Thermodynamic and Dynamic Ice Thickness Changes in the Canadian Arctic Archipelago in NEMO-LIM2 Numerical Simulations

Xianmin Hu, Jingfan Sun, Ting On Chan, and Paul G. Myers

January 17, 2018

Reply to Reviewer 1:

We thank reviewer 1 for pointing out the misleading title, as well as the other comments. We have updated the draft. Details are given as follows.

Answer to general comments: "Hu and others developed and presented a high resolution model to look at simulated sea ice thickness in the CAA from 2002-2016. They compared their model output to ice thickness from the Canadian Ice Service. From the title, I was expecting the authors to look at thermodynamic and dynamic processes contributing to variability and change but they only scratched the surface. Overall, I feel the authors did not really use the model to its full potential. I think some additional analysis and interpretation is required and I offer the following suggestions:

1. I was very surprised the authors chose not to look at the entire CAA ice thickness time series separating out dynamic and thermodynamic from 2002-2016 similar to their Figure 4 site specific plots. Doing this would probably illustrate when (and then where) changes in these processes are occurring over the longer term record and this certainly would allow for more discussion. Also, related to thickness distribution changes they could investigate if the model can identify the regions of very thin ice (i.e. invisible polynyas) similar to Melling et al. 2015 and look at longer term variability."

We apologize for the old misleading title. We were not focusing on the inter-annual variability but wanted to present the spatial distribution and seasonal cycle in the original draft. "Change" was used in the title to avoid "negative seaice growth" (melting period).

However, it turned out be more misleading. We changed the title to "Thermodynamic and dynamic ice thickness contributions in the Canadian Arctic Archipelago in NEMO-LIM2 numerical simulations" to make it clear. In addition, we added a new chapter on ice volume budget in the northern CAA, Parry Channel and Baffin Bay to better describe the ice changes in our study area. We do see some polynya features, e.g., relatively thinner thickness, in the ice thickness field or the dynamic component of the ice thickness contribution, but the simulations does not produce thin enough or a good enough concentration field to investigate the polynya processes in detail. We keep that in mind for future investigation.

"2. Section 3.2.1 provides useful information by separating the dynamic and thermody- namic component of ice thickness but it would also be better use the model to identify locally grown MYI from MYI advected from the Arctic Ocean. It would be also be use- ful to spatially illustrate changes in the source of MYI. Furthermore, why not construct an ice mass budget for the CAA and look at how it changes from 2002-2016? These additions would give more substance to the manuscript."

A section about ice volume budget is added to provide some related information. Note that with LIM2, we can not identify the MYI directly.

"3. Why did the authors chose to start the study in 2002? I would think looking at longer term changes would provide more useful information to the readers and provide more opportunity to compare to Sou and Flato (2009)."

This is due to the availability of the atmospheric forcing. The high resolution CGRF data set goes back to 2002 only. Even with other forcing data, the computation cost, limits our ability to carry out long runs of 1/12 degree resolution.

Answer to specific comments:

- "Page 1, Line 1: Sea ice thickness evolution within the Canadian Arctic Archipelago (CAA) is of great interest. Why?"
  Changed to "Sea ice thickness evolution within the Canadian Arctic Archipelago (CAA) is of great interest to science, as well as local communities and their economy"

- "Page 2, Line 5 National security issues?"
  Changed "secucrity" to "safety"

- "Page 2, Line 5 Replace opening with using"
  Done as suggested.

- "Page 2, Line 13 The dates of that study are from 1979-2008. Does this statement still hold true? Looking at recent work posted on The

Cryosphere Discussion appears to indicate large changes have occurred in the last 10-years which could negate that statement. Rephrase. See Mudryk et al. (2017) in The Cryosphere Discussions."

Updated based on the recommended reference. The revised version is " Reduction in the September MYI cover is also found to be -6.4% per decade until 2008 (Howell et al., 2009). But this trend was not yet statistically significant due to the inflow of MYI from the Arctic Ocean mainly via the Queen Elizabeth Islands (QEI) gates in August to September (Howell et al., 2009). With extended data in recent years (until 2016), Mudryk et al. (2017) showed that the summer MYI decline rate has almost doubled"

