To the editor,

As requested, modifications in the manuscript are listed in the following file. If more than one reviewer brought up a modification suggestion, it is stated only once in the list of modifications.

Point by point answers to each reviewer are available as the second section of this document, after the list of modifications.

Finally, a version of the manuscript where modified section are highlighted, is available as the last section of this document. Figures that were modified or added are surrounded by a red line in the file. Minor modifications and vocabulary changes have been made to the document according to the reviewers suggestions.

CG

LIST OF MODIFICATIONS

N.B. As suggested by many reviewers, all maps were rectified so the north points upward. This is the case for figures 1, 4 and 8.

REVIEWER #1

- **(LINES 94 to 111)** Details about the different ice regimes in the HBS were added to section "2. The Hudson Bay System".
- **(LINES 52 to 61)** We have modified text in order to make sure that readers are aware that other "probabilistic" products are available, though based on a different calculation approach.
- **(LINE 494)** The fact that IcePAC data are available on a web interface was added to the conclusion.

REVIEWER #2

- **(LINES 29 to 31)** The sentence was modified to put emphasis on the fact that effect of climate change is "stronger" in the Arctic and that this phenomenon, the "Arctic Amplification", is expected to strengthen in the decades to come.
- Figure 5 was modified to make sure every parameter presented in the flowchart was correctly identified.
- Figure 6 was modified to make sure its interpretation was easier for the readers.
- **(LINES 362 to 367)** Clear definitions of the freeze-up and melt-put events in the IcePAC model were added.

REVIEWER #3

- **(LINES 146 to 173)** Relevant information on the impact of land spillover, its definition and corrections mechanisms applied in the OSI-409 and OSI-430 products was added in section "3.1 Sea ice concentration dataset". Information on other potential error sources was also added in order to state all possible limitations of the input dataset.
- The original figure 3 was replaced by a figure presenting a time series for a costal site of the HBS on week 50 (i.e. freeze-up), its detected trend and the impact on the time series.
- **(LINES 221 to 238)** Maybe it wasn't correctly explained in the previous version of the paper that, even though the distribution model fit is made on detrended data (pure SIC% signal) the information on the trend is kept and reused during model queries to generate valid results. As such, we can say that the trend is "managed" in IcePAC. To make sure readers understood this essential information, we added a paragraph describing the way the trend is managed in IcePAC in section "3.2.3 Trend Estimation and Removal".
- We modified the Figure 5 (the model flowchart) in which we indicate where the trend is either removed or reinjected into the results depending on the query made.
- **(LINES 409 to 424)** Some details were added regarding the ice charts production at CIS in section "4.2 Comparison with the Canadian Ice Service Atlas".

REVIEWER #4

- **(LINES 344 to 346)** The error observed at Frobisher Bay does not appear at other coastal locations since the OSI409 and 430 algorithms used a coastal correction approach that we described in the manuscript. The OFB error is caused by a combination of two factors. First, we did identify an error, specific to Frobisher Bay area and west Southampton Island (Roes Welcome Sound) in a NSIDC climatological mask that the OSI-409 algorithm uses to ensure that no ice is detected in area where it is not likely to appear. The mask falsely declares that ice presence in these two areas is plausible during all summer months. Given the fact that the climatology mask states that there is possibly ice in Frobisher Bay at that date, the algorithm attempts to measure it, with erroneous results.

- **(LINES 458 to 467)** A new section addressing the applicability of IcePAC outside the HBS was added as section 4.3 "Applicability of the IcePAC approach to other location and data sources"

REVIEWER #5

- **(LINES 44 to 51) – (LINES 62 to 67)** Information on the choice of passive microwave and discussion about potential applications of the tool has been added in the Introduction.
- **(LINES 173 to 177)** A short paragraph outlining the divergences of passive microwave estimated SIE (extent) versus the CIS maps estimated SIE has been added.
- We added two comparison sites in the revised version of this manuscript: Offshore Northern Ungava Bay (ONUB) at the entrance of the Hudson Strait and Coastal Hall Beach (CHB) in the northwestern part of Foxe Basin. The ONUB location was selected because of its strategic position in the navigation corridor in the Hudson Strait while the CHB location was added to represent the particular ice regime in the Foxe Basin.
    - **Given this addition of two new sites :**
        - Figure 1 was modified.
        - Description of site selection was modified **(LINES 308 to 312)**
        - Analysis of sea ice spatiotemporal evolution was modified to take into account the new locations **(LINES 319 to 331)**
        - New analysis was added regarding Hall Beach polynya **(LINES 428 to 448)**
        - Figure 9 was modified to include Hall Beach as a community of the HBS
        - Figure 10 was added to present the specificity of Hall Beach spatiotemporal dynamic and its detectability in IcePAC outputs
- **(LINES 487 to 492)** We did add information regarding possible applications of IcePAC to engineering, fauna protection, navigation in the Conclusion.

ICEPAC – A PROBABILISTIC TOOL TO STUDY SEA ICE SPATIOTEMPORAL DYNAMIC: APPLICATION TO THE HUDSON BAY

ANSWERS TO REVIEWER #1

Reviewer #1,

We thank you very much for your valuable and helpful comments on our work. We made all suggested modifications to our manuscript.

CG

R = Reviewer comments **A** = Author response and **B** = Manuscript modifications

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GENERAL COMMENTS

R: **In the introduction, I feel like the authors do not fully understand the area of interest. The ice conditions in the Foxe Basin/Hudson Bay areas are very different than the ones found in the Hudson Strait. Studying some products available like the ones on the CIS website would be useful to better understand the ice conditions in the AOI.**

A: Details about the different ice regimes in the HBS were added to section “2.The Hudson Bay System”. Also, an additional site (Hall Beach) was added to the analysis to outline the specific difference in sea ice concentration behaviors between Foxe Basin and the rest of the HBS.

B: New content about sea ice, trends and polynyas in the HBS were added.

R: **I feel like the authors need to tone down the language when saying that this is a completely new approach. There are many studies that have used very similar approaches in the past in other AOIs. A more thorough literature review might be needed. The method and the validation of the data and results are thorough here and this is not always clear in other studies. This is a strength, in my opinion, of this study**

A: As you rightfully suggest, other studies have brought a probabilistic perspective on the behavior of sea ice concentrations. However, to our knowledge, all of the studies we have identified as “probability modeling” approaches of sea ice concentrations were based on a “classical” probability calculation. They were using the common approach to probability calculation, consisting of measuring the number of occurrences of a specific situation (for example 40% SIC or more) over the total number of observations.

Therefore, none were basing their probability estimates on the “underlying distributions” as we do. This is why we were stating that our approach was an innovation.

B: We have modified our sentence in order to make sure that readers are aware that other “probabilistic” products are available, though based on a different approach.

R: **I understand that the different ice products are scattered everywhere on the web and there are many (probably too much to cite them all). I would be careful to say that no similar products exists. Many products exists, not necessarily in the same format and many are not necessarily accessible to the public but the outputs can be seen in different products of National Ice Services (Canadian, US, Finnish, Danish, etc.). If IcePAC is planned to be accessible to the public, I would underline it since it will be of great use to many. I would tone down the language on this topic as well.**

A: We have made sure to underline the fact that the IcePAC approach was based on the frequency analysis method at a weekly pace. We have outlined that other sea ice products, based on the “classical” approach (as described in the previous remarks) were already providing probabilistic information on sea ice. Nevertheless, most of the probabilistic products available provide information on the “sea ice presence” probability, not the concentration. Introduction was reformulated to ensure that readers understood that national ice services and others were also providing probabilistic information on sea ice. As you suggested, the fact that IcePAC data are available on a web interface was added to the conclusion.

MINOR COMMENTS

All suggested corrections in the PDF file were applied to the manuscript.

ICEPAC – A PROBABILISTIC TOOL TO STUDY SEA ICE SPATIOTEMPORAL DYNAMIC: APPLICATION TO THE HUDSON BAY

ANSWERS TO REVIEWER #2

Reviewer #2,

We thank you very much for your valuable and helpful comments on our work. We made all suggested modifications to our manuscript.   CG

R = Reviewer comments   **A** = Author response and **B** = Manuscript modifications

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GENERAL COMMENTS

R: **I agree with the comments from Referee #1 that the use of "meltdown" throughout the text and figures should be changed to "melt".**

A: The terminology was modified throughout the manuscript.

R: **This sentence should be revised. "raise" should be "increase" or similar. Clarify if the Arctic has warmed or will warm by 2 deg. C. Apprehend is not the best word choice in this sentence. "…will tend to amplify" Are you suggesting the process of Arctic Amplification here? More background detail on the physical processes is needed to make this connection.**

A: The sentence was modified to put emphasis on the fact that effect of climate change is "stronger" in the Arctic and that this phenomenon, the "Arctic Amplification", is expected to strengthen in the decades to come.

B: Modifications were made.

R: **The phrase "permit to analyze" implies that there are restrictions on how the data may be used. Probability analyses may not be readily available to users, but this does not mean that they could not be produced. I suggest revising this sentence.**

A: Other reviewers suggested this modification too. Therefore we have changed the sentence formulation as suggested.

B: Modifications were made.

R: **Cryogenic cycle isn't the right phrasing here. I suggest changing to seasonal sea ice cycle or similar.**

A: The terminology was modified throughout the manuscript.

R: **These are competing ideas. If complete freeze-up occurs in late December, why is the annual maximum extent in April? This needs to be clarified.**

A: We agree with your comment.

B: This sentence was reformulated to make things clearer.

R: **Markus et al. (2009) is not a study of sea ice extent. It should not be cited here. Also, Cavalieri and Parkinson (2012) is an update of the data examined in Parkinson and Cavalieri (2002, 2008) and Parkinson et al. (1999). Citing just the 2012 paper is sufficient.**

A: As suggested, only the (Cavalieri and Parkinson 2012) paper was kept as a reference.

R: **Figure 2: Adding some more description of the different panels in the figure caption would be helpful since the later steps of the process have not yet been described in text.**

A: Description of the steps was added to the Figure 2 caption.

R: **Figure 5: "C%det" is not explicitly defined in text or the figure. Is this the same as SICdet? Define the notation in the figure caption or text.**

A: Figure 5 was modified to make sure every parameter presented in the flowchart was correctly identified.

R: **Expand the acronym for NSIDC the first time it is used. Also, the content of the webpage listed changes frequently. A specific link to the anomaly maps that were compared with the author's data needs to be provided.**

A: The NSIDC acronym is now defined the first time it is used in the text.

B: The definition is given in the manuscript.

R: **Figure 6: I agree with Referee #1, I think a regular scatter plot would better show the spread in the probability curves for each site and take less time for readers to interpret**

A: Figure 6 was modified to make sure its interpretation was easier for the readers.

B: Interpretation was provided in the text.

R: **After what inquiry? Is this personal communication? With whom? (About the OFB site showing incoherent sea ice concentration behavior)**

A: Using the term "inquiry" was maybe not appropriate here. The term was literally translated from French and was not necessary in the context. Therefore, it was removed.

R: **Figure 7: The MODIS data need to be properly cited.**

A: Done.

R: **It is important to note that SIC thresholds to define sea ice retreat (advance) should be used only after the annual SIE maximum (minimum). For example, the first week that SIC is above 15% at a given pixel during a calendar year would likely be in week 1, not during autumn freeze-up. What time constraints were applied to the data to define the likely freeze-up or melting periods?**

A: Queries for the freeze-up events were from week 44 (September 1st) and up and those for melt events were made from week 14 (April 1st) and up. Both events were to be sustained for at least 3 consecutive weeks to be considered valid. These details were added to the manuscript in section "4.1 Analysis with the IcePAC tool".

B: The modifications were made.

TECHNICAL CORRECTIONS

All technical corrections were done to the manuscript.

ICEPAC – A PROBABILISTIC TOOL TO STUDY SEA ICE SPATIOTEMPORAL DYNAMIC: APPLICATION TO THE HUDSON BAY

ANSWERS TO REVIEWER #3

Reviewer #3,

We thank you very much for your valuable and helpful comments on our work. As suggested, more details were added regarding the importance of the trend in our procedure. Many sentences and words were rephrased in order to improve the overall quality and comprehensibility of the manuscript. All maps orientations were modified as suggested.

CG

R = Reviewer comments **A** = Author response and **B** = manuscript modifications

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GENERAL COMMENTS

R: **“My main question/concern is the effect of trends on the effectiveness of the tool. The authors note that the trend must be subtracted for the stationarity condition to be met, which is necessary for the frequency modeling approach. However, it seems to me the trend is quite relevant in terms of using the method as a forecast tool. If there is a trend towards a longer ice-free period (as there is in the Hudson Bay region), it seems a forecast that doesn’t account for that, will gradually become less and less effective? Perhaps I’m missing something here. I can understand that frequency modeling requires removal of the trend, but does that make such a method less effective in an environment with a strong trend? I think bit more discussion on this would be helpful.”**

A: You are right to say that the model cannot render significant predictions without taking into account the trend. Maybe it wasn’t correctly explained in the previous version of the paper that, even though the distribution model fit is made on detrended data (pure SIC% signal) the information on the trend is kept and reused during model queries to generate valid results. As such, we can say that the trend is “managed” in IcePAC.

B: To make sure readers understood this essential information, we added a paragraph describing the way the trend is managed in IcePAC in section “3.2.3 Trend Estimation and Removal”. We also modified the Figure 5 (the model flowchart) in which we indicate where the trend is either removed or reinjected into the results depending on the query made.

