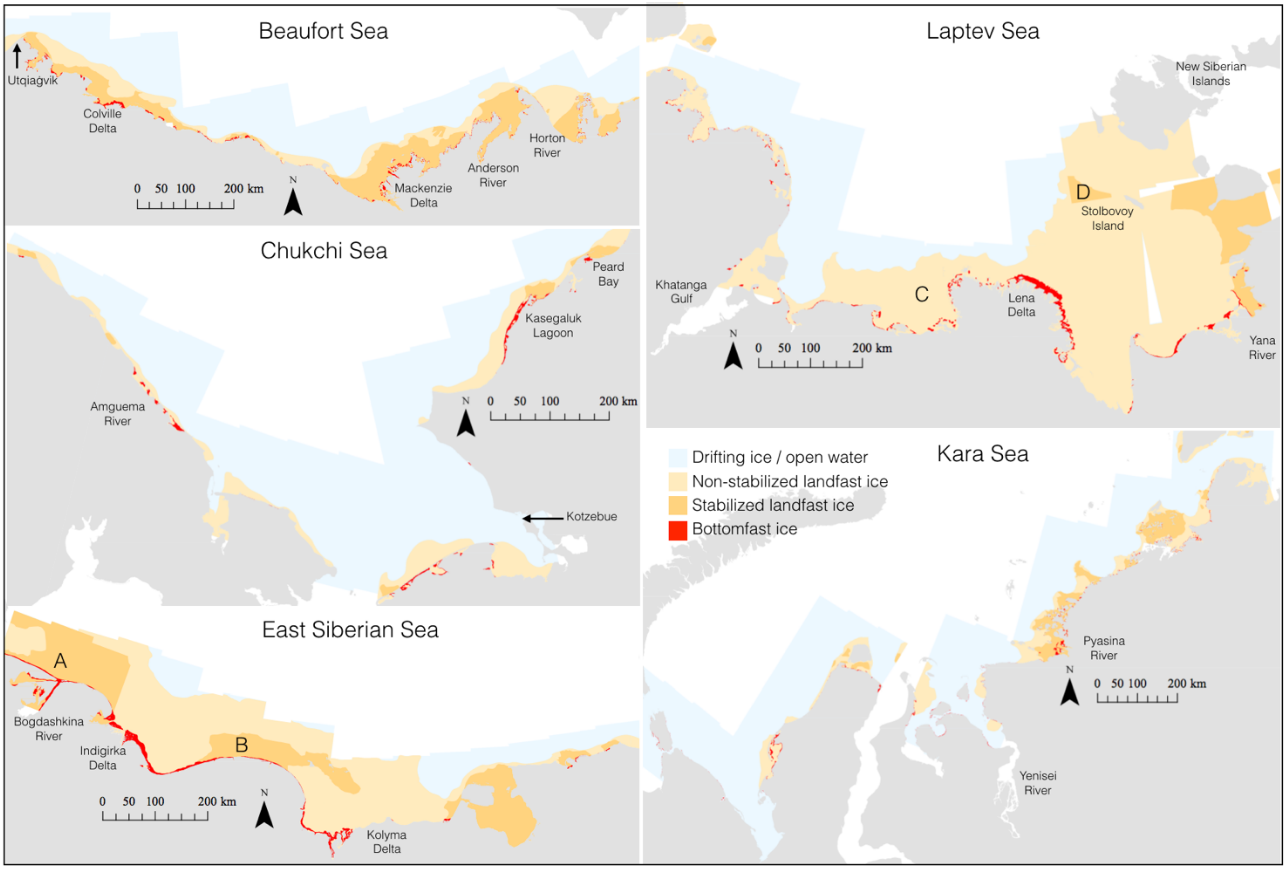
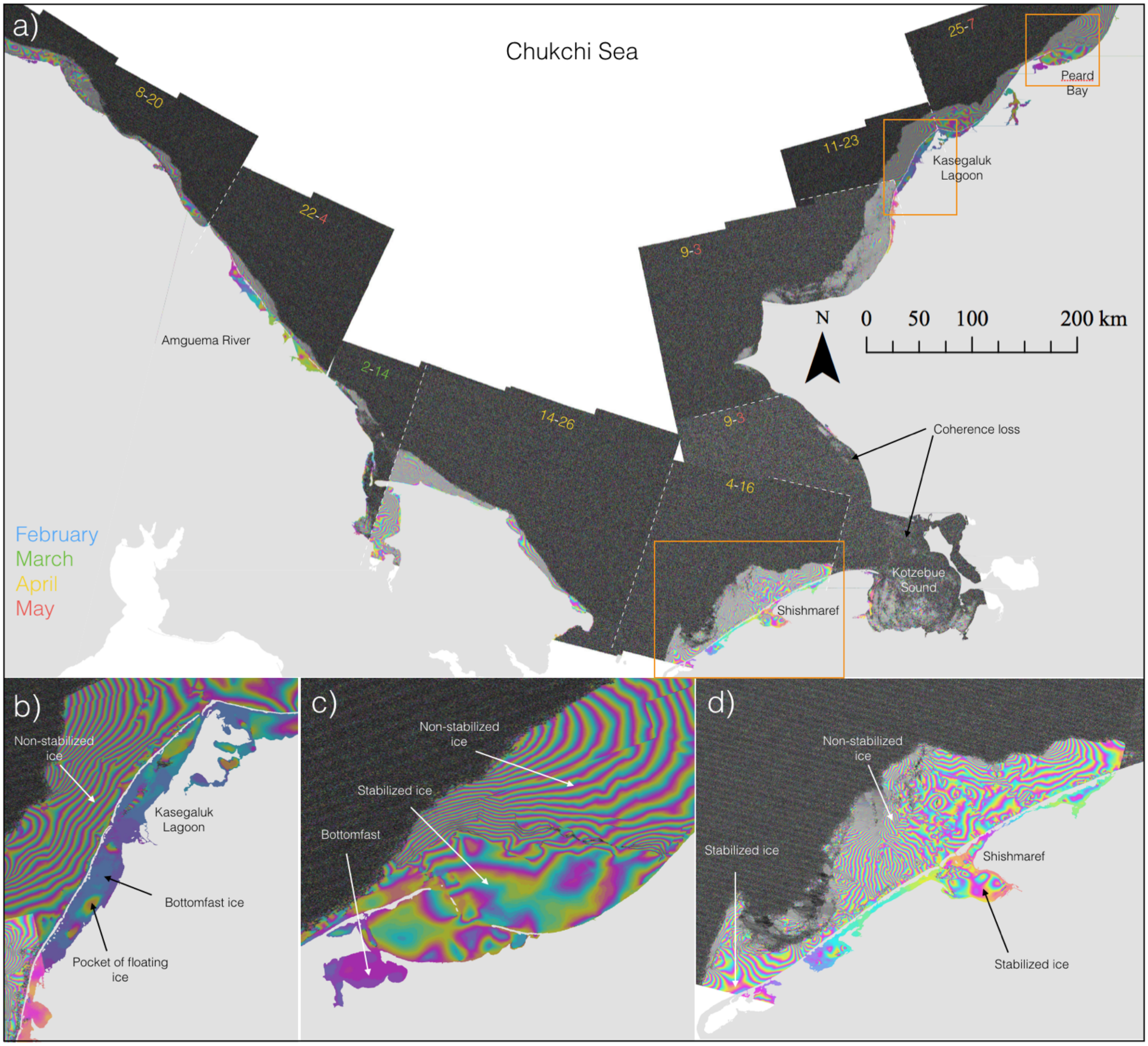