- "Page 2, Line 23 Replace export with transport and replace in the past with known to occur."
  Changed as suggested.
- "Page 6, Lines 9 to 18 I think it is important to state that the sites are all on landfast sea ice."
  Added text to make is clear the observations are landfast ice. To evaluate the performance of the model in terms of ice thickness, simulated ice thickness is compared to the observed landfast ice data from Environment and Climate Change Canada (ECCC) New Icethickness Program (hereafter ECCC thickness).
- "Page 6, Table 2 I think the reader could better identify with actual place names and not an acronym."
  Agree. We use full names in both table 2 and texts now in the revised version. Acronyms are now used only in figure 1 to keep it concise.
- "Page 8, Line 10 It would be useful to include some correlation coefficient values for comparison."
  We think the correlation in our case could be biased by the seasonal cycle. In the revised version, we added the seasonal cycle plot. It provides more information to our current comparison. Our time series might be too short to provide a robust interannul correlation.
- "Page 24 Could you confirm this by looking at a long time series? Im puzzled by the 2002 start date."
  It is due to the availability of our high resolution atmospheric forcing data.
- "Page 11, Line 5 It is been shown MYI flows down into these regions. How much is convergence compared to thick MYI?"
  In LIM2, we can not identify the MYI. Thus, we can not accurately do this task. We hope the reviewer is happy with our new ice budget section.

- “Page 12, Section 3.3 A lot of methodology and techniques are being introduced the results section. Suggest moving to methods.”
  Moved the the methodology and techniques texts to method section, “2.3 Wavelet analysis” as suggested.

- “Figure 2. There are no y and x-axis labels.”
  Added as suggested.

- “Figures 4-6 No y-axis labels. Also, why not produce this figure for the entire CAA? That would be more useful and also show changes in ice thickness (dynamic versus thermodynamic) over a 15-year period. I dont feel the work reflections the title. See major suggestion 1.”
  Added the y-axis labels. We were focusing on the spatial distribution over the CAA rather than how it behaves over the entire region. It does show significant spatial variability. It is better to average over a region with fields that do not vary a lot in space. Anyway, we think the new ice budget section provides interesting information.

Thermodynamic and Dynamic Ice Thickness Changes in the Canadian Arctic Archipelago in NEMO-LIM2 Numerical Simulations

Xianmin Hu,Jingfan Sun, Ting On Chan and Paul G. Myers

January 17, 2018

Reply to Reviewer 2:

We thank reviewer 2 for pointing out various issues with our manuscript. Here are our responses.

Answer to general comments:

"This manuscript compares simulated sea-ice thickness profiles with those from observation from a handful of locations in the Canadian Arctic Archipelago. I have a hard time pinpointing the overall purpose of the manuscript. The observations seems to indicate largely thermodynamic growth and melt i.e. relatively smooth seasonal cycles with production of 1.5 - 2m of ice during the winter which then melts out during the summer. The model simulations seem to capture this well at some locations, while at other locations there are discrepancies between the obs. and the simulations. This point is discussed in passing in the manuscript; however a much more thorough explanation of this issue is of interest. This is particularly problematic considering that Dumas et al (2006) have shown that a 1-D thermodynamic model can largely recreate observed sea-ice thickness in the CAA at the same locations.

Furthermore, I find the methods used to compare the in-situ (point) observations to the model output to be unsatisfactory. The sea-ice thickness from the simulations as described by the author is a grid-cell mean - i.e. already smoothed compared to the observations. Yet, the authors go on to further smooth the model output with a 9 grid cell stencil. This issue likely does not substantially change the results of the comparison since the ice growth/melt is largely thermodynamic (relatively smooth and large decorrelation length scale). However, this choice to further smooth the fields is confusing and does not make logical sense.

The authors separate the dynamic and thermodynamic contributions to the change in sea-ice thickness during the Arctic winter. This is the most interesting part of the manuscript and should be expanded on. The results indicate a net thinning of the ice in Baffin bay due to dynamics and an associated thermodynamic growth. I suspect this is due to the formation of polynyas and the resulting first year ice production in Nares Strait region. It would be interesting if the authors could show timeseries of the separated thermodynamic and dynamic growth at some of these points to see if/when the polynya forms every year. It would also be useful to add a panel to figure 3 which shows the difference between panel a and panel b in order to see the full Δ_h field.

In my opinion, one of the interesting questions that arises from this manuscript is: why does the model produce much thicker ice at Eureka and Alert compared to the observations? Why is the magnitude of the interannual variability at Alert in some sim- ulations/years so much greater than all other locations. The manuscript would be more relevant and useful to the community if this was investigated and a solution proposed to fix this issue.

The manuscript goes on to present a complicated wavelet analysis to study the seasonal and diurnal cycle in sea-ice thickness. This analysis is entirely unnecessary as it is expected (and obvious) that there is a seasonal cycle in sea ice thickness. Furthermore, the seasonal cycle is already clearly shown in the obs and simulations in figure 2. The analysis of the diurnal cycle dummer is also unnecessary as the conclusion is exactly what must be the case- i.e. daytime melt overwhelming slight nighttime freezing.