R: "In the discussion on the CIS analyses, I think it's important that other potential limitations of these are that (1) their input data are not always consistent, (2) they use human interpretation of imagery. These mean that the analyses are somewhat subjective and may be inconsistent. For CIS, they've been using SAR for the Canadian region, so consistency is less of an issue than perhaps for other ice services, but still worth noting I think."

A: We agree with your comment.

B: Some details were added regarding the ice charts production at CIS in the "Introduction" but mostly in section "4.2 Comparison with the Canadian Ice Service Atlas".

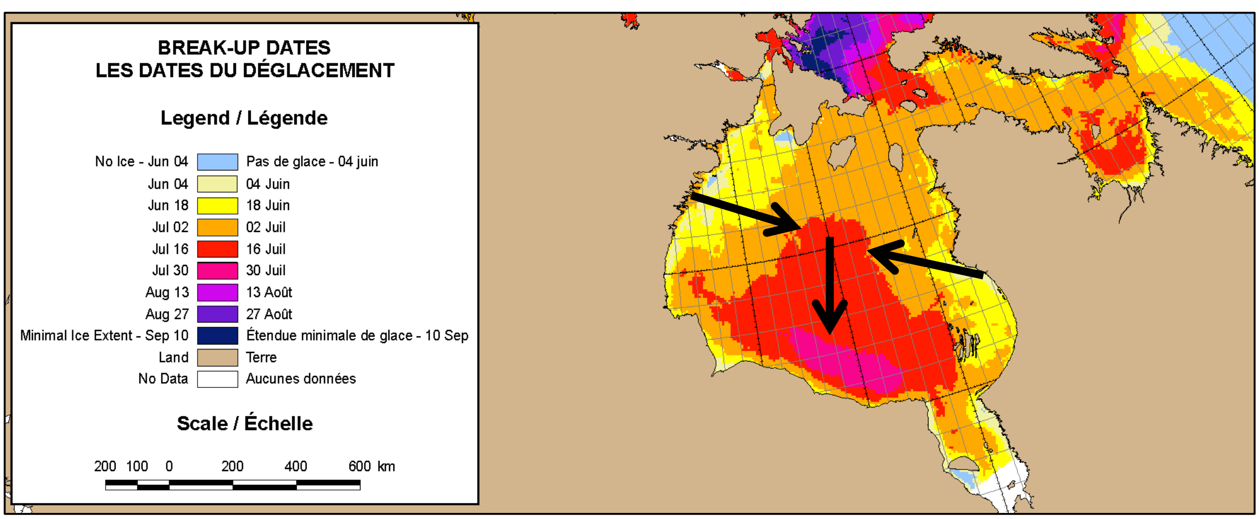
R: "You say complete freeze-up happens in late December, but then say the annual maximum is usually achieved in April. But isn't the maximum reached when complete freeze-up occurs? I think you mean that complete freeze-up happens in late December and the HBS remains fully frozen through April."

A: We agree with your comment.

B: This sentence was reformulated to make things clearer.

R: "meltdown is driven from the shores to the center of the bay… – this isn't quite true though. As shown in Figure 8, the SW Ontario shore is the latest to melt out, so it's more of a NE to SW melt out pattern, right?"

A: Figure 8 (IcePAC outputs), as well as CIS analysis (see image below: taken from https://iceweb1.cis.ec.gc.ca/30Atlas/page1.xhtml?lang=env), show that sea ice starts melting along the east and west shores of the Hudson Bay and gradually melt toward the center part of the Bay, culminating in the end, to a final melt in the southcentral part of the Bay, in front of Winisk (as explained in Figure 9). If the ice melt started only from the east coast of the Hudson Bay, we would have agreed to say that it was a NE to SW pattern but since the melt gradually evolves from both sides of the Bay, we've kept our formulation as it was in the previous version.



R: **“Also, I’d say “the predefined area is commonly represented by a pixel. (As a nit-picky thing, for data fields, I think “grid cell” is better than “pixel”, which technically refers to an image, but I guess this is a matter of personal taste.)”**

A: For the “pixel” versus “grid cell” terminology, other reviewers have also brought that point.

B: Terminology was modified accordingly.

R: **“OSI-430 is simply a near-real-time version of OSI-409, isn’t it? The algorithm is the same and the input data is very similar. So, I don’t think it qualifies as an independent data source.”**

A: The sentence was modified to simply clarify the fact that OSI-430 wasn’t used as an input to estimate the parameters of the distribution models.

B: Information on the OSI-430 dataset has been added to the "Data and Methods/Sea Ice Concentration dataset" section.

R: **“sea ice dynamics”. You don’t mean “dynamics” in terms of dynamical forcing of ice motion, do you? I think you mean something more like “regime”. But I’m not sure. If it’s not related to forcing or motion, then you shouldn’t use “dynamics” here.**

A: Terminology has been modified in the text to make sure there is no confusion.

B: Now we are using the expression "sea ice spatiotemporal pattern" or behavior.

R: **The anomaly maps from NSIDC are actually part of the NSIDC Sea Ice Index (though they’re used on the News and Analysis website). Suggest referencing the Sea Ice Index, https://nsidc.org/data/seaice_index/. Fetterer, F., K. Knowles, W. Meier, M. Savoie, and A. K. Windnagel. 2017, updated daily. Sea Ice Index, Version 3. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5K072F8.**

A: This was added to our references list.

R: **I don’t totally understand what Figure 6 is showing. I think it needs more explanation, either in the text and/or in the caption**

A: Other reviewers suggested that Figure 6 should be modified to be easier to interpret. A new version of the Figure was then produced and therefore our discussion links to Figure 6 was slightly modified.

B: Explanations were provided in the text.

R: **As I was reading this, I was wondering about land-spillover. It’s good that it’s noted, but I think it deserves more discussion. Readers may not understand what land spillover is. And it’s not clear what the impact is on your results. With a relatively small area and a lot of coastline, I can see where it may have an impact. Of course, much of the effect is filtered out (which should also be mentioned), but whatever remains may have an impact.**

A: Relevant information on the impact of land spillover, its definition and corrections mechanisms applied in the OSI-409 and OSI-430 products was added in section “3.1 Sea ice concentration dataset”. As it turns out, the error at the OFB point was linked with an error in the NSIDC monthly climatological mask of sea ice extent used in the OSI-409 algorithm. The mask was indicating that, during all summer months, there is a possibility that sea ice would be present in Frobisher Bay (an identical situation appears in Roes Welcome Sound). Therefore, the OSI-409 algorithm was processed in the area and was affected by the land spillover effect as there was absolutely no ice in the Bay.

B: Explanations on the errors occurring in the IcePAC results were added. More details on the land-spillover and its correction in OSI-409 were added.

R: **Speaking of "dynamics" (as noted above), I wonder what the effect of motion will be on your statistics. You use "first week" to define melt-out and freeze-up, which is fine. But it is possible to have a pixel melt-out and then ice drift into the cell from a neighboring pixel; and similarly, could have a pixel freeze-up and then advect away, leaving open water again. I imagine this effect is small, but it's worth noting that the ice is not necessarily static.**

A: The effect of ice motion on our statistics is expected to be very small as we work with 30+ year time series for each grid cell and that they are weekly averages of 7 daily SIC% maps. As ice motion can be fast, especially for drifting ice during melt-out, we don't suspect such a phenomenon has an effect on our statistics. Also, considering the 12.5 km grid cell, the drifting ice floes would have to be numerous or very large to have an effect on the statistics.

R: **Maybe adding a figure (earlier in the paper, e.g., between Figures 3 and 4) showing an extent time series for the HBS and the trend would be helpful. This would show the magnitude of the trend and suggest the impacts of its removal.**

A: The original figure 3 was replaced by a figure presenting a time series for a costal site of the HBS on week 50 (i.e. freeze-up), its detected trend and the impact on the time series.

B: We have made a new figure 3 that presents such a series.

R: **Should note that the maps made by trained analysts are made from remote sensing imagery. This could also be noted earlier when the CIS analyses are first mentioned.**

A: We agree and made modifications according to your comment.

B: The information was added to the manuscript.

ICEPAC – A PROBABILISTIC TOOL TO STUDY SEA ICE SPATIOTEMPORAL DYNAMIC: APPLICATION TO THE HUDSON BAY

ANSWERS TO REVIEWER #4

Reviewer #4,

We thank you very much for your valuable and helpful comments on our work. As suggested, more details were added regarding the importance of trend removal and how it is handled in IcePAC. We made all the suggested modifications to our manuscript.

CG

R = Reviewer comments **A** = Author response and **B=** manuscript modifications

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GENERAL COMMENTS

R: **"Limitations of passive microwave sea ice concentration data for this sort of high temporal and spatial resolution probabilistic modeling should be stated. More details about the CIS product used and more background on the OSI-SAF sea ice concentration product are needed."**

A: Done.

B: Limitations of the passive microwave data for its usage in probabilistic modelling exercise were stated in section 3.1 "Sea Ice Concentration Dataset". The CIS products were described in more details in section 4.2 "Comparison with the Canadian Ice Service Atlas".

R: **"Would this tool be equally useful for locations outside the HBS?"**

A: Yes it would be.

B: A new section addressing this question was added as section 4.3 "Applicability of the IcePAC approach to other location and data sources"

R: **"More discussion is needed on trend removal, why it is necessary, how it changes the results. The addition of a simple figure showing a decade or so of the weekly SIC at one of the coastal locations would be good"**

A: We agree.

B: Numerous details about the trend removal process and its impact on the results and how it is managed in IcePAC were added. We also justified the fact that we use a systematic removal. A new figure (Figure 3) presenting an original coastal SIC% series and its de-trended version was added.

SPECIFIC COMMENTS

R: **“Nevertheless, these datasets do not carry information on the nature of the underlying statistical distributions of sea ice parameters, such as sea ice concentration (SIC), at any given point and nor do they permit to analyze the probability of occurrence of a specific sea ice condition.”**

A: We are not sure that we understand your comment. The ice services generally draw polygons around areas that are given attributes including a range of concentration values within the polygon, and usually more information like the form of predominant ice and its stage of development. Because the ice charts are not generally available as SIC in gridded form, it may be inconvenient to use them for obtaining statistical distributions of SIC, but it is not impossible.

The confusion could come from the last part of the sentence from the previous version of our manuscript “[…] *and nor do they permit to analyze the probability of occurrence of a specific sea ice condition*”. We agree that others sources, such as the NSIDC dataset, would be relevant to analyze the probability of occurrence of specific sea ice conditions. We did not want to suggest that it was not the case in our phrasing.

B: We modified this paragraph to make clear that the IcePAC product is different from existing products as it is based on a “description” of the underlying distribution (Beta in our case) of the SIC% for every grid cell in the HBS domain.

R: **“Sea ice extent has displayed an important decline […] as it can be observed with remote sensing images acquired since 1978.” Suggest changing to “as is observed with passive microwave remote sensing data acquired since 1978.” This because there was passive microwave before 1978, as well as VIS and IR, so the sentence can be misleading as it is.**

A: We agree.

B: The sentence was modified accordingly.

R: **“While the SIC data may have a 12.5 km grid cell size, I think it’s erroneous to say it has a 12.5 km resolution. I am not familiar with the OSI-409 SIC data, but if it uses SSMI(S) instrument data and Bootstrap algorithm, it is using the 19GHz channel which has an elliptical spot size of as large as about 75km in one dimension. It could be that the OSI-409 processing includes some measure to improve the effective resolution. Please add more information about how the algorithm improves effective resolution, if this is what it does, and information on the accuracy estimates for the algorithm SIC values.”**

A: We agree that we used erroneously the word resolution, it is the pixel grid.

B: A new paragraph was added to section 3.1 “Sea ice concentration dataset” describing the procedure used to represent data from the 19GHz and 37GHz channels with large footprints (respectively 56 and 33 km) into 12.5 km grid cells.

R: **“I didn’t understand Figure 3. A more complete figure caption, or a figure legend, would help. Are the dots yearly averages? What points (grid cell locations) are the three plots from?”**

A: Other reviewers have the same comment.

B: Figure 3 as it was in the original version was removed from the paper as it didn’t bring pertinent information for the understanding of the method.

R: **“OFB is a point where OSI-430 validation data show less ice, and the greater ice in the statistical model prediction is traced to erroneous ice detection due to the land spillover effect. (OSI-430 used for validation. OSI-409 is used in the statistical model development. Both are passive microwave SIC data sets.) I’m surprised that land spillover isn’t more of a problem for the other coastal locations”**

A: As it turns out, the error does not appear at other coastal locations since the OSI-409 and 430 algorithms used a coastal correction approach that we described in the manuscript. The OFB error is caused by a combination of two factors. First, we did identify an error, specific to Frobisher Bay area and west Southampton Island (Roes Welcome Sound) in a NSIDC climatological mask that the OSI-409 algorithm uses to ensure that no ice is detected in area where it is not likely to appear. The mask falsely declares that ice presence in these two areas is plausible during all summer months. Given the fact that the climatology mask states that there is possibly ice in Frobisher Bay at that date, the algorithm attempts to measure it, with erroneous results.

B: The above information was also added to the manuscript to ensure the readers understand that this is not an error that affects the entire coastal area which is prominent in our simulation domain.