Figure 4: (a) Sentinel-1 interferograms derived from image pairs acquired over the Beaufort Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May respectively. (b)-(d) represent three enlarged areas identified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


Beaufort Sea
Utqiagvik
Colville
Delta
Horton
River
Anderson
River
Mackenzie
Delta
0 50 100 200 km
N
Chukchi Sea
Peard
Bay
Kasegaluk
Lagoon
Amguema
River
0 50 100 200 km
N
Kotzebue
East Siberian Sea
A
Bogdashkina
River
Indigirka
Delta
B
0 50 100 200 km
N
Kolyma
Delta
Laptev Sea
New Siberian
Islands
D
Stolbovoy
Island
Khatanga
Gulf
C
Lena
Delta
Yana
River
0 50 100 200 km
N
Drifting ice / open water
Non-stabilized landfast ice
Stabilized landfast ice
Bottomfast ice
Kara Sea
Pyasina
River
N
0 50 100 200 km
Yenisei
River



5 **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 enlarged areas identified in (a) further discussed in the text.**

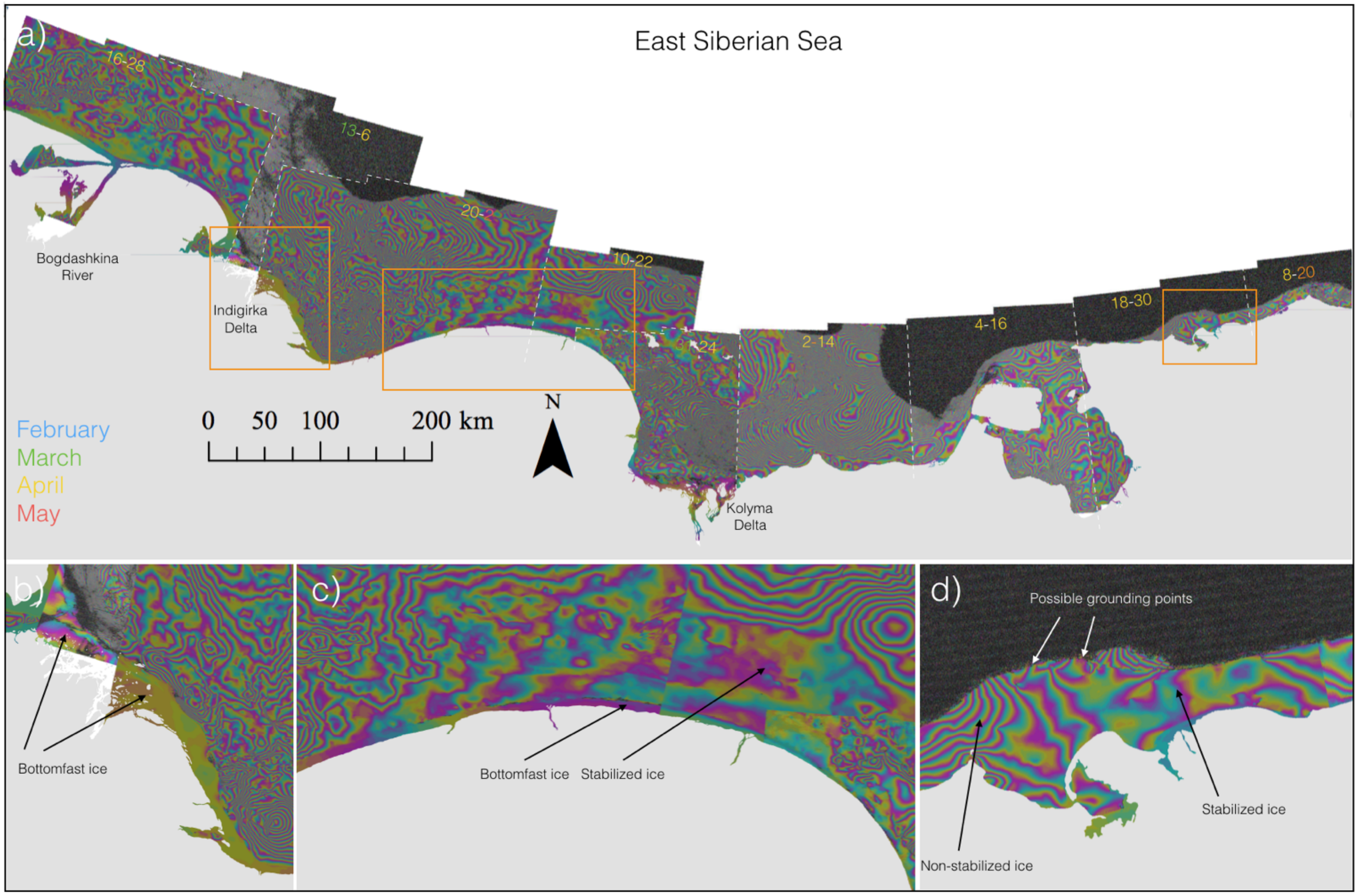


Figure 6: (a) Sentinel-1 interferograms derived from image pairs acquired over the East Siberian Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May respectively. (b)-(d) represent three enlarged areas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