I would also encourage the authors to generally use a simpler and more concise sentence structure. There are many long and confusing sentences which makes it difficult to follow the authors arguments."

First, in our original comparison, we did not address clearly the differences between in-situ observed and simulated ice thickness. This is pointed out by #3 reviewer. The observation (ECCC site data used in this study) represents the "immobile level first-year (seasonal) ice of the uniform thickness that forms close to shore, and is forced by thermodynamic processes". Second, we have to consider the differences between 1d and 3d simulations. The on site ice thickness can be better or easier captured by the 1d simulation, e.g., in Dumas et al. (2006). But, in 3d coupled ocean and sea ice simulations, it is very difficult to reproduce such local behavior because of the resolution of both the model and atmospheric forcing data. However, we need 3d simulations to better understand seaice processes, particularly when they are not dominated by thermodynamics and their spatial distribution.

An estimate of the skill of the model is needed but very limited time series are available for a fair comparison. Neither the inter-

polation or the nearest point method is perfect in such comparisons because it is essentially not resolved by such simulations. Thus, we do not think the method used in this study itself affects our results here.

The differences between the observed and simulated ice thickness also explain the reviewer's question on ice thickness at Eureka and Alert.

The polynya related questions are great and interesting questions. We think they could be further investigated in a future study. In this study, we focus more on the big picture aspects of the simulations.

For the wavelet analysis, the simulations do show the fact (seasonal and diurnal cycle) that we might have expected from the real world. Instead of thinking "it must be the case", we prefer to show and quantify it. In addition, we do think it is a good thing to see that the model can reproduce the basic physical processes because models do not always do the right thing. Thus, we still think we do have some scientific contribution in this study.

Answer to particular issues:

- "P1 L12-13: It is well known that thermodynamic growth of ice is inversely proportional to thickness. This is not a contribution of your work."
  We think this sentence should be read considering the contex of the whole abstract. We are trying to describe what we see based our analysis (thus it is part of our results), but not to declare that we are the first one who found "thermodynamic growth of ice is inversely proportional to thickness".

- "P2 L8: 10% of the sea-ice area? Or volume? Please clarify"
  Added "volume" in the text.

- "P2 L20: Landfast Ice implies u=v=0, not just 100% concentration"
  Added "without motion" to the text.

- "P2 L28: Model simulations are not substitutes for in-situ observations. Your manuscript is showing discrepancies between the obs and the simulations!"
  We did not attempt to express that model simulations can replace the in-situ observations. The point here is to say why we need numerical simulations and that we need to evaluate them and understand their strengths and weaknesses.

- "P4: L17-20: There are many more recent and informative studies regarding the time scale and decay of the artificial elastic waves. From my experience, your choices of number of subcycles is far too low particularly at 1/12 degree resolution. See for instance: Lemieux et al (2012), Boullion

et al (2013), Kimmritz et al (2016), Williams et al (2017)."
We added the suggested references."Note that recent studies (e.g., Lemieux et al., 2012; Bouillon et al., 2013; Williams et al., 2017) showed that more iterations are needed to reach a viscous-plastic (VP) solution. Without doing that, the divergence field will be affected, i.e., being noisy (Dupont, 2017, personal communication). Thus, to what degree it will impact the final averaged ice thickness will vary in space. Such an investigation in the CAA is beyond the scope of this study."

- "P4 L27: How are the 33km wind fields used to force the simulations with different spatial resolutions? There seems to be many issues which could arise here."
We added the text "These forcing fields are linearly interpolated onto model grid". This is done using the NEMO on-the-fly interpolation, which is a standard way to do this in numerical models.

- "P5 L5: It is unclear how the CORE II simulations incorporate the interannual variablity of the atmospheric forcing. What is the climatological mean? This deserves more explanation."
The CORE-II dataset provides the inter-annual atmospheric fields although with different temporal and spatial resolutions. The climatology of the data set is documented in the reference, Large and Yeager (2009). We understand the CORE-II inter-annual dataset is based on a mixture of NCEP reanalyses and satellite observations with adjustments. This is different from the CGRF (from a GEM simulation) used in other simulations involved in this study. However, the differences between the forcing fields and their impacts are not the focus of this study.

- "P7 - see 3rd paragraph in general review"
An estimate of the skill of the model is needed but very limited time series are available for a fair comparison. Neither the interpolation or the nearest point method is perfect in such comparisons because it is essentially not resolved by such simulations. Thus, we do not think the method used in this study itself affects our results here.