ICEPAC – A PROBABILISTIC TOOL TO STUDY SEA ICE SPATIOTEMPORAL DYNAMIC: APPLICATION TO THE HUDSON BAY

ANSWERS TO REVIEWER #5

Reviewer #5,

We thank you very much for your valuable and helpful comments on our work. We made interesting discoveries about the behaviour of our model by adding the Hall Beach site which showed a different sea ice spatiotemporal evolution pattern from the other sites. We made all suggested modifications to our manuscript.

Thank you for the time invested in our manuscript.

CG

R = Reviewer comments **A** = Author response and **B** = manuscript modifications

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MAJOR COMMENTS

R: "I think the author needs to provide some more context on the Hudson Bay ice cover, discuss the limitations of passive microwave datasets and directly discuss where this tool could be applicable."

A: We added the information and modified the manuscript as suggested.

B: Information on the Hudson Bay sea ice cover, the choice of passive microwave and discussion about potential applications of the tool has been added in the *Introduction*. As for the limitations of passive microwave imagery, a paragraph was added in the *Data and Methods/Sea Ice Concentration dataset* section.

R: "Several papers have now highlighted trends toward earlier breakup, later freeze-up and a longer open water season within the HBS. Provided the timing of these seasonal changes is an integral part of the IcePAC tool they should be discussed."

A: Done.

B: Information on trends regarding ice season duration have been added.

R: "The OSI-430 dataset needs to be introduced and contrasted from the OSI-409 dataset."

A: Done.

B: Information on the OSI-430 dataset has been added to the *Data and Methods/Sea Ice Concentration dataset* section.

R: "This would be a good place to compare the known differences between SIC derived from passive microwave sensors and the CIS charts."

A: Done. We gave the information to make sure that the limitations, especially during summer and fall were brought forward for the readers.

B: A short paragraph outlining the divergences of passive microwave estimated SIE (extent) versus the CIS maps estimated SIE has been added. A reference to Agnew and Howell (2003) was added.

R: "In terms of coastal and offshore comparison sites, why did you choose these 6 locations?"

A: These locations were selected for their difference in latitude, their expected sea ice spatiotemporal variability and their respective specificities such as the expected stability for the Central Hudson Bay point (OCHB), the interest of the shipping community for Churchill (OC) and Iqaluit (OFB), the known polynya at Cape Dorset (OCD). We thought using these specific sites would make it possible to outline the different scenarios of spatiotemporal dynamic one could expect in such a complex sea ice environment.

As for the OFB point, we originally considered it as part of the HBS, though we understand that the limits of the Hudson Strait are considered to be at the southwest point of Frobisher Bay. Nonetheless, we did keep the OFB point as it outlined that, even if the result obtained by the model are obviously erroneous, it is not due to the approach but clearly to the data source.

B: Nevertheless, following reviewers comments about those locations, we added two comparison sites in the revised version of this manuscript: Offshore Northern Ungava Bay (ONUB) at the entrance of the Hudson Strait and Coastal Hall Beach (CHB) in the northwestern part of Foxe Basin. The ONUB location was selected because of its strategic position in the navigation corridor in the Hudson Strait while the CHB location was added to represent the particular ice regime in the Foxe Basin.

MINOR COMMENTS

R: Remove "Northeastern Canada" from title.

A: Done,

B: "Northeastern Canada" was removed from the title.

R: The term meltdown is used instead of melt throughout the paper.

A: Corrected.

B: Terminology has been modified throughout the manuscript.

R: **“Sea ice dynamics” implies sea ice ridging, rafting, transport, motion, etc. Another wording has to be used to refer to the variability in spatiotemporal patterns of sea ice.**

A: Terminology has been modified in the text to make sure there will be no confusion.

B: Now, we are using "sea ice spatiotemporal pattern" or behavior.

R: **Elaborate and provide references on the statement “Given the increase in activity noticed in the Arctic…”**

A: Done**.**

B: Expected causes of increasing activities in the Arctic where listed and 3 references added to the manuscript.

R: **“This is an oversimplification of the CIS. The ice atlas does provide climatological conditions but weekly ice charts are available and do provide more detailed information.”**

A: More detailed explanation on the different ice products available from CIS, such as the weekly and daily maps, ice concentration and development stage maps as well as reports has been added to the text.

B: These information were added in the Introduction.

R: **“A complete freeze-up in late December. An annual maximum extent is usually achieved in April….” Once the HBS is completely frozen over, the spatial extent of sea ice can no longer increase. This needs to be revised.**

A: We agree**.**

B: The text was modified to clearly differentiate the period where the freeze-up made most of the HBS ice covered in December versus the actual sea ice maximum extent in April.

R: **“How are the three different states defined?”**

A: As you suggested, this part of the text was removed as it brought no pertinent information to the following analyses.

R: **“When discussing the variations in and out of the predicted range of SICs, the three factors listed should be discussed in the introduction or methods. There is notable natural variation in SIC within the HBS; this should be discussed in the introduction. What are highly improbable events in the ice cover?”**

A: We agree and made sure more information and details were provided to the readers concerning this matter. Note that Figure 6 was modified as suggested by many reviewers.

B: We did add a discussion about the natural variation of sea ice conditions in the HBS in part 2 – Description of the HBS. The expression “highly improbable events” was removed from the text, but it simply referred to events with very low probabilities of occurrence.

R: **“To compare the PMW derived IcePAC tool with the CIS there needs to be a more through discussion of the ice charts.”**

A: We do agree with you that a comment on the ice charts was lacking in the manuscript.

B: We added information regarding the regional ice charts used for building the CIS 1981-2010 atlas. We outlined the main differences between the two dataset, so the readers could interpret the results adequately.

R: **“It would be suitable in the conclusions to include a statement about the applicability of this tool to marine transportation or coastal engineering as a predictive tool.”**

A: We did add information regarding possible applications of IcePAC to engineering, fauna protection, navigation in the *Conclusion.*

B: We added the information in the *Conclusion*.

FIGURES AND TABLES

B: modifications made on Figures and Tables:

- All maps have been rotated so the north is upward.
- Hall Beach has been included in our list of coastal communities and maps have been adjusted accordingly.
- Hall Beach was added to the ice free season length analyses; therefore, it was included on Figure 9, as suggested.
- Figure 3 was removed as, like you suggested, it didn’t bring relevant information for the reader.
- Figure 4 has been modified to reflect the importance of trend removal as it ensures results spatial continuity.
- Figure 5 (queries flowchart) has been modified according to your suggestion.
- Figure 6 was entirely modified.
- Figure 9 was modified given your suggestions. Hall Beach was added to the analysis.
- Table 1 was referred in the text.

IcePAC – a Probabilistic Tool to Study Sea Ice Spatiotemporal Dynamic: Application to the Hudson Bay area

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Abstract. A reliable knowledge and assessment of the sea ice conditions and their evolution in time is a priority for numerous decision makers in the domains of coastal and offshore management and engineering as well as in commercial navigation. As of today, countless research projects aimed at both modelling and mapping past, actual and future sea ice conditions were completed using sea ice numerical models, statistical models, educated guesses or remote sensing imagery. From these research, reliable information helping to understand sea ice evolution in space and in time are available to stakeholders. However, no research has, as of today, assessed the evolution of the sea ice cover with a frequency modelling approach, by identifying the underlying theoretical distribution describing the sea ice behaviour at a given point in space and time. This project suggests the development of a probabilistic tool, named IcePAC, based on frequency modelling of historical 1978-2015 passive microwave sea ice concentrations maps from EUMETSAT OSI-409 product, to study the sea ice spatiotemporal behaviour in the waters of the Hudson Bay System in northeast Canada. Grid cells scale models are based on the generalized Beta distribution and generated at a weekly temporal resolution. Results showed coherence with the Canadian Ice Service 1981-2010 Sea Ice Climatic Atlas average freeze-up and melt-out dates for numerous coastal communities in the study area and showed that it is possible to evaluate a range of plausible events, such as the shortest and longest probable ice free season duration, for any given location on the simulation domain. Results obtained in this project open a path towards various analyses on sea ice concentrations spatiotemporal distribution patterns that would gain in information content and value by relying on the kind of probabilistic information and simulation data available from the IcePAC tool.

1. Introduction

Numerous scientific projects recognized the link between climate change and changes in the spatiotemporal sea ice distribution (Andrews et al., 2017; Cavalieri and Parkinson, 2012; Comiso, 2011, 2002; Comiso et al., 2008; Gloersen et al., 1998; Johannessen et al., 2004; Rothrock et al., 1999; Stocker, 2014; Stroeve et al., 2007; Stroeve et al., 2014; Stroeve et al., 2012; Wang and Overland, 2009). The climate change in the Arctic (60°N–90°N) is expected to be, on average, 1.9 times greater than the global mean warming (Winton, 2006) and this ”Arctic amplification” is expected to strengthen in coming decades (Serreze and Barry, 2011).

In this changing environment, an adequate and efficient monitoring of sea ice is of key importance to better understand the climate and its impacts on marine and coastal areas (Barnhart et al., 2014; Bintanja and Selten, 2014; Davies et al., 2014; Holland et al., 2006; Kowal et al., 2017; Manabe and Stouffer, 1995; Overeem et al., 2011; Peterson et al., 2002; Rahmstorf, 1995; Rahmstorf and Ganopolski, 1999; Vermaire et al., 2013), on the security of economical and logistical activities in northern communities (Aksenov et al., 2017; Andrews et al., 2017; Ho, 2010; Lasserre and Pelletier, 2011; Liu and Kronbak, 2010), on arctic marine fauna protection (Bhatt et al., 2010; Castro de la Guardia et al., 2013; Darnis et al., 2012; Laidre et al., 2015; Post et al., 2013; Wassmann et al., 2011) and on the traditional way of life of Inuit communities (Durkalec et al., 2015; Laidler et al., 2010).

To understand and appreciate the role of the sea ice cover regarding climate, marine and coastal environment management, fauna protection and the cultural traditions of northern communities, access to informative and reliable sea ice spatiotemporal distribution information is fundamental. Engineers, stakeholders, Inuit and northern populations, navigators and scientists must be able to quantify hazards related to the sea ice cover in order to efficiently evaluate, anticipate and minimize the risks of usage, building and exploitation in marine and coastal areas. Given the increase in activity like tourist cruises, shipping and mining observed in the Arctic and the North (Dawson et al., 2018; Lasserre and Pelletier, 2011; Pizzolato et al., 2016), one can expect the demand in information to also increase. For example, engineers could make use of the probabilistic data to assess the potential duration of sea ice presence at an infrastructure they are planning to build; mariners could use the data to estimate the best departure date from their attach port to reach their final destination according to a certain sea ice concentration probability threshold; fauna specialists could use the data to estimate the risk encountered by species dependant of sea ice cover for their fitness, such as polar bears and seals; and finally, Inuit communities could use the tool to evaluate if their planned travel routes are risky for a given period of the year given the known history of the sea ice spatiotemporal behaviour.

Despite a large number of Earth Observation datasets on the sea ice cover, only a few provide both high temporal and spatial resolution. National ice services, such as the Canadian Ice Service (CIS), provide the users with sea ice conditions climatology that are a reliable source of descriptive statistics on the sea ice spatiotemporal behaviour, such as the average freeze-up or maximum extent date. The CIS also provides daily and weekly regional ice conditions maps that inform on the observed concentrations and ice development stage reached by sea ice, as well as detailed sea ice conditions reports, for all regions of the Canadian Arctic. These maps and reports are created by experienced and skilled professional sea ice analysts who make use of diverse sources of sea ice information such as radar, optical and passive microwave imagery in combination with in-situ observations to prepare their analyses (Iacozza, 2000). However, even if the CIS data and other national ice services products do provide probabilistic information, these datasets do not carry information on the nature of the underlying statistical distributions of sea ice parameters, such as sea ice concentration (SIC%), at any given point.

To build a probabilistic model of sea ice concentrations, historical information are needed and must answer specific needs such as long-term availability, reliability, large spatial coverage and high temporal frequency. As visible imagery is largely affected by the cloud coverage, especially prominent in the Arctic, it is not a reliable source of information to build our model. In spite of its independence on atmospheric conditions, SAR imagery doesn’t provide a sufficient spatial coverage for our purpose. Therefore, passive microwave observation turned out to be the compromise dataset that, even if its resolution is coarse, provides daily data for the entire arctic and for which historical data is available since 1978.

By exploring an innovative probabilistic sea ice concentrations modelling avenue, this study proposes a tool, named IcePAC, to characterize the underlying statistical distributions of the SIC% at any point in the Hudson Bay System (Saucier et al., 2004) based on historical passive microwave remote sensing data from 1978 to 2015. These data are than used to analyse the spatiotemporal behaviour of SIC% in the Hudson Bay area with a probabilistic perspective and compared to the CIS climatology.