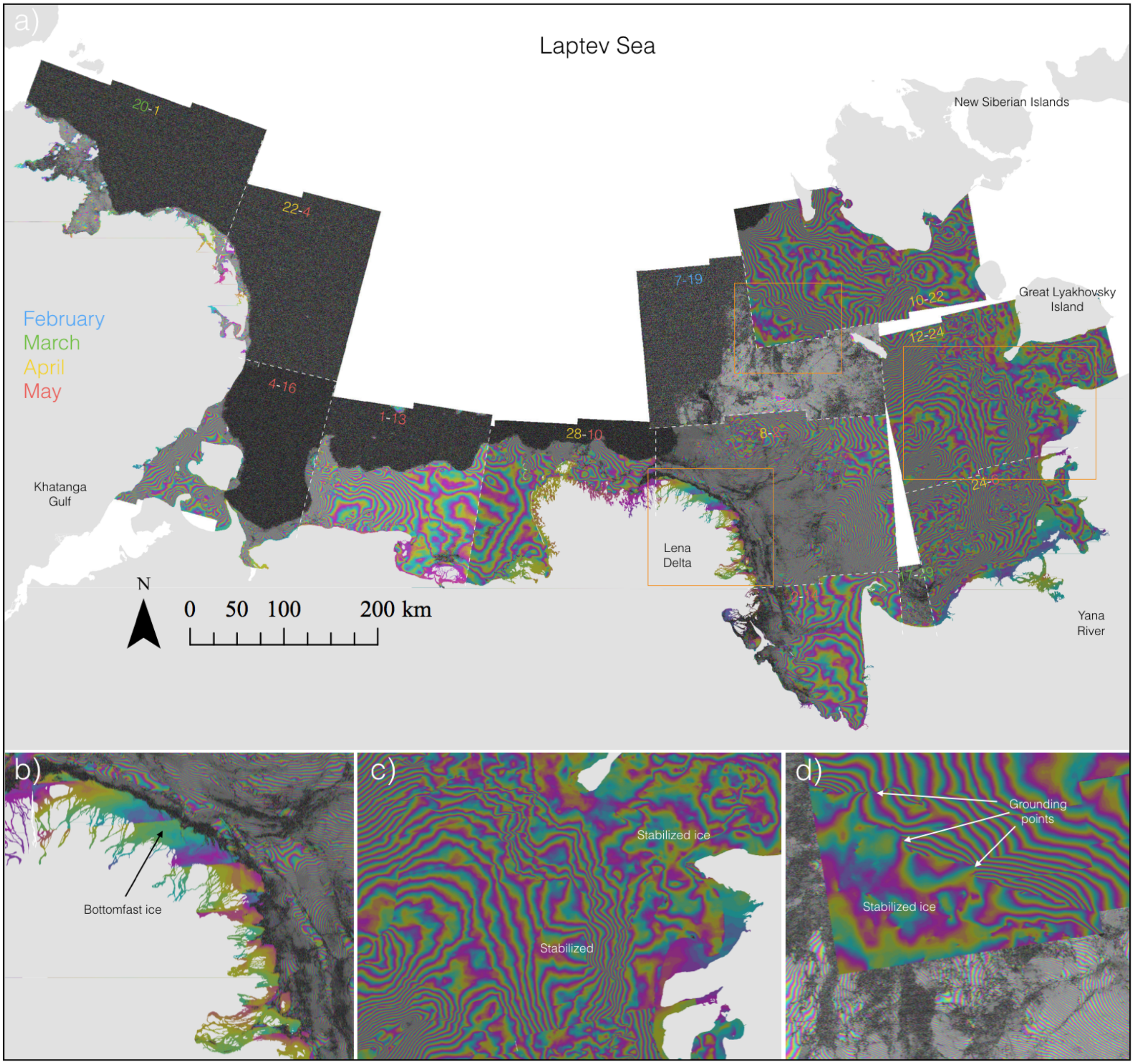


Figure 7: (a) Sentinel-1 interferograms derived from image pairs acquired over the Laptev Sea between February and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May respectively. (b)-(d) represent three enlarged areas identified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