- "P8 - see 1st and 4th paragraph in general review"
First, in our original comparison, we did not address clearly the differences between in-situ observed and simulated ice thickness. This is pointed out by #3 reviewer. The observation (ECCC site data used in this study) represents the "immobile level first-year (seasonal) ice of the uniform thickness that forms close to shore, and is forced by thermodynamic processes". The differences between the observed and simulated ice thickness also explain the reviewer's question on ice thickness at Eureka and Alert.

- "P8 L25 Its not clear how the data assimilation is taking place. What fields are being assimilated, and in which simulations? How does this affect the results? What if no assimilation is done?"
  We changed the text to "which is likely due to data assimilation in GLORYS2v3" to make it clear. Data assimilation is done only in GLORYS2v3 here, and the technical details of the data assimilation in GLORYS2v3 is documented in the reference, Masina et al., (2015). In their simulation, only the concentration field is assimilated for seaice. Basically, we are including this additional experiment to show that data assimilation can change the model behavior in the region but not necessarily make it closer to observations.

- "P9 Fig 2: All of the observed timeseries look similar in this figure. Perhaps another figure showing the differences due to location would be useful."
  Different y-axis scales were used in the plots. The observations were not sampled at the same time, thus interpolation will be involved for the difference-type plot. We tried to keep the original data as close as possible. Thus, we added "Different y-axis scales are used." in the caption to make it clear. As well, the addition of figure 3 with the mean seasonal cycles, helps highlight the differences.

- "P12-15: Full timeseries of these fields would be much more interesting to see at these locations rather than seasonal cycles. This would allow us to see if there is a correlation between particular dynamic events and the thermodynamics feedbacks that we expect. Perhaps keep the seasonal cycles as well for completeness."
  Agree the timeseries without averaging can help to see whether there is any interaction between the two processes but the full timeseries are hard to read on paper unless presented one row for each year. We did have one example at Resolute for 2012 only in our original draft (fig 6 in the old version, and now fig 7 in the revised version). We can add them if the editor think they are worth the space.

- "P16-20: I do not see what this analysis adds to the story. We already see that there is a seasonal cycles and it must be that daytime melt outweighs nighttime freezing during the melt season."
  This analysis presents information on the dominant periods of variability (thermodynamic), the lack thereof in terms of the dynamics as well as some detailed information on the details of thermodynamic changes during the break-up period. Thus we think this material is worth retouching.

Answer to specific comments:

- "P1 L11: A relatively small"
  Changed.

- "P1 L22- P2 L4: Confusing, rephrase"
  Rephrased to "Economically, shipping through the CAA , via the Northwest Passage (NWP), is of particular interest to commercial transport between Europe and Asia because of the great distance savings compared to the current route through the Panama Canal (e.g., Howell et al., 2008; Pizzolato et al., 2016, 2014). This has been a hot topic under the context that Northern Hemisphere sea ice cover has been declining dramatically (e.g., Parkinson et al., 1999; Serreze et al., 2007; Parkinson and Cavalieri, 2008; Stroeve et al., 2008; Comiso et al., 2008; Parkinson and Comiso, 2013), especially after 2007."

- "P2 L13: Rephrase. Also remove the quotes around statistically significant"
  The quoted words are from the original reference. We think it is the proper way to cite the original words from a reference. We rephrased the the sentence to "Reduction in the September MYI cover is also found to be -6.4% per decade until 2008 (Howell et al., 2009). But this trend was not yet statistically significant due to the inflow of MYI from the Arctic Ocean, mainly via the Queen Elizabeth Islands (QEI) gates in August to September (Howell et al., 2009). With extended data in recent years (until 2016), Mudryk et al. (2017) showed that the summer MYI decline rate has almost doubled" to make it clear.

- "P2 L17: There are"
  Corrected.

- "P2 L24: conditions"
  Changed.

- "P4 L19 can does not make sense here. No-slip boundary conditions define that the velocity is zero at the coast line"
  Removed as requested.

- " P6 L6: This sentence is unclear and further explanation of the assimilation process is required."
  This sentence has been removed.

- "P6 L12: delete only"
  "only" here is to address the number of observation sites is less in the New Icethickness Program compared to the original one. So we prefer to keep it.

- “P6 L13: delete period”
  Removed.
- “P7: L9: calculation”
  Corrected.
- “P9 L3: Cambridge Bay rather than the Cambridge Bay”
  Corrected.