2. The Hudson Bay System

The study area is the Hudson Bay System (HBS), consisting of Hudson Bay, Hudson Strait, James Bay and Foxe Basin (Fig. 1). The HBS is surrounded by the three Canadian provinces of Quebec, Ontario, Manitoba and the territory of Nunavut. It is the largest inland sea on Earth, with a total area of 1 300 000 km^2 (Etkin, 1991; Gagnon and Gough, 2005a; Martini, 1986) and is located in both subarctic and arctic regions. An estimated 20 % of the flux of freshwaters to the Arctic Ocean are thought to come from rivers flowing into the HBS, which represents 900 km^3/yr^{-1} (Déry and Wood, 2005; Déry and Wood, 2004). It is connected to the Labrador Sea by the Hudson Strait while waters from the Arctic Ocean flow through Hecla and Fury Strait to the Foxe Basin (Prinsenberg, 1986) and it is characterized by shallow depths of less than 100 m in the Foxe Basin, of a maximum of 125 m in the Hudson Bay and of more than 200 m in the Hudson Strait (Jones and Anderson, 1994). It has cyclonic currents generated mostly by winds, with a maximum intensity in November (Saucier et al., 2004).

A large number of researches has been done to document the average sea ice behavior in the HBS (CIS, 2013; Gagnon and Gough, 2005a, b; Hochheim and Barber, 2010; Hochheim and Barber, 2014; Kowal et al., 2017; Maxwell, 1986), which goes every year through a complete freeze-thaw cycle. The sea ice cover in the HBS is primarily constituted of first-year ice, with the exception of traces of multi-year ice drifting in the Foxe Basin (CIS, 2013; Etkin and Ramseier, 1993). The sea ice cover initially forms in the northwestern part of the HBS near Southampton Island in late November and progresses towards the southeastern part of the HBS (Hochheim and Barber, 2014; Maxwell, 1986) to finally cover most of the HBS in late December. Sea ice maximum extent in the HBS is usually achieved in April (Gagnon and Gough, 2005b), after which the melt begins in May along the northwestern shoreline of the HBS. The melt progresses from the shores toward the center of the Hudson Bay which usually results into an agglomerate of sea ice in the southcentral part of the Hudson Bay in late July (CIS, 2013). In summary, the HBS is, on average, frozen in late December and free of ice in mid-August (Mysak et al., 1996; Wang et al., 1994).

Many authors have studied the trends in sea ice cover extent for the Hudson Bay area (Galbraith and Larouche, 2011; Hochheim and Barber, 2014; Tivy et al., 2011). Among them, Tivy et al. (2011) arrived to the conclusion that the Hudson Bay area was affected by some of the strongest downward trends regarding the ice season duration in the entire circumpolar Arctic. Confirming the results of Tivy et al. (2011), Hochheim and Barber (2014) measured trends of the open water seasons duration comparing a 1996–2010 with a 1980–1995 climatology based on a modified Comiso SIC% dataset. Their results showed lengthening of ice free seasons in Foxe Basin, Hudson Strait and Hudson Bay, respectively of 3.5, 4.9 and 3.1 weeks. It is worth to note that, since the HBS is in its most parts covered by first year ice, the natural variability of the sea ice conditions is considerable since it is mostly driven by warming temperatures, but also by changes in atmospheric circulation (Mudryk et al., 2018).

Ice thickness during winter in the HBS range from 1 to > 2.5 m according to numerical modelling studies, though, as reported by Landy et al. (2017), these studies do not agree on the spatial distribution of sea ice. Gough et al. (2004) identified an east-west asymmetry in long-term trends of sea ice thicknesses in the HBS using drill-hole measurements acquired between 1960 and 2000. These trends show a tendency of thickening on the western side (+ 0.1 – 1.5 cm yr^{-1}) of Hudson Bay while the eastern side shows, on the opposite, a trend towards a thinning ice pack (-0.5 – 0.8 cm yr^{-1}).

Polynyas are also present in the HBS, such as the northwestern Hudson Bay polynya between the western coast of Hudson Bay and Southampton Island that forms occasionally throughout the winter and spring (Gough et al., 2004), the Hecla, Fury Strait and Hall Beach polynyas (Barber and Massom, 2007), located in northwestern parts of the Foxe Basin and the Cape Dorset polynya which is a shore lead polynya (Stirling, 1980).

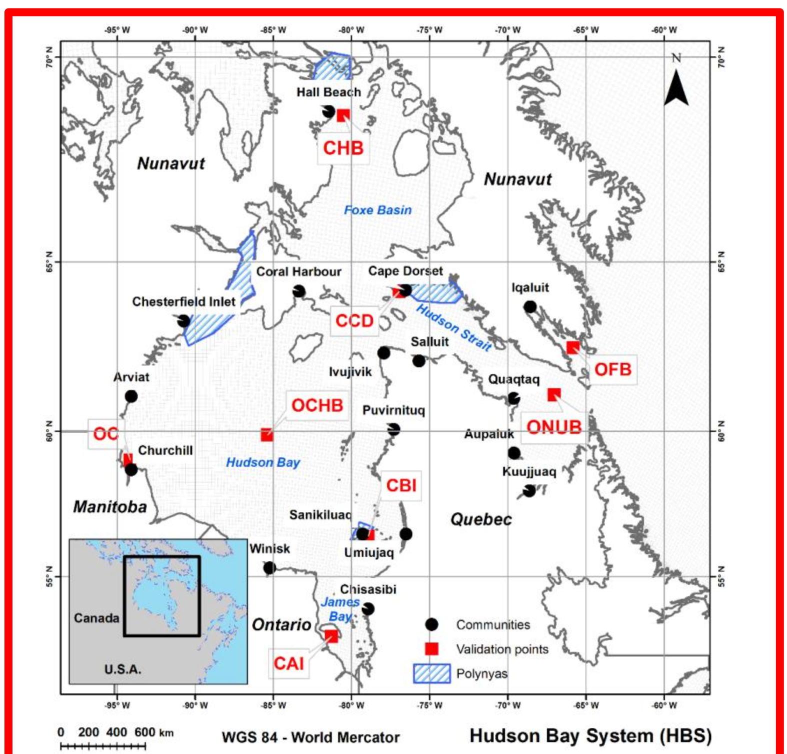

Figure 1: The Hudson Bay System with communities, model validation points and polynyas

3. Data and methods

Sea ice extent has displayed an important decline in the last decades (Cavalieri and Parkinson, 2012), as it can be observed with remote sensing data, such as passive microwave acquired since 1978. Another important source of information on the sea ice cover are model predictions which come from deterministic models (Hunke et al., 2017; Rousset et al., 2015; Weaver et al., 2001), based on dynamical and thermodynamic equations evolving in synergy inside a modelling framework, or from statistical models, based on statistical tools such as simple and multiple regression analysis (Ahn et al., 2014; Drobot, 2007; Pavlova et al., 2014) to explain an expected sea ice parameter value (e.g. sea ice extent, sea ice area, sea ice concentration, sea ice thickness).

Another statistical approach, focusing on the estimation of the probabilities of occurrence of specific sea ice related events, has been used in recent research (Dirkson, 2017; Rajak et al., 2015). It is achieved either by using the simple count method (e.g. an event occurred four times in the last ten years, which corresponds to a 40 % probability of occurrence) or by using the frequency modelling method, which consists of adjusting a theoretical distribution to a series of observations, consequently defining the plausible sea ice events for the entire range of probabilities (i.e. p = 0 to 100 %). In this research, the frequency modelling method is used on series of passive microwave historical SIC% remote sensing data to adjust distributions to a total of 20 738 grid cells or sites within the HBS (i.e. the spatial dimension) for each of the 52 weeks of the year (i.e. the temporal dimension), resulting in a total of 1 078 376 distribution fits.

The datasets used and protocols followed in the IcePAC tool to model SIC% distributions at every grid cell in the HBS are described in the following sections.

3.1 Sea ice concentration dataset

Sea ice concentration is defined as the proportion of sea ice covering a predefined area, expressed as a percentage. In remote sensing, this predefined area is represented by a grid cell. The choice of a SIC dataset for frequency modelling in our study is highly influenced by the extent of the HBS (1 300 000 km^2) and has been made to ensure uniformity and continuity of the series used for analysis.

Multiple SIC datasets are generated using either visible/thermal, SAR or passive microwave remote sensing. As the objective of the IcePAC tool is to provide the capacity to evaluate the spatiotemporal evolution of the SIC, the source of data needed to ensure a complete coverage of the HBS (i.e. the spatial dimension) and to ensure continuity in the series (i.e. the temporal dimension). A passive microwave dataset was chosen as it meets these two needs.

The OSI-409 – Reprocessed Global Sea Ice Concentration dataset (Eastwood et al., 2015; Tonboe et al., 2016) was selected as it enables the reconstitution of SIC series on more than 30 years with a 12.5 km grid size and is processed with a unique hybrid SIC algorithm. The hybrid algorithm uses only the information taken from the Bootstrap algorithm (Comiso, 1995) when SIC < 70 %, linearly weights the SIC estimated by the Bootstrap and Bristol (Smith, 1996) algorithms when 70 % < SIC > 90 % and uses only the information from the Bristol algorithm when SIC > 90 %. Another passive microwave based SIC% dataset is used in this study as comparison dataset, the OSI-430, and its only difference from OSI-409 is that it uses SSM/I data obtained from NOAA instead of recalibrated SSM/I data from RSS (Remote Sensing Systems). The difference in the resulting SIC% product is, according to Eastwood et al. (2015), expected to be minimal.

In OSI-409, the passive microwave channels used for ice concentration mapping have foot-print sizes ranging from 56 km for the 19GHz channels to 33km for the 37GHz channels. As SIC% values are represented on 12.5 km grid cells in the OSI-409 and 430 products, inputs of different resolutions are combined using a gridding procedure that loads all passive microwave observations within the period of a day for a 12.5 km grid cell (centred on 12:00 UTC) and averages them using a weighting value (dependent on the distance between the observation and the centre of the grid cell) and an influence radius, (dependant on the passive microwave channel resolution). A detailed explanation of the method is provided in Eastwood et al. (2015).

It is important to note that passive microwave SIC% datasets are known to be affected by diverse error factors such as a land spill-over effect along coasts that triggers false higher SIC% estimation if not taken into account. To mitigate the errors caused by this phenomena, a coastal correction is applied to the data with a method inspired from Cavalieri et al. (1999). This method first calculates monthly average SIC% for all months and finds the minimum ice concentration from these averages. This minimum is then used to correct the ice concentration values in the coastal zone if adjacent non-coastal grid points are ice free. Also, a climatological maximum extent masking is done to mask out erroneous ice outside areas where sea ice is ever likely to occur using a sea ice extent monthly climatology from the NSIDC (National Snow and Ice Data Center) (NSIDC, 2013).

Another error factor with passive microwave is data gaps which can occur either in the form of missing scan lines, missing orbits and polar observation hole. As reported by Eastwood et al. (2015), these gaps, when small, can be corrected by simple interpolation. However, when facing large gaps, a blurring effect appears in the interpolated area. To correct this effect, an interpolation approach using the information from the past and next days is used in the OSI products. And last but not least, the effect of ponds appearing during the melt is that the resulting maps tend to underestimate SIC% during summer since there is confusion between open water areas and melt ponds on top of sea ice. Finally, another underestimation of the SIC% results from thinner ice types who do not act as a radiometric insulator for the passive microwave frequencies around 19 and 37 GHz that are the base of the OSI-409 and OSI-430 datasets (Eastwood et al., 2015).

These different error sources in the process of estimating SIC% using passive microwave imagery are known to have an impact on the reliability of the data, especially during the freeze-up and the melt periods, as brought forward by Agnew and Howell (2003) who noticed that the underestimation of ice extent in the Hudson Bay during summer, when compared to CIS maps, could go up to 43.5±27.9% (while considering the CIS data as ground truth). Since the HBS is an area where new ice forms every year, this systematic underestimation from passive microwave data must be kept in mind.

The data has been clipped to the HBS extent using the Natural Earth (NaturalEarth, 2014) vector dataset with an estimated spatial resolution of 500 m (Wessel and Smith, 1996), well beyond the resolution of the OSI-409 and OSI-430 datasets. As the coasts of the HBS are highly dynamic, other datasets could have been used such as the CanVec product from Natural Resources Canada which is updated regularly. However, considering the 12.5 km grid size, the Natural Earth product was chosen.

3.2 Frequency modelling

The IcePAC tool uses frequency modeling to describe the underlying SIC% probability distribution at a given site with a simplified model fitted on historical SIC data. The first step in this approach is to build the time series of historical data, then to ensure their quality using preliminary tests and finally to identify and fit the model on the data (Fig. 2).