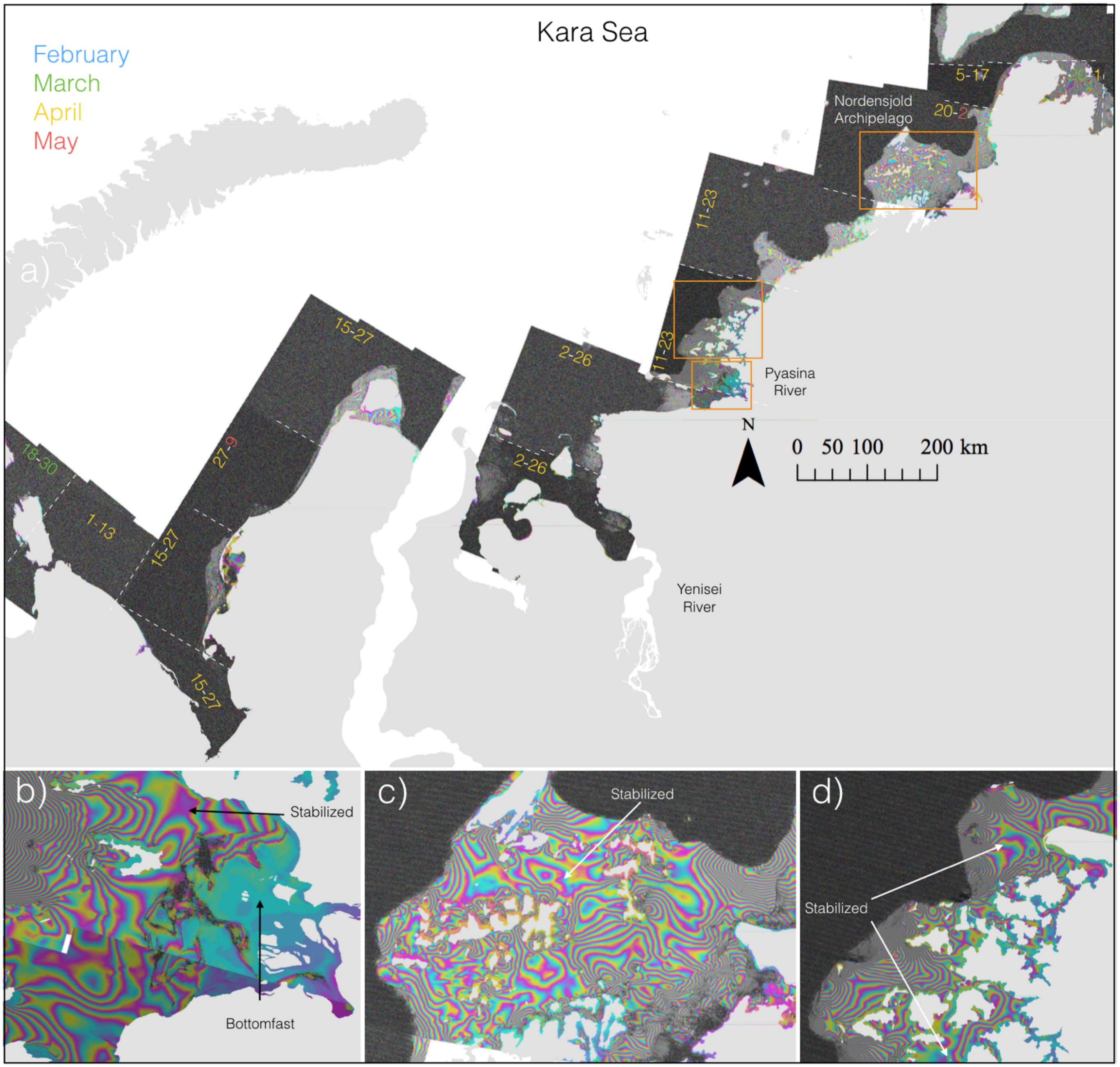


Figure 8: (a) Sentinel-1 interferograms derived from image pairs acquired over the Kara Sea between March and May, 2017. Numbers on images represent date ranges where the colors blue, green, yellow, and red signify the months of February-May respectively. (b)-(d) represent three enlarged areas identified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

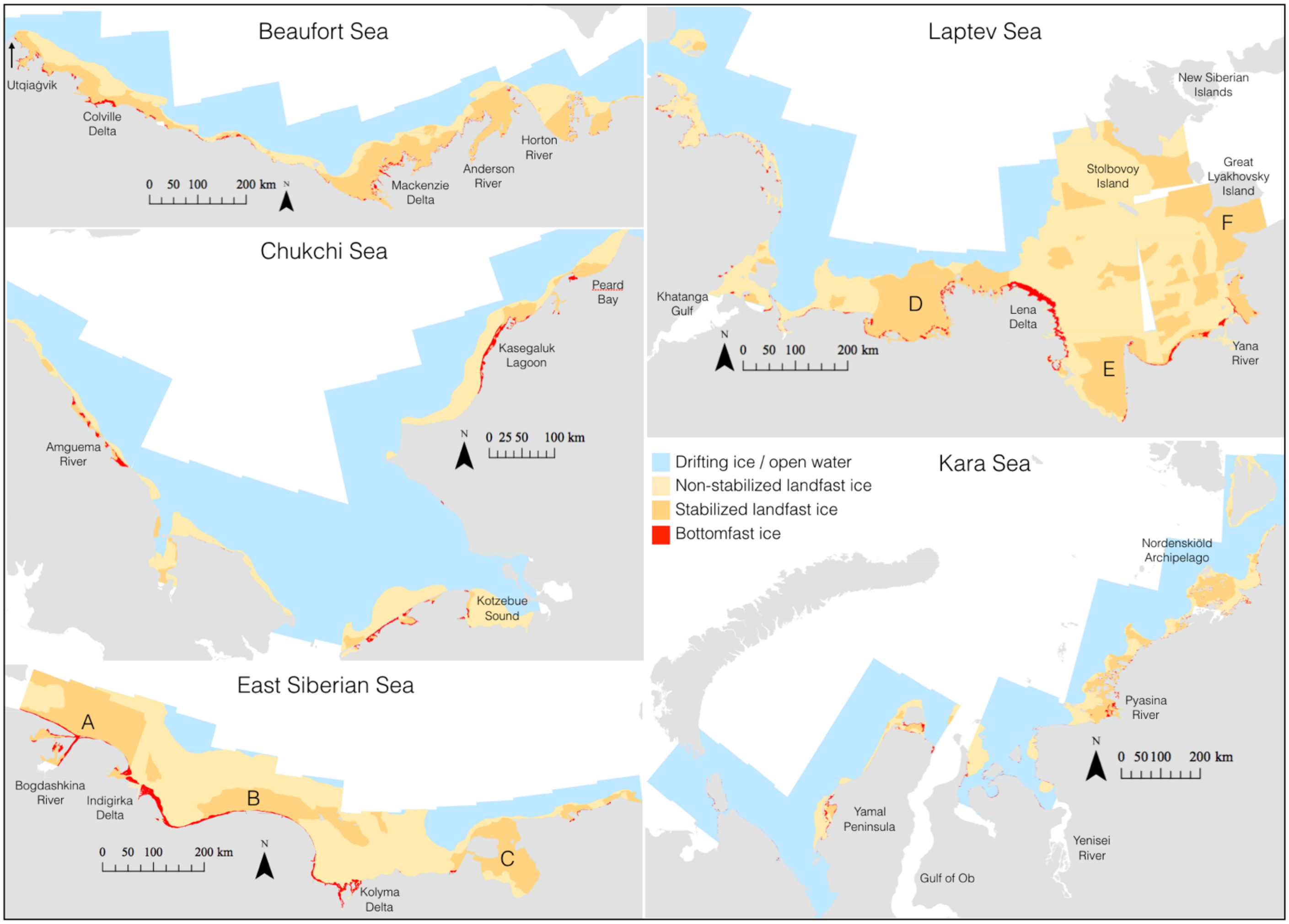


Figure 9: InSAR-derived map of non-~~stabilize~~stabilized and stabilized landfast ice and bottomfast ice from ~~52~~ Sentinel-1 image pairs acquired predominately between March and May, 2017. Letters "A-~~D~~"-"G" mark areas discussed in the text. Land is masked out in light grey. ~~Due~~This map of stability zones is subject to ~~minor inaccuracies~~limitations and uncertainties outlined in the ~~landmask,~~text.