Thermodynamic and Dynamic Ice Thickness Changes in the Canadian Arctic Archipelago in NEMO-LIM2 Numerical Simulations

Xianmin Hu, Jingfan Sun, Ting On Chan, and Paul G. Myers

January 17, 2018

Reply to Reviewer 3:

general comments: "This is an interesting study, comparing sea ice thickness simulations from a numerical model with landfast ice thickness observations at eight sites in the Canadian Arctic Archipelago, separating simulated changes in ice thickness into thermodynamic and dynamic contributions, and describing diurnal oscillations in ice thickness and thermal ice production. However, I feel that the purpose of the work is not clearly articulated. I suggest it could say something like first, to evaluate the skill of a numerical model in simulating sea ice thickness by comparing the simulations with observations of landfast ice thickness at several sites in the CAA. Two features of the simulations will be then be discussed: 1) the relative importance . . .. I also feel that the paper does not make sufficiently clear the difference in the properties of the observation data versus the simulation data. The observation data represents immobile level first-year (seasonal) ice of uniform thickness that forms close to shore, and is forced by thermodynamic processes. The simulation data (page 8, line 12) gen- erally represents ice found beyond the near-shore ice and is a mixture of deformed (ridged/rafted) and level first-year ice, young ice and old (perennial) ice, is mobile for part of the year, and is forced by both thermodynamic and dynamic processes. The degree to which we should expect them to agree therefore depends on the concentration of old ice and deformed ice, differences in the timing of freezeup/breakup, etc.

I think that more detail is required to describe the skill of the model. The summary (but not the abstract) mentions the capability of capturing the seasonal cycle and amplitude of ice thickness. This would be clearer if the seasonal cycles were plotted as in Howell et al. (2016). In addition, such a plot would more clearly show the differ- ences/agreement between model results and observations at Resolute and Cambridge Bay. Perhaps the dynamic processes in

Figures 4 and 5 could then be used to explain, in part, these differences. Does the model have any significant skill with respect to interannual variability (or does it not, because of snow depth variations on small horizontal scales)?"

We thank reviewer #3 for the comment about the differences between different types of sea ice, particularly on the site observations ("immobile level first year ice"). This helps us a lot in understanding the discrepancies between the simulated and observed ice thickness. We added the related text both in the data section and the comparison section to state the differences clearly. Please see more in our detailed answers. In the revised version, we added a new section on the ice volume budget within different regions in our study area. Comparisons with previous studies are also included to support the inter-annual variability seen in our results.

minor comments:

- "Page 1, lines 3-6: the model captures well the general spatial distribution . . . (4m and thicker). While this may be true, the model was compared with landfast ice thickness observations (first year ice only, no old ice or deformed ice), that are generally not much greater than 2m. Why not describe a general comparison with published data from IceSat, CryoSat or other sources (e.g. Laxon et al., 2013; Tilling et al.,2015), which include the thicker ice types?"
We added the related references of ice thickness observations to support our statement. "Here we focus on the ice growth process between December and April of the following year. Figure 4a and 4b show the simulated ice thickness in ANHA12 at the beginning of December and at the end of April, respectively. Geographically, at the end of April, a) very thick sea ice is located in the northern CAA ($\sim$ 4 m by the end of April) with regional maximum ($> 4.5\,m$) at the openings to the Arctic Ocean. This is consistent with the ICESat and Cryosat-2 estimations (e.g., Laxon et al., 2013; Tilling et al., 2015; Kwok and Cunningham, 2015). b) less thick sea ice covers western, and central Parry Channel (just in the west of the site Resolute) and MClintock Channel with a thickness of 2.5 m to 3 m. These values are similar to previous obser- vations from airborne electromagnetic surveys (Haas and Howell, 2015) and satellite (Tilling et al., 2017). "

- "Page 1, lines 6-8: What is meant by compares well? Do you mean the

seasonal cycles and amplitudes, as stated in the summary? Is agreement with first-year landfast ice better in the south because there are low concentrations of old ice?"
To make it clear, the text has been revised to "simulated ice thickness compares reasonably (seasonal cycle and amplitudes) with weekly Environment and Climate Change Canada (ECCC) New Icethickness Program data at first-year landfast ice sites but not at the northern sites with high-concentration of old ice".

- "Page 1, line 13: Add at two sites after ice fields"
  Added as suggested.

- "Page 2, line 34: this downward trend is mostly associated with changes in snow depth. The meaning of this is not clear. Do you mean that in most cases, the down- ward trend in ice thickness is associated with a positive trend in snow depth (since ice thickness is negatively correlated with snow depth)? Only one of the cases had a significant trend in snow depth, and it was negative, not positive."

  We revised to "They found statistically significant thinning at the sites except at Resolute, and the detrended inter-annual variability is highly (negative) correlated with snow depth due to insulating effect of the snow (Brown and Cote, 1