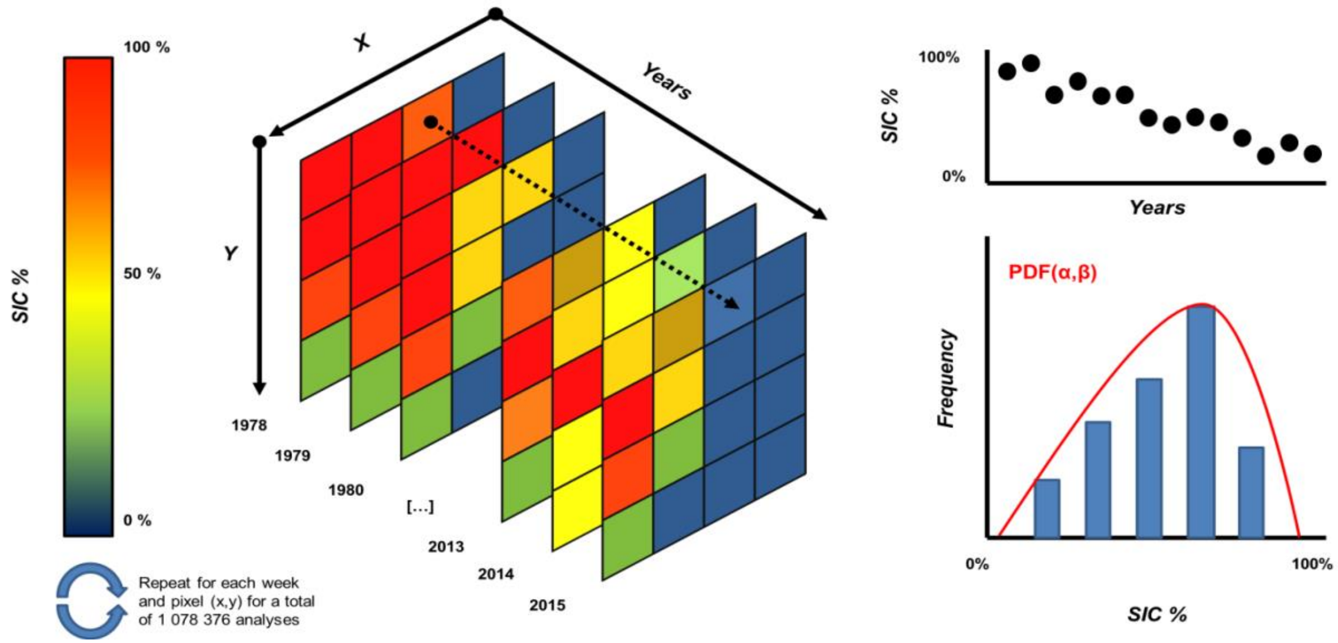

Figure 2: The process of frequency modelling from series building to model fit. On the left, the SIC% data stacking and series building for every pixel in the simulation domain, on the upper right, an example of a unique site complete series plotted, and on the lower right an example of model fit (Beta) to the density distribution of the SIC% values in the series with the α and β model parameters .

3.2.1 Building the sea ice concentration (SIC) series

The SIC series are built to represent the SIC state for a specific week, for all years between 1978 and 2015. It is on these series that we adjust a theoretical distribution to estimate the probabilities of SIC related event. First, the daily OSI-409 data have to be averaged every 7 days to create weekly datasets. This operation is made following a 365-days “no-leap” calendar convention (i.e. every year has 365 days), separated in 52 weeks (December 31st is included in week 52). Second, the data for each week number are stacked in chronological order, from 1978 to 2015.

3.2.2 Preliminary tests

Series have to go through a set of preliminary tests to assess their stationarity, homogeneity and independence, assuring they are suitable for frequency modelling. The tests used in IcePAC are the Mann-Kendall test for stationarity (Mann, 1945), the Wald-Wolfowitz test for independence (Wald and Wolfowitz, 1940) and the Wilcoxon test for homogeneity (Wilcoxon, 1945).

Series are considered independent if the subsequent unique SIC observations have no incidence on one another; they are considered homogeneous if they are reputed to be from the same distribution and; they are stationary if they are not affected by a trend. In the case of a detected non-stationarity, the trend is modeled and subtracted from the series (Cave and Pearson, 1914).

All the time series, either original or detrended in regards to the Mann-Kendall test, satisfied the preliminary tests for signification level of $\alpha = 0.05$.

3.2.3 Trend estimation and removal

The estimation of a trend on a percentage data series has the particularity that the trend must, in order to be coherent with the physics of the studied phenomenon, be bounded in a [0,1] domain (Baum, 2008). In other words, we must ensure we do not measure a trend that generates SIC values larger than 100 % or smaller than 0 %. To guarantee the respect of this criterion, a generalized linear model with a logit link function has been used to estimate the trend. The logit link function linearizes the SIC values using the logit transformation (Eq. 1) and it is on these transformed values that a linear regression of the form $\alpha x + \beta + \varepsilon$ is measured.

$$logit(SIC) = \ln(SIC/1 - SIC) \;\; where\ SIC\ is\ defined\ on\ ]0,1[\qquad (1)$$

For the trend to be removed from the series, an inverse transformation (Eq. 2) must be applied to the estimated trend to bring back its logit values into SIC values.

$$SIC = \exp\left(\frac{exp\big(logit(SIC)\big)}{\big(1 + exp\big(logit(SIC)\big)\big)}\right) \qquad (2)$$

The removal of the trend in the time series ensures that we model the natural variability of the sea ice concentrations phenomenon, without any influence from the trend (Fig. 3). In IcePAC, the trend is modeled using the aforementioned method (GLM with logit link), then removed from the original SIC% data and finally the residuals are used to adjust the distribution model.

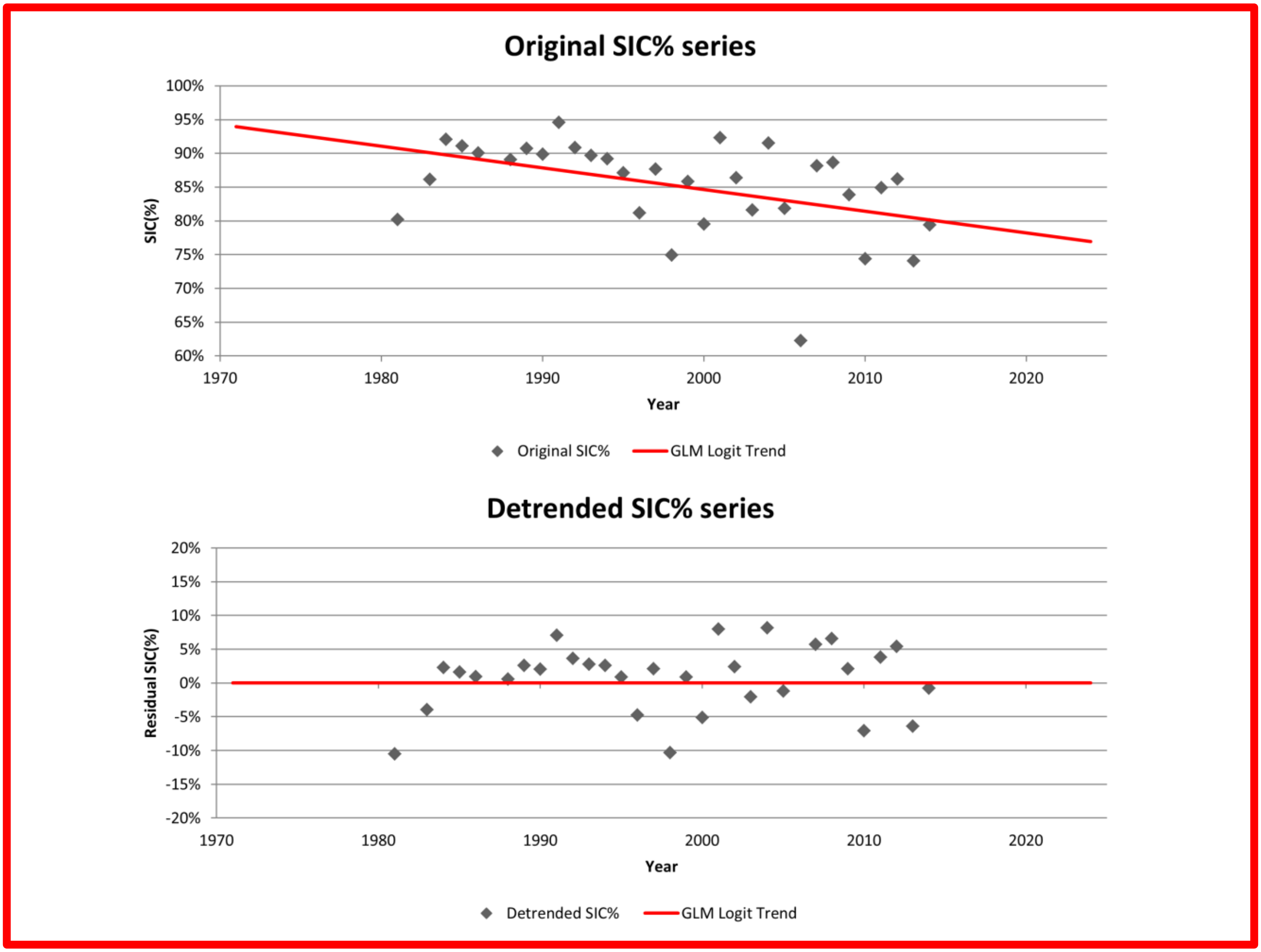

Figure 3: The trend removal process applied to a SIC% time series for a coastal grid cell extracted from OSI-409 data for week 50.

Once adjusted, the distribution models are used for queries, in conjunction with the trend that is taken into account to generate the final result. For example, one could ask for the probability of a specific SIC%. In such a case, the trend for the prediction year is first removed from the SIC% and the probability of the residual is then estimated from the distribution model. Inversely, one could ask for the SIC% for a given probability. In such case, the probability is first used to get the corresponding residual value (representing the natural variability of sea ice) and the trend is afterward reinjected to obtain a realistic SIC% value. In both cases, the trend is managed to trigger the final results.

It is important to note that frequency analysis is not a projective approach but a predictive approach. In other words, IcePAC is not to be used to get an outlook of long-range future SIC% conditions (projection) but to assess what is expected for the short-term (prediction). As the trend will change in time with the addition of new SIC% data, the further we try to temporally expand our prediction, the more erroneous our probability estimates may be.

3.2.4 Distribution selection and fit

The selection of adequate candidate distributions to fit on the series is largely limited by the bounded nature of the data. The selected distribution has to be bounded to [0,1] and be available in a generalized form in order to adapt to detrended series which are bounded to [-1,1]. Their generalized forms are to be used with the position parameter *a* fixed to -1 and the scale parameter *b* fixed at 2, in coherence with the phenomenon. It must also present enough flexibility in shape to adapt to the different type of SIC series in the HBS domain. Two different distributions, the generalized Beta distribution and Johnson's SB distribution (Johnson, 1949), both bounded and displaying flexibility in shape, have been fitted on the series using the maximum likelihood estimator (MLE) (NIST, 2013) and compared by measuring the root mean square error (RMSE) between observations and adjusted curves as well as the Akaike Information Criterion (Akaike, 1998) and the Bayesian Information Criterion (Schwarz, 1978).

The generalized Beta distribution (Eq. 3) has four parameters which are the p ($p > 0$) and q ($q > 0$) shape parameters, the position parameter $a = -1$ and the scale parameter $b = 2$. In Eq. 3, B is the Beta function. This distribution has been used before in climatology (Dirkson, 2017; Falls, 1974; Henderson-Sellers, 1978; Sulaiman et al., 1999), in seismology (Lallemant and Kiremidjian, 2015), to study air pollution (Nadarajah, 2008) and in hydrology (Chen and Singh, 2017; Yao, 1974).

$$f(\mathrm{x}) = \frac{(\mathrm{x}-\mathrm{a})^{\mathrm{p}-1}(\mathrm{b}-\mathrm{x})^{\mathrm{q}-1}}{\mathrm{B}(\mathrm{p},\mathrm{q})(\mathrm{b}-\mathrm{a})^{\mathrm{p}+\mathrm{q}-1}}, \text{where } \mathrm{a} \le \mathrm{x} \le \mathrm{b}; \mathrm{p},\mathrm{q} > 0 \tag{3}$$

The Johnson's SB (Eq. 4) is, under its generalized form, a four parameters distribution, for which the γ and δ ($\delta > 0$) are the shape parameters, the parameter $a = -1$ is position and the parameter $b = 2$ is the scale. This distribution has been used before in meteorology (Cugerone and Michele, 2015; Wakazuki, 2013), in forestry (Rennolls and Wang, 2005) and in hydrology (D'Adderio et al., 2016).

$$f(x) = \frac{\delta}{\sqrt{2\pi}} \frac{(b-a)}{(x-a)(b-x)}^{\left[-\frac{1}{2}\left\{\gamma+\delta ln\left(\frac{x-a}{b-x}\right)\right\}^{2}\right]}, \text{where } \mathrm{b}, \delta > 0 \tag{4}$$

Two approaches were tested for distribution selection. The first approach considered fitting the distributions to the series according to their Mann-Kendall test results (i.e. managing detected trends only). The second approach considered fitting the distributions to systematically detrended series (i.e. removing trend from every time series in the simulation domain) in order to ensure spatial coherency in the IcePAC outputs.

The use of a systematic trend removal approach is justifiable by the fact that natural phenomena are considered by nature non stationary (Lins, 2012; Rao et al., 2012) and by the relative shortness of the series which can have an effect on the conclusions of the Mann-Kendall test (Hirsch et al., 1982). Also, it is important to state that the frequency analysis approach is rarely used to generate spatialized results like it is in the IcePAC approach where every time series (linked to a specific location or grid cell) is processed as an individual station.

The two trend removal approaches, tested on 958 randomly chosen series, yielded similar conclusions. In 71.4 % of cases, the Beta distribution outperformed the Johnson's SB distribution. For the remaining 28.6 % adjustments where the Johnson's SB distribution did perform better, both the information criterion and the RMSE showed a non-significant difference with the Beta distribution. In light of these results and to preserve parsimony in IcePAC, it was decided to use only the Beta distribution for all series, for which a systematic trend removal was applied.

As expected, using an approach which systematically corrects for trends in time series before distribution fit improved the spatial coherency of the resulting probability maps generated by IcePAC (Fig. 4).