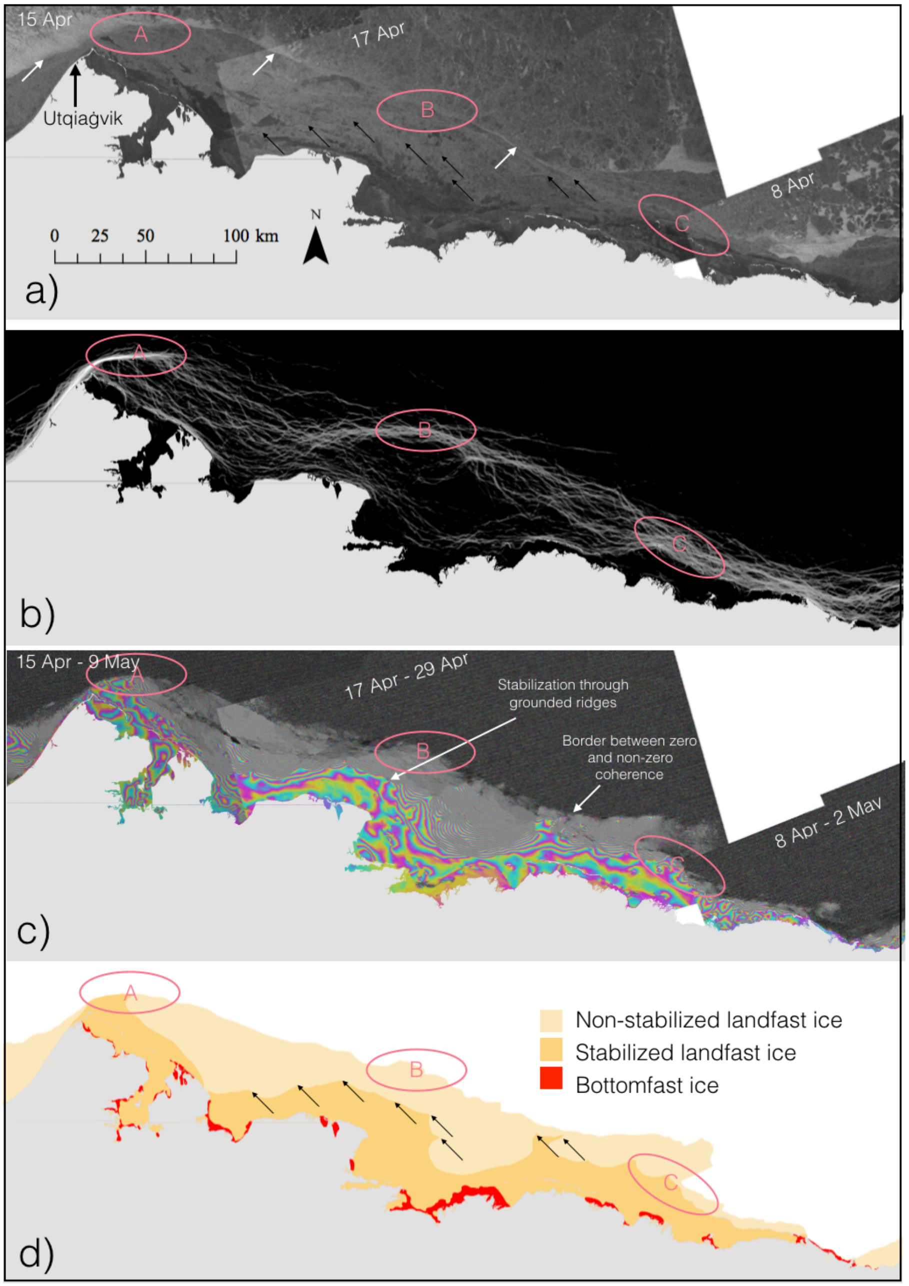
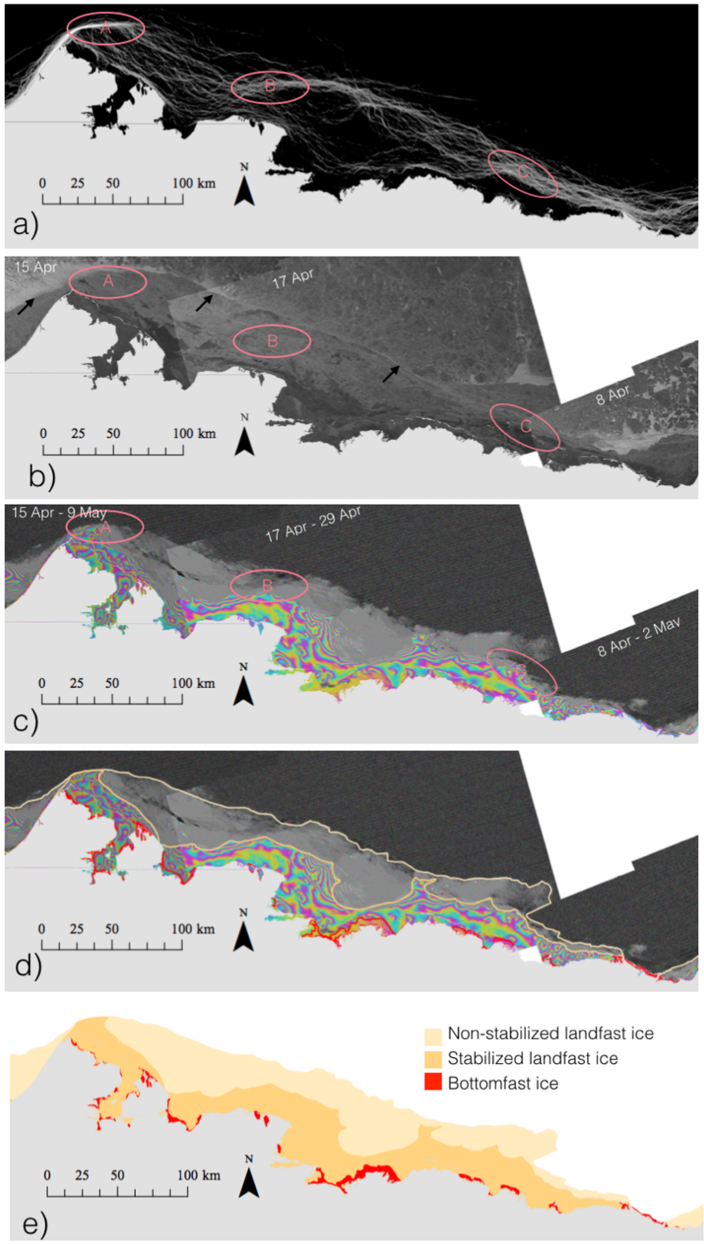
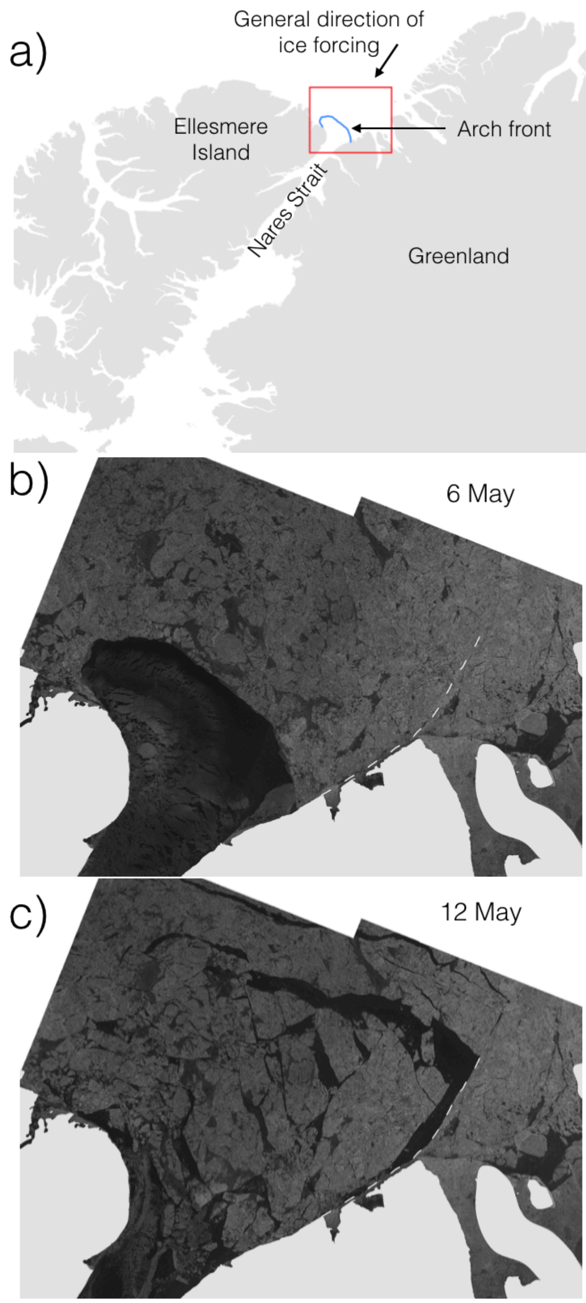