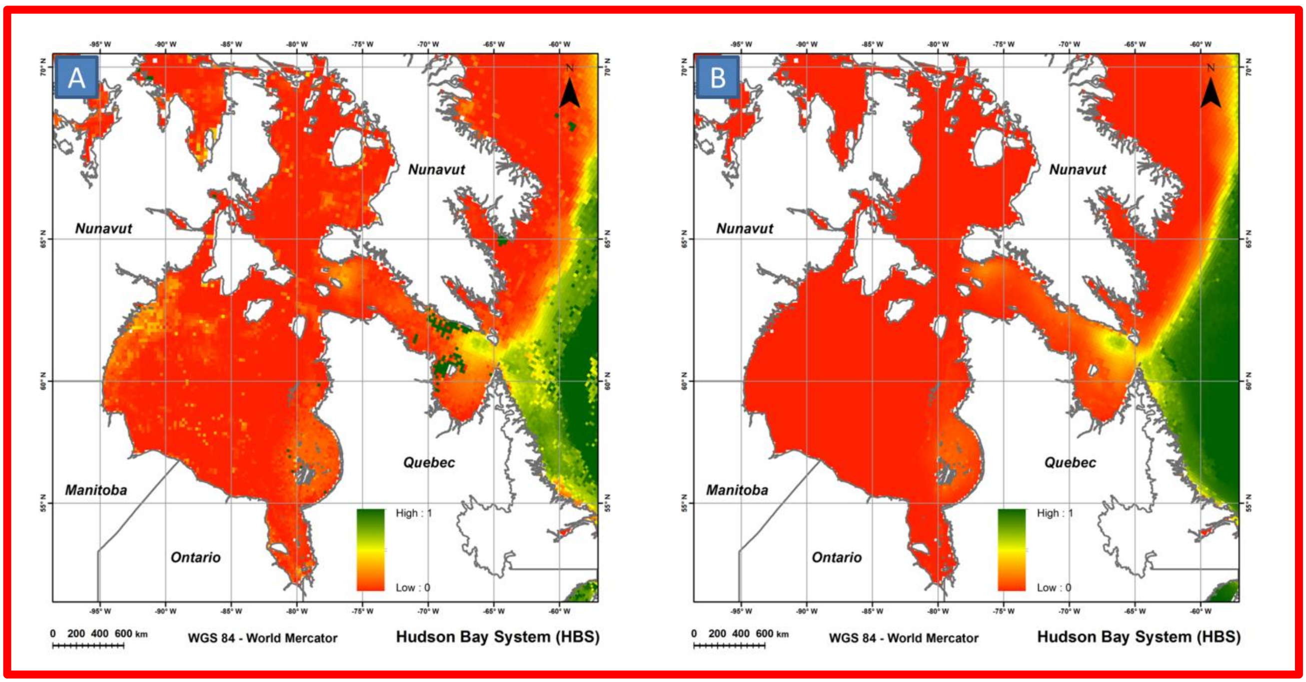

Figure 4: Comparison of IcePAC results for non-systematic (i.e. based on Mann-Kendall test result) trend removal (A) and systematic trend removal (B), on the resulting map for the probability of observing a SIC < 50% on week #1

3.2.5 Model queries

Queries with the IcePAC tool are possible via three important functions resulting from the distribution fit, the probability density function (PDF), the cumulative distribution function (CDF) and the percent point function (PPF). These functions are obtained using the fitted parameters from the Beta distribution independently for each of the 20 738 grid cells in the IcePAC simulation domain.

The PDF is obtained by fitting a theoretical distribution on the frequency histogram of the SIC% observations. The selected distribution in IcePAC is the Beta distribution for which the parameters of Eq. (3) were estimated using the MLE. The PDF informs on how probability is distributed between SIC% values and how it evolves.

Derived from the PDF, the CDF (Eq. 5) informs on the probability for a given range of SIC% values. It corresponds to the area under the PDF curve for a specific range of SIC values, usually from 0 % to $SIC\%_{MAX}$. As a CDF example, one could query to know the probability of non-exceedance (p) for a sea ice concentration of 25 % (SIC_{MAX}) for week number 1 for the year to come.

$$F_x(SIC\%) = \int_0^{SIC\%_{MAX}} f_x(SIC\%)dt \quad (5)$$

The inverse function of the CDF, the PPF (Eq. 6) estimates the SIC% value for a given probability of non-exceedance. As a PPF example, one could query to know the $SIC\%_{MAX}$ for a probability of non-exceedance of 55 % for week number 1 for the year to come.

$$Q = F^{-1}(p) \quad (6)$$

Since the IcePAC fits are made on detrended series (e.g. residuals), the trend has to be taken into account when processing queries, meaning that it has to be either removed from the $SIC\%_{MAX}$ value if the CDF is used or added to the result of the PPF query in order to render a physically valid result. The query flowchart is presented in Fig. (5).

3.2.6 IcePAC versus observations in 2016

The assessment of the validity of IcePAC predictions was done by comparing IcePAC weekly outputs time series for the entire year with the OSI-430 product, a data source not used in IcePAC development but based on the same SIC% retrieval algorithm (Tonboe et al., 2016). The comparison was made between the 2015-2016 sea ice season SIC% values (not included in the input data for IcePAC) and the IcePAC SIC% for a non-exceedance probability of 90% (P = 0.9)

Eight different comparison sites were selected to represent different sea ice spatiotemporal behaviours (see Fig. 1). Four coastal sites, the Akismi Island (CAI), Cape Dorset (CCD), Belcher Islands (CBI) and Hall Beach (CHB), were sampled to assess the behavior of IcePAC predictions along the coastline, at different latitudes. Also, four offshore sites, Frobisher Bay (OFB), Central Hudson Bay (OCHB), Churchill (OC) and Northern Ungava Bay (ONUB) were sampled to assess the behavior of IcePAC predictions offshore, at different latitudes and at nevralgic navigation passage points.

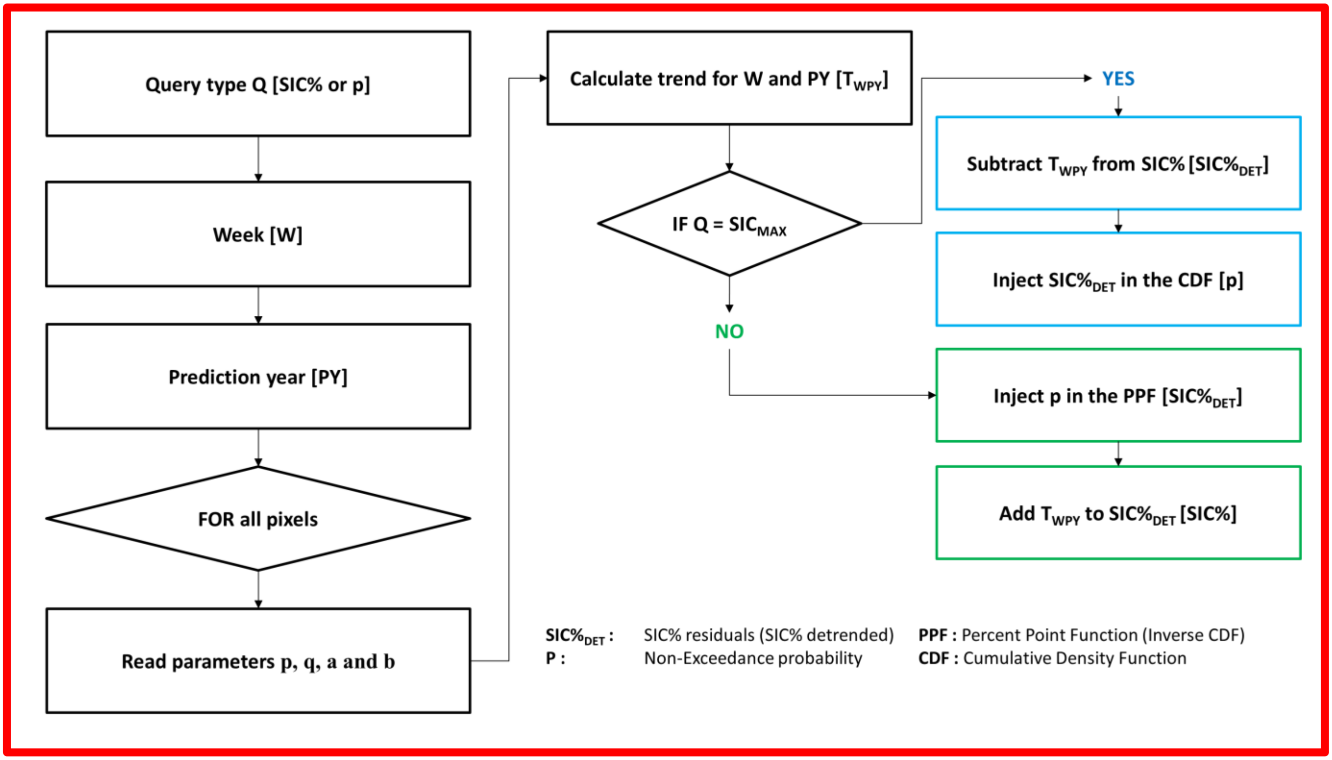

Figure 5: IcePAC queries flowchart

Figure 6 displays SIC% predictions outputs from IcePAC, for a probability of non-exceedance of 90%. Each comparison site shows a modeled dynamic which is coherent with reality and with the OSI-430 2015-2016 observation data. As it could be expected, for all sites, it is during the freeze-up and melt periods that we can observed the largest differences between the 2015-2016 OSI-430 SIC% observations and the model outputs, compared to stable cover periods where the range of probable SIC% values narrows down (i.e. the mean and the P=90% lines are almost overlaid) and therefore the observations tend to rejoin with the model output. Some anomalies of various intensities can be detected in the series such as: early 2015 melt-out events at Hall Beach and Churchill (▲ in Fig. 6), late 2016 freeze-up events at points Akismi Island and Churchill (● in Fig. 6), and early 2016 melt-out event at Hall Beach (♦ in Fig. 6), which all are in agreement with the anomaly maps (Fetterer et al., 2017) of the NSIDC's Arctic Sea Ice News and Analysis (https://nsidc.org/arcticseaicenews/). The fact that the Cape Dorset site displays a SIC% for a probability of non-exceedance of 90% of about 80% at most is coherent with its shore lead polynya status. Similar conclusions can be made for the Hall Beach point for which the polynya tends to appear by late may, which in our case was earlier in 2015 and 2016, as confirmed by NSIDC. In figure 6, daily model outputs (green lines) are presented as a comparison with the weekly outputs (black dots) in order to justify why the IcePAC model outputs were generated at a weekly interval, to filter the effects of the daily variability of SIC% estimations in OSI-409, especially visible at coastal sites.

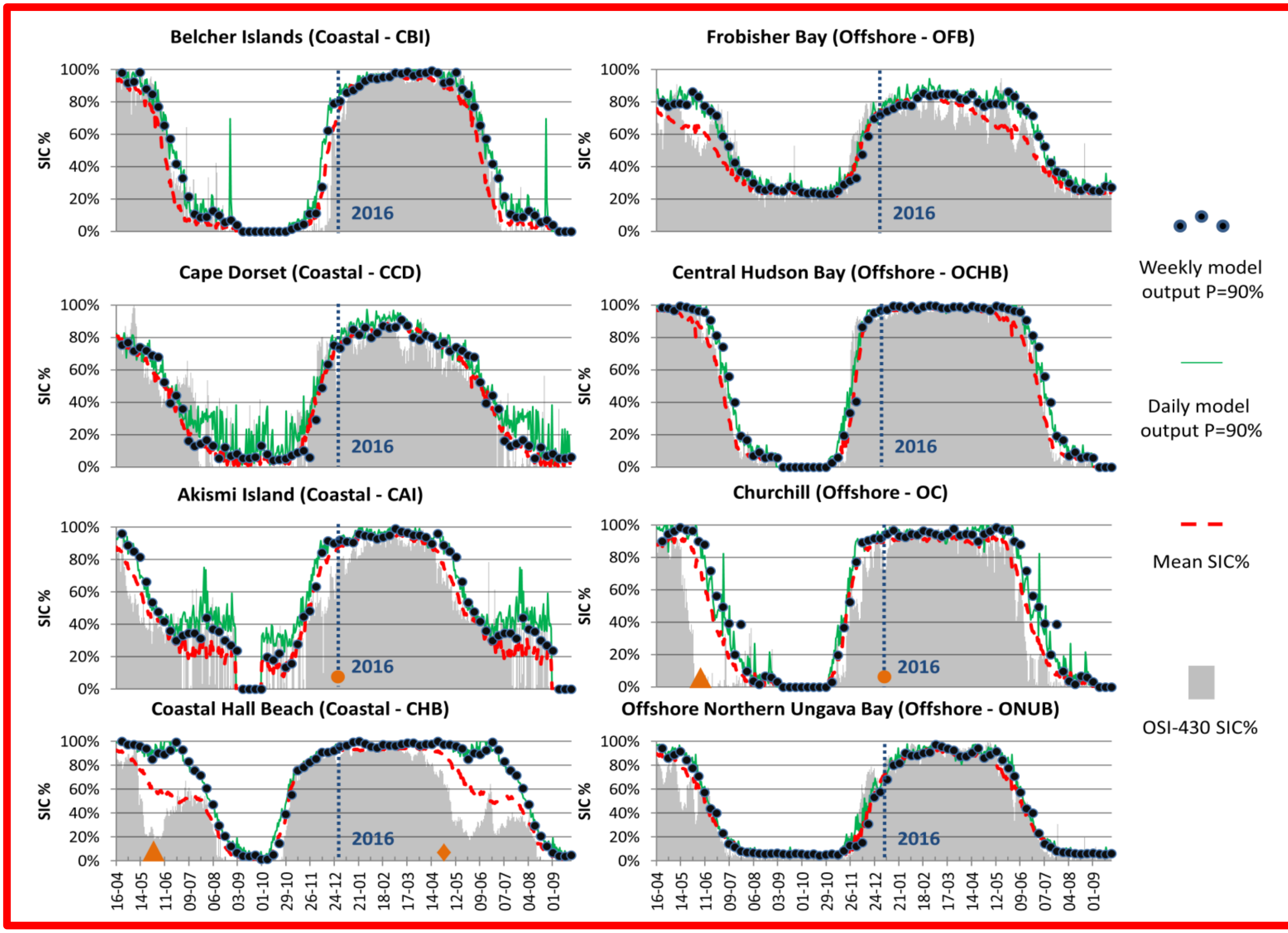

Figure 6: IcePAC weekly and daily P=90% outputs (i.e. it represents a value of SIC% for which there is a 90% probability to be equal or lower to) versus OSI-430 SIC% observations for the 2015-2016 sea ice season. Some anomalies of various intensities can be detected in the series such as: early 2015 melt-out events at Hall Beach and Churchill (▲), late 2016 freeze-up events at Akismi Island and Churchill (●) and early 2016 melt-out event at Hall Beach (♦)