Figure 10: Sentinel-1 backscatter images over the ~~occurrence of bottomfast~~western Beaufort Sea. White arrows signify the landfast ice ~~can appear sporadic.~~



~~Figure 5: (a) Landfast~~edge as identified by contrasting backscatter. (b) 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 "~~noeds. (b) and~~nodes. (c) ~~Sentinel-1 backscatter images and~~ interferograms ~~of landfast ice~~ between mid April and mid May 2017~~,~~. (d) ~~map of landfast ice, grounded landfast ice, and bottomfast ice superimposed on the interferograms, and (e)~~ different ~~landfast ice regimes~~stability zones derived from ~~the interferograms.~~ (c). Potential grounding points as identified in (d) are marked with black arrows in (d) and (a). Land is masked out in light gray.


a)
General direction of ice forcing
Arch front
Ellesmere Island
Nares Strait
Greenland
b)
6 May
c)
12 May

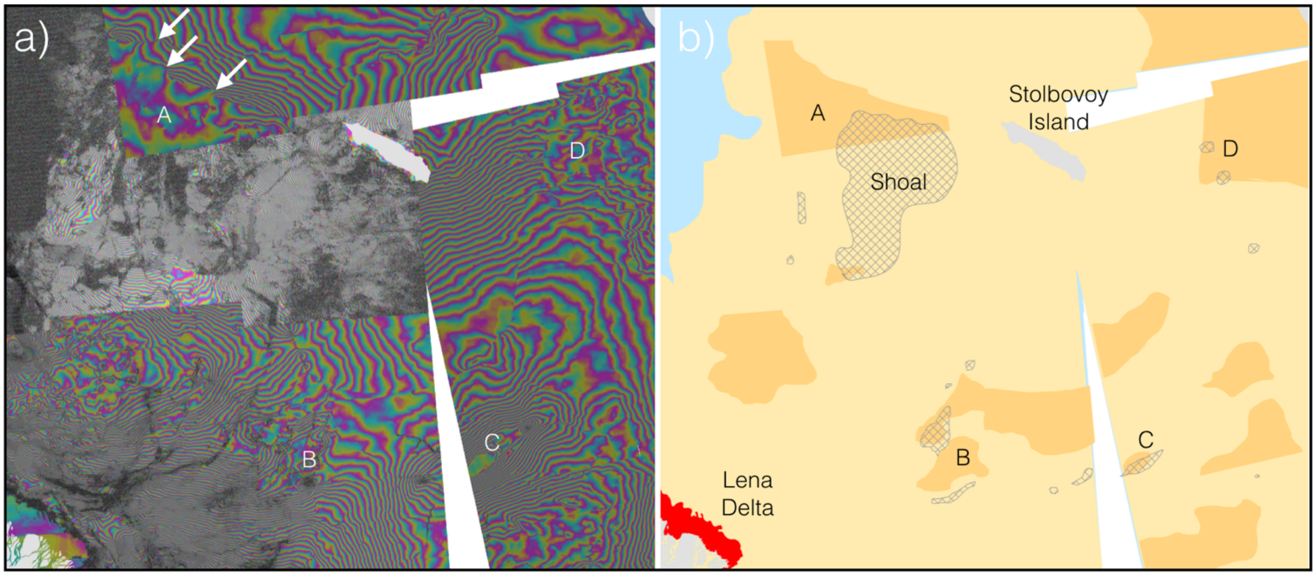


Figure ~~6~~11: (a) ~~overview~~Sentinel-1 interferograms over Laptev Sea near Stolbovoy Island between February and May 2017. (b) outlined non-stabilized (light orange) and stabilized (dark orange) ice. Shallow areas (< 10 m) (Jakobsson et al., 2012) are marked with gray cross hatching. Stabilized ice 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.