The OFB site, near Iqaluit, has a behavior that indicates an underlying error. In fact, neither the predictions, nor the observations reach a SIC% value of 0 %, which is improbable in our study area. The reason behind this discrepancies with the validation data is that the OSI-409 product does not adequately estimate the SIC in this area, as it can be seen in Fig. (7). The Frobisher Bay is usually ice free around mid-July, which is never the case in the OSI-409 dataset. The source of this error is the “land spill-over effect” (i.e. land contamination) on estimated SIC combined with an inadequate sea ice presence estimation in the NSIDC sea ice monthly maximum extent climatology used as a mask for restricting areas where sea ice is likely to occur. Given the fact that the climatology mask states that there is possibly ice in Frobisher Bay at that date, the algorithm attempts to measure it, with erroneous results. It has been found that this condition does occur in Frobisher Bay and also west of Southampton Island, in Roes Welcome Sound.

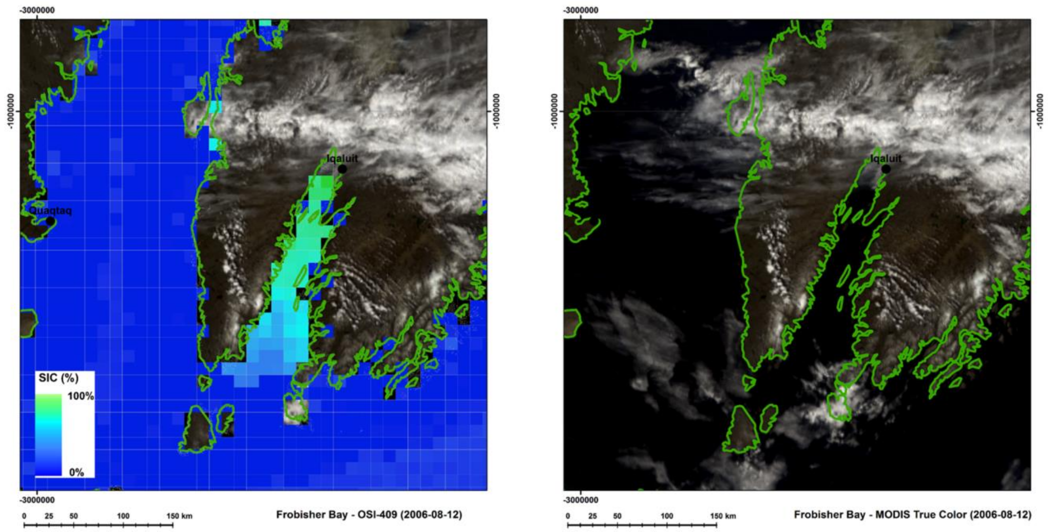

Figure 7: Frobisher Bay OSI-409 error and time concordant MODIS True Color composite (Vermote, 2017)

Such errors make it important to emphasize that the results obtained from the model are to be used with care and ideally in combination with other sources of information such as local knowledge, other remote sensing imagery and historical sea ice maps from national sea ice services.

4. Analysis of Hudson Bay sea ice spatiotemporal dynamic

The major asset of the IcePAC tool is that its output data gives a probabilistic perspective on relevant sea ice event, comparatively to the usual static descriptive statistics. Therefore, IcePAC gives not only the capacity to determine the mean event, but also to estimate the range of plausible events for a given site and date.

Here, the IcePAC outputs are used to assess the sea ice spatiotemporal dynamic given different probability scenarios and in terms of three cover indicators which are the length of the ice free season (or its corollary the ice covered season), the probable complete melt-out week and the probable complete freeze-up week.

4.1 Analysis with the IcePAC tool

Before presenting any results, the ice indicators analyzed in the next paragraphs must be clearly defined. First, the probable complete melt week corresponds to, for varying probability scenarios, the first week for which the SIC% is below 15 % at a given grid cell (starting its research from week 36 – September 1st – and up). Second, the probable complete freeze-up week corresponds to, for varying probability scenarios, the first week for which the SIC% is above 15 % at a given grid cell (starting its research from week 14 – April 1st – and up). To be considered valid, these events must be sustained at least 3 consecutive weeks. Finally, the probable duration of the ice free season corresponds to the gap, in weeks, between the different probable melt-out and freeze-up weeks.

The use of the 15 % limit to define presence or absence of sea ice is a convention used by many authors (Andersen et al., 2006; Cavalieri et al., 1997; Cavalieri et al., 1999; Divine and Dick, 2006; Gloersen et al., 1993; Pang et al., 2018) for SIC derived with passive microwave data and was therefore used in this analysis.

To estimate the aforementioned ice indicators, the probable SIC value for a given non-exceedance probability (p) was extracted from IcePAC for every location and week. For this analysis, a range of non-exceedance probabilities going from 5 % to 95 % were evaluated, with a step of 5 % between each analysis. Time series of the results were compiled and it is on these series that the complete freeze-up and melt-out events were identified. Figure 8 shows the estimated freeze-up and melt-out events weeks for p = 50 %.

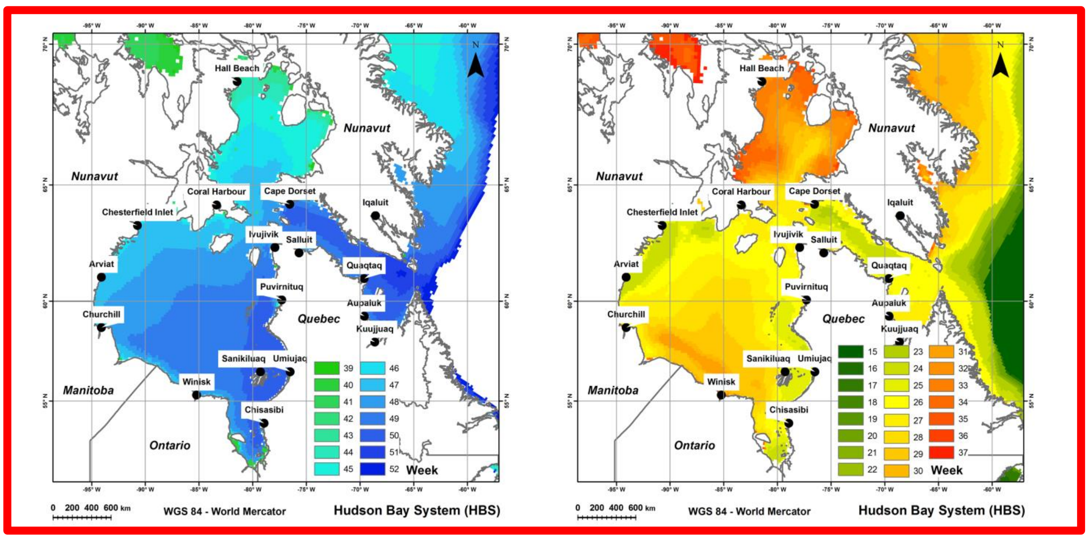

Figure 8: Estimated freeze-up (A) and melt-out (B) weeks for p=50 % in the HBS

This detection process was repeated for each of the 20 738 grid cells of the simulation domain and for each probability step. It is worth noting that while the melt is described as a non-exceedance event (SIC < 15 %), directly deduced from p, the freeze-up is actually defined as an exceedance event (SIC > 15 %), deduced from 1-p.

Figure 9A presents the probable freeze-up and melt-out events for the coastal community of Puvirnituq, located in the northeastern part of the Hudson Bay. In this figure we notice that melt has a 25% probability to be completed by week 25 (Jun. 18th to Jun. 24th), only a 10% probability of being completed for week 24 (Jun. 11th to Jun. 17th) and is certain to be completed by week 31 (Jul. 30th to Aug. 05th). According to the two curves plotted in Fig. (9A), we can state that a complete freeze-up and complete melt at Puvirnituq can be respectively expected, with a very high probability of occurrence (p > 95 %)

on weeks 50 (Dec. 10th to Dec. 16th) and 31 (Jul. 30th to Aug. 05th). Figure 9B shows an assessment of the range of probable ice free season duration made for the same coastal community. Here, the freeze-up curve is inversed (1-P) as the shortest possible ice free season duration is a combination of the latest possible melt (high exceedance probability) and the earliest possible freeze-up (high non-exceedance probability). By comparing the space between the two curves for the 5 % to 95 % probability range, we observe that the shortest possible ice free season at Puvirnituq is of 14 weeks and that the longest is of 26 weeks. Figure 9C shows the ice free season duration estimated for numerous coastal communities located in the study area using the method described for Fig. (9B). Particularly remarkable cases can be noticed such as Cape Dorset, which displays a large variability in possible ice free season duration given the shore lead polynya located in front of the community, Hall Beach in Foxe Basin with generally shorter ice free seasons with outliers corresponding to the occasional enlargement of the Hall Beach polynya and finally Winisk, located in the southcentral part of the Hudson Bay, where ice tends to form early and melt late, which explains the shorter ice free seasons when compared to other communities.

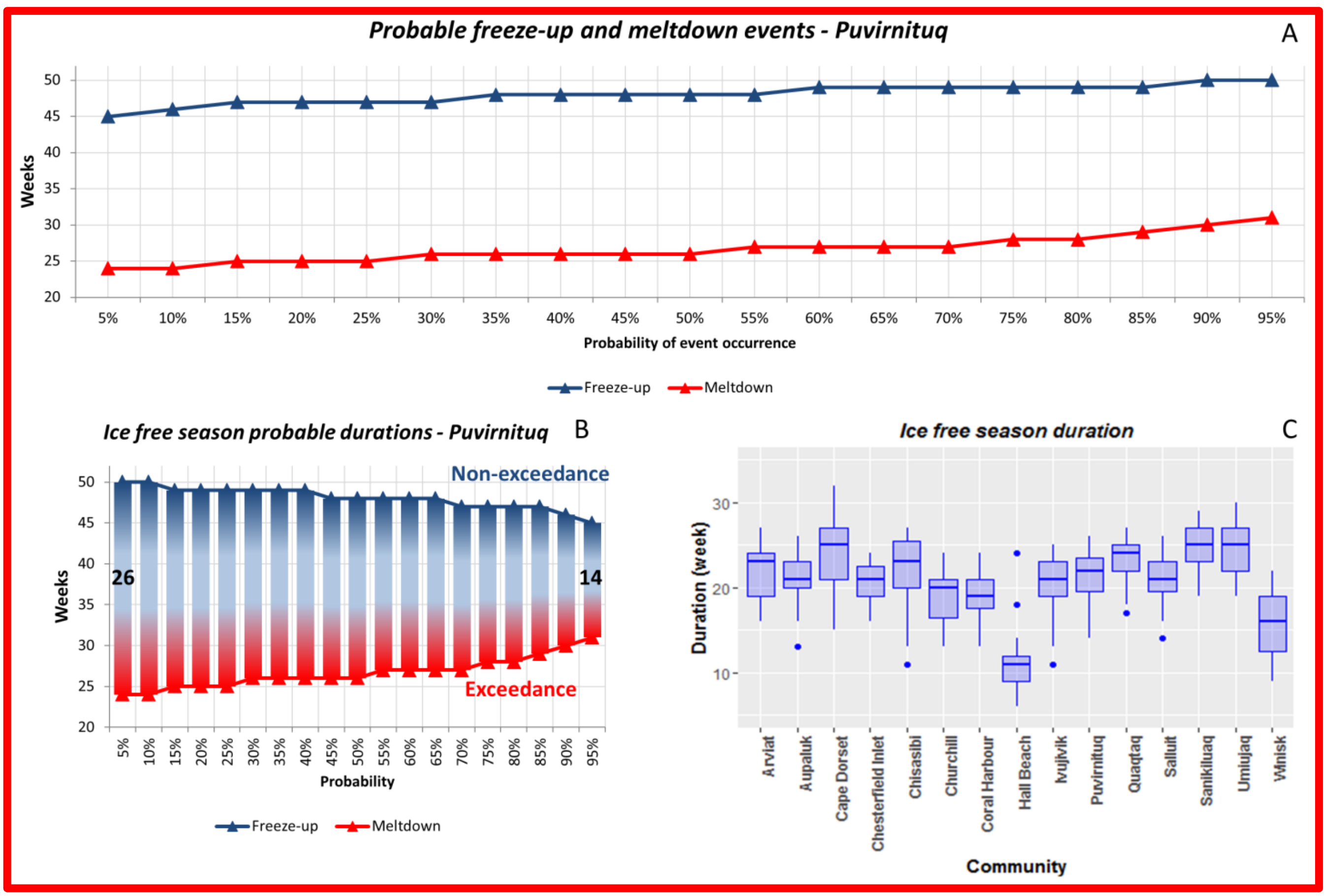

Figure 9: Probable freeze-up and melt-out events for the coastal community of Puvirnituq (A), range of probable ice free season duration for the same community (B) and probable ice free season lengths for all coastal communities of the HBS (C)

4.2 Comparison with the Canadian Ice Service Atlas

The HBS has been analyzed since 1972 (i.e. first regional Hudson Bay map) by the Canadian Ice Service (CIS) and they have gathered numerous sea ice conditions maps in the area from which they built a 30 years sea ice climatological atlas (CIS, 2013), portraying the average sea ice conditions, freeze-up and melt-out dates. As the information provided by the CIS atlas is given based on median SIC% values, a comparison with the p = 50 % IcePAC output gives an outlook on the coherency of the model when compared with another source of data, built around a different methodology.