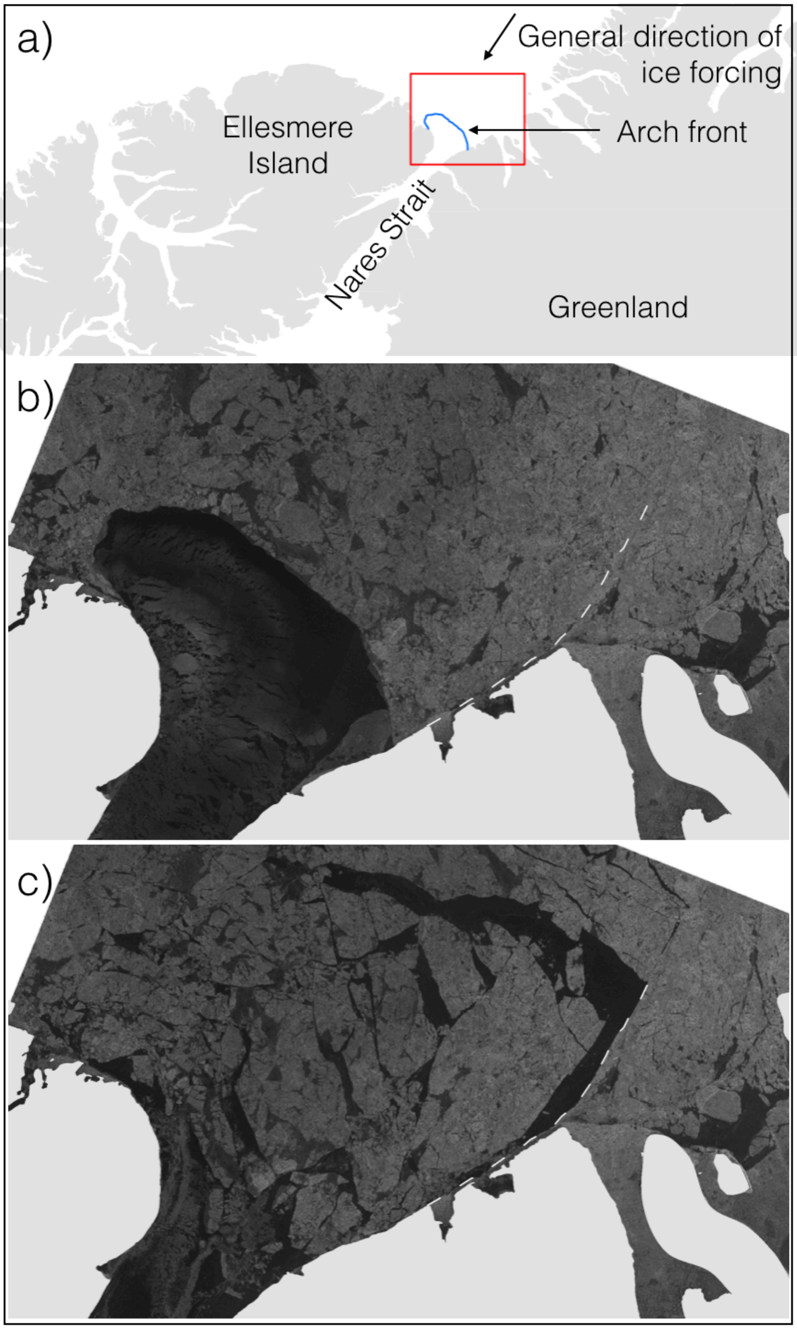
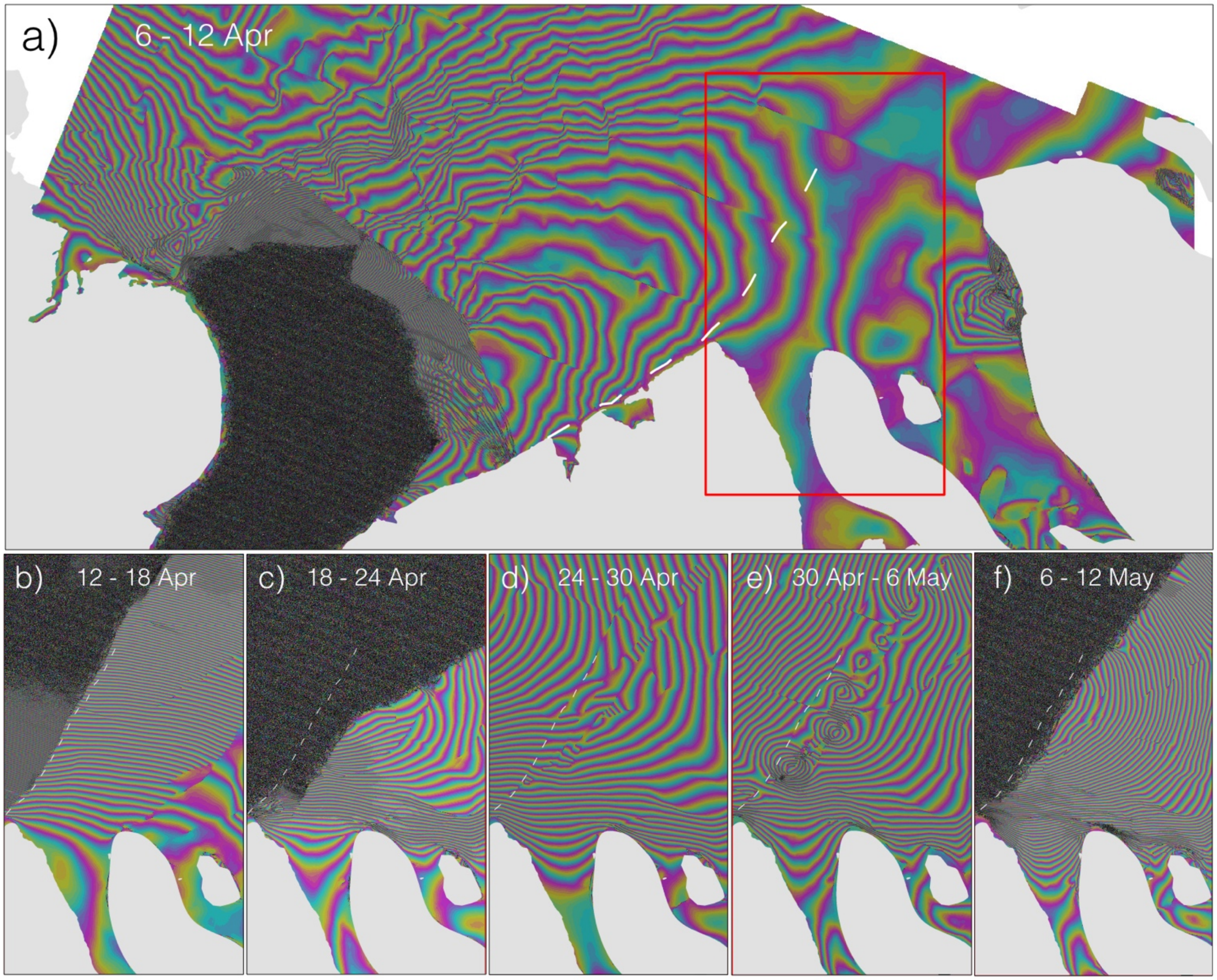


Figure 12: Map of Nares Strait ~~and location, location of Sentinel-1 imagery (red rectangle), and delineation of the arch (blue line) as obtained from (b). Backscatter~~(a), and Sentinel-1 backscatter images over the 2017 ice arch (blue line in a) before (b) and after (c) failure. The line of failure is identified in ~~Figure 6b~~(c) and marked as a dashed line in both (b) and (c). Land is masked out in light gray.


a)
6 - 12 Apr
b)
12 - 18 Apr
c)
18 - 24 Apr
d)
24 - 30 Apr
e)
30 Apr - 6 May
f)
6 - 12 May

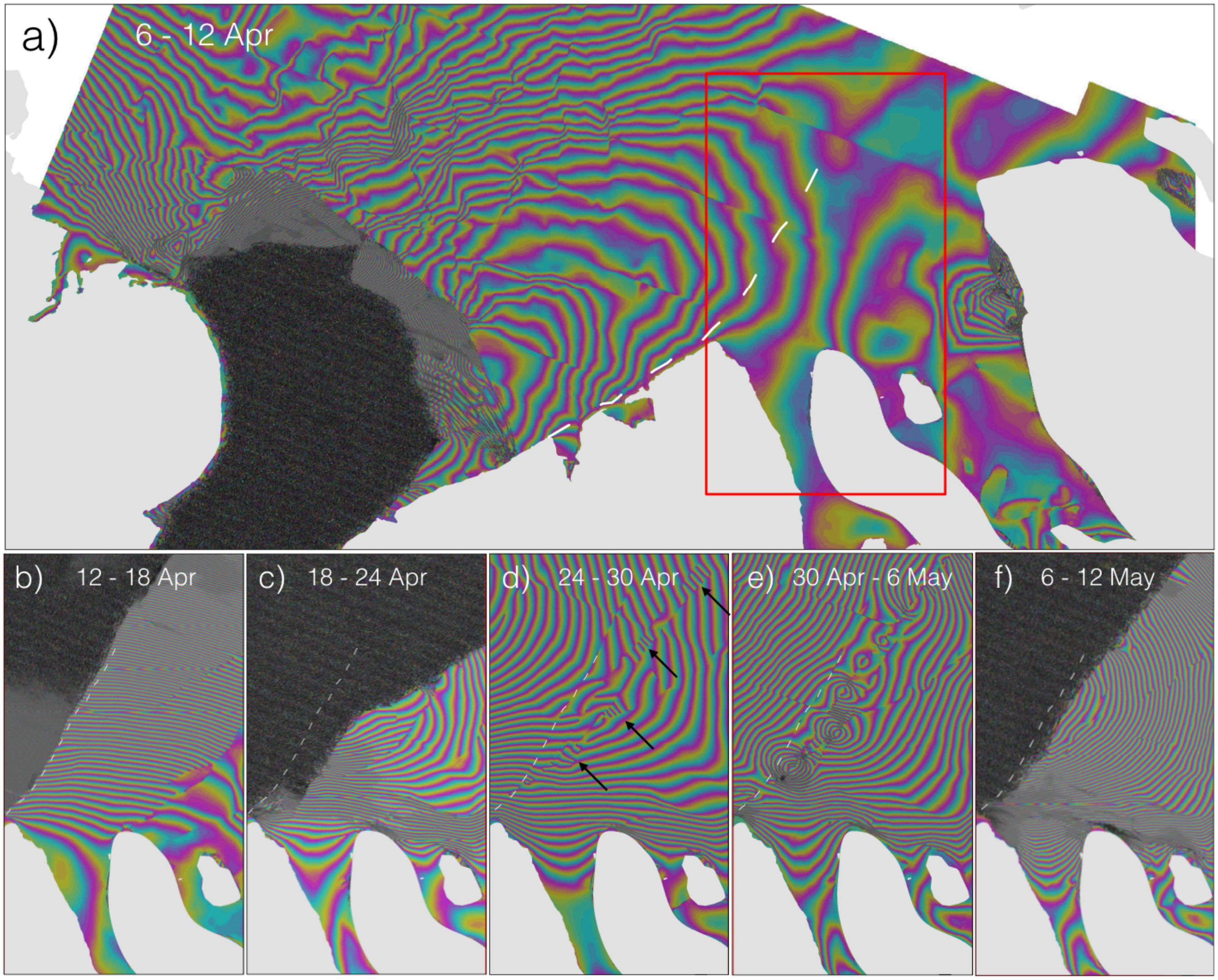


Figure ~~7~~13: Interferogram over the Nares Strait ice arch in 2017 covering the time period 6 - 12 Apr. (a). Smaller panels show consecutive interferograms within the box for 12 - 18 Apr (b), 18 - 24 Apr (c), 24 - 30 Apr (d), 30 Apr - 6 May (e), and 6 - 12 May (f). The dashed line represents the line separating the fast and moving ice in Figure ~~6b.~~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 ~~and typical deformation rates~~

	Landfast ice regime	Stability	Stability zone	Identified by	~~Deformation rate (cm/km/month)~~
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 ~~and subsides~~ as the ice thickens.	Bottomfast	No identifiable phase difference from the adjacent land	~~0~~
~~2~~	~~Floating ice sheltered in lagoons or fjords~~	~~High stability. Ice is largely enclosed by land and is sheltered from more dynamic ice. Deformation is dominated by cm- to dm-scale thermal creep and fracture.~~	~~Stabilized~~	~~Poorly defined, widely spaced fringes or abruptly reduced fringe spacing compared to offshore ice~~	~~~0.1 – ~1~~
~~3~~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	
~~4~~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 may remain attached (Mahoney et al., 2004) or can break-off from the stabilized ice.	Non-stabilized	Well defined fringe orientation or patterns	~~< ~100~~

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

Area	Bottomfast ~~ice~~	Stabilized	Non-stabilized	Total area of landfast ice	~~Non~~Area fraction: non-stabilized / stabilized
Beaufort Sea	2.5	35	~~30~~29	~~65~~67	0.~~86~~83
Chukchi Sea	1.8	~~0.95~~4.6	~~27~~25	~~29~~31	~~28~~5.43
East Siberian Sea	5.1	~~40~~45	~~81~~80	~~126~~130	~~2.0~~1.78
Laptev Sea	4.1	~~33~~74	~~164~~127	~~201~~205	~~5.0~~1.72
Kara Sea	2.~~5~~6	16	~~38~~37	56	2.~~4~~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 ~~significant~~non-zero coherence and the bottomfast ice, stabilized ice, or the landmask.