The "Dates of Freeze-up and Break-up" charts of the CIS 1981-2010 atlas depict the extent of ice on a bi-weekly basis during the freeze-up and break-up periods (CIS, 2013). They provide a pictorial representation of the evolution of the ice extent during those two periods. The freeze-up and break-up dates are estimated using median values for 1981-2010 computed from CIS regional ice charts, a collection of over 40 years of data who were digitized in the late 1990's as raster with a 1km grid size. These charts were prepared by trained sea ice analysts who used as inputs to their analyses, high resolution RADARSAT images, since its acquisitions started in 1996, in combination with AVHRR, NOAA, SSM/I and ERS-1 data. However, all maps produced prior to 1996 were made without RADARSAT and therefore could be apprehended as "less accurate" then maps produced post-1996. The CIS also started using RADARSAT-2 in 2008. Another important information is that SIC% is estimated in tenths in CIS datasets in respect to the formalism of the egg code, meaning that SIC% marked as 1/10 in an egg code could be in reality any value between 10 and 19.99%. Considering this, ice presence is defined as SIC => 1/10 for CIS data (CIS, 2013) while we stated that it was an SIC% => 15 % for OSI-409.

Compared to the CIS data, IcePAC is based on algorithmically generated weekly averaged ice maps and calculated from adjusted frequency models. Also, there is a difference in spatial resolution between the two products; CIS uses 1km digitized historical ice charts while IcePAC uses passive microwave estimated SIC% resampled at 12.5 km grid size. Finally, there is a timeframe difference as the CIS atlas is built with data from 1981-2010 (30 years) while IcePAC is built with data from 1978-2015 (37 years).

The comparison, as displayed in Table 1, confirms that the freeze-up and melting dates identified by IcePAC are realistic when compared to the CIS historical data. Small differences in weeks are present and may be linked to a multitude of factors, the most important being the different methodologies used to generate the data.

The melt of the Hall Beach point does however come out as a relevant difference between the CIS and IcePAC melt week estimate. Since we find the freeze-up week adequately at the Hall Beach point and that we use the same model distribution to derive both the freeze-up and melt information, it would be incorrect to simply flag this point as erroneous.

The overestimation of the ice free season at Hall Beach by a 9 weeks gap compared to CIS could be explained by considering:

- the land spill-over effect that would make the OSI-409 overestimate SIC%;
- the fact that the selected point (Hall Beach) is located on the edge of the polynya area;
- that the melt week statistics aren't measured exactly on the same time period (1981-2010 versus 1978-2015);

- that we compare a CIS chart based on median of tenths SIC% values with IcePAC outputs based on OSI-409 SIC% averages and that the definition of melt isn't the same for both products (CIS is <= 1/10 while IcePAC is < 15 %).

By comparing the IcePAC P = 50% and P = 15% melt week output (Fig. 10) with the CIS melt dates, we can easily note that the CIS melt dates are quite variable in the polynya area and that by selecting a point a little further offshore, the results would have been comparable, advocating toward the land spill-over effect as a coherent explanation. However, as we also compared the CIS melt weeks with a lower probability scenario (P = 15%), it turns out that the Hall Beach polynya does appear close to the community, as expected. This specific situation is certainly linked to the fact that IcePAC uses average SIC% values compared to the CIS median values. As the SIC% in this specific area tend to be either very low (open polynya) or very high (consolidated sea ice cover), it is credible to think that the average and median values do differ considerably. In a case of frequent low concentration like the Hall Beach polynya, the median tends toward a low SIC% while the few higher SIC% events do bring the average SIC% up, increasing the gap between the median and the average values, enough so that with an average value we cannot detect the "melt-out", therefore giving a plausible explanation to the 9 weeks difference noticed here.

Table 1: Comparison between the CIS atlas and IcePAC p = 50 % modeled occurrence weeks for the freeze-up and melt-out events at selected sites in the HBS. (F = Freeze-up, M = Melting)

COMMUNITY	CIS (F)	CIS (M)	P=50% (F)	P=50 % (M)	DIFF. (F)	DIFF. (M)
Arviat	47	25	47	24	0	1
Aupaluk	48	28	48	27	0	1
Cape Dorset	49	24	49	24	0	0
Chesterfield Inlet	47	25	46	25	1	0
Chisasibi	NA	27	49	26	NA	1
Churchill	47	27	47	27	0	0
Coral Harbour	45	26	46	27	-1	-1
Hall Beach	43	23	44	32	-1	**-9**
Ivujivik	48	25	48	27	0	2
Puvirnituq	48	25	48	26	0	-1
Quaqtaq	48	25	49	25	-1	0
Salluit	49	24	48	26	-1	-2
Sanikiluaq	48	25	50	25	-2	0
Umiujaq	49	25	50	25	-1	0
Winisk	46	30	47	31	-1	-1

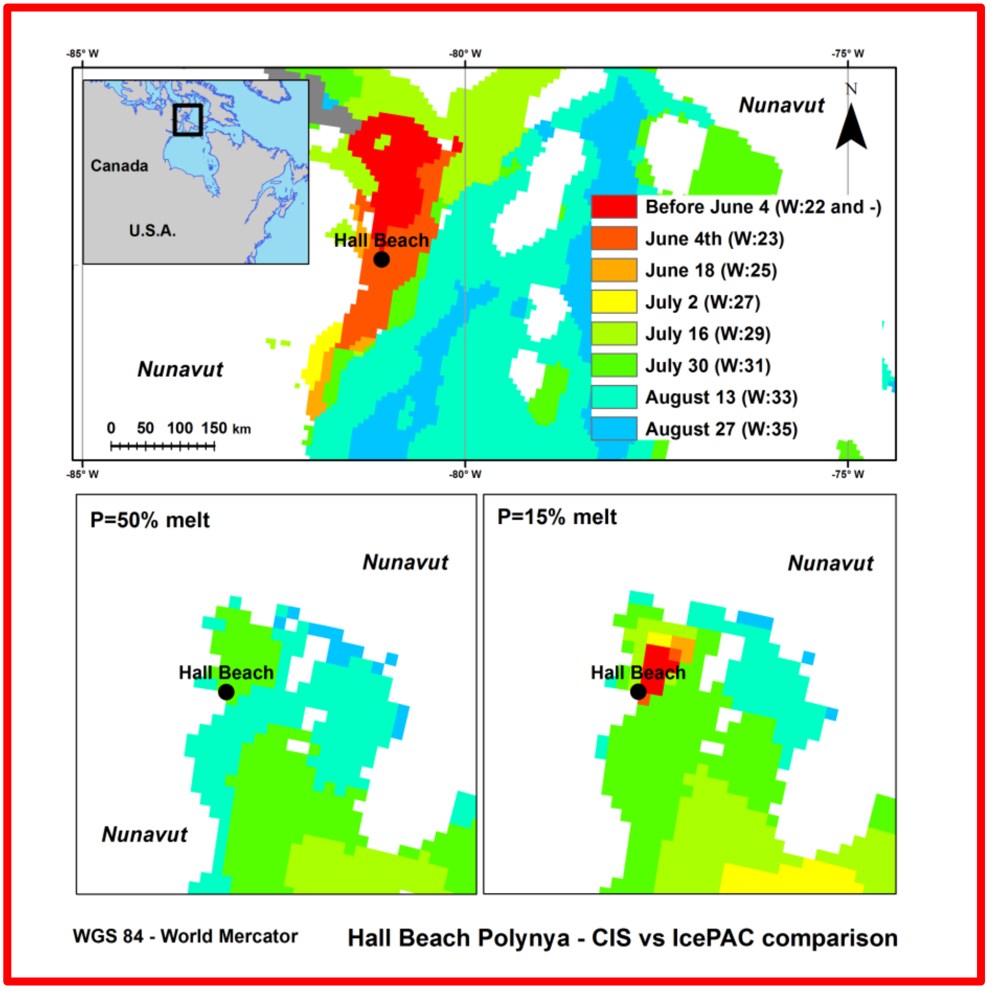

Figure 10: Comparison of probable melt weeks for the coastal community of Hall Beach in Foxe Basin with the CIS melt weeks (Up) and two IcePAC melt week scenarios for 50 % (Lower left) and 15 % (Lower right) probabilities. No data does appear north of the IcePAC outputs since Hall Beach is located at the upper limit of the IcePAC model test domain.

4.3 Applicability of the IcePAC approach to other locations and data sources

The IcePAC modelling approach is replicable to any site for which SIC% data are available. Evidently, to ensure relevance for the resulting probability maps, the length of the time series used as inputs to adjust the Beta models must be sufficient (~30 years). Logically, the simulation domain grid cells will fall in one of the three following categories: (1) Ice covered grid cells with constant high SIC%, during the stable cover period; (2) Marginal zone grid cells where SIC% will oscillate from high to low for the different years, during the freeze-up and melt periods; and (3) Open water grid cells with constant low SIC%, during the ice free season. As these are the ice regimes one could expect anywhere in the Arctic, including the HBS, there is no limitations on this side for using the IcePAC approach in other locations.

Other data sources could also be used with the IcePAC approach such as climate model outputs or different sea ice concentration maps. As climate model outputs provide future projections of SIC%, an evaluation of the range of probable SIC% patterns for a future year could be achieved (i.e. 2050 or 2080). However, one downside of these datasets is their coarse spatial resolutions.

5. Conclusion

The IcePAC tool permits an assessment of plausible sea ice related events for the entire range of probabilities for 20 738 sites (grid cells) in the Hudson Bay System, for all 52 weeks of the year. It is based on local (grid cells) models that use the generalized Beta distribution to describe the sea ice behaviour with four parameters at each site (with position and scale being fixed), based on historical 1978-2015 information from passive microwave imagery (OSI-409). From these parameters, IcePAC generates spatialized sea ice probabilistic information that can be used in any geographic information system or a web based map interface for further analyses.

An analysis has been made to define, for each grid cells in the simulation domain, the plausible scenarios for each probability. A subsequent comparison with 1981-2010 Canadian Ice Service sea ice climatology atlas (CIS, 2013) showed that the information generated with the IcePAC tool, for the p = 50 % case, renders coherent probabilities for freeze-up and melt events over the HBS. A noticeable difference in the melt weeks was detected for the community of Hall Beach, suggesting that using median values instead of average SIC% could be of interest in order to be able to adequately detect specific events like polynyas. Another analysis, focused the community of Puvirnituq, showed that it is possible to evaluate locally the range of plausible scenarios in term of ice free season length.

The model outputs generated with the IcePAC tool are providing a novel probabilistic perspective regarding important events related to sea ice dynamics that was not available before. With its capacity to be utilized in other areas (with respect to the grid size of the passive microwave product), and the fact that it could easily be updated using new data, the IcePAC tool has the potential to provide valuable information on probable freeze-up and melt weeks as well as on ice presence and ice free season lengths.

This relevant information will help decision makers such as engineers wanting to build a new marine coastal or offshore infrastructure estimate ice hazards, fauna specialists trying to understand the vulnerability of a given species living dependent of the ice cover or a mariners wanting to estimate the feasibility of navigating a certain route. Turning the raw probabilistic information gathered from IcePAC into valuable thematic information will give stakeholders a plus-value to apprehend the possible spatiotemporal sea ice concentration patterns and to prepare for an effective mitigation of climate change impacts on the coastal and offshore environments.

IcePAC data is available on a web interface at http://icepac.ete.inrs.ca.

Author Contribution

CG defined the objectives of this research project, processed the data, coded the IcePAC tool, analysed the results, wrote and reviewed this research paper. MB and KC participated in defining the objectives, guiding the development of the tool and writing this paper.

Competing Interests

The authors declare no conflicts of interest.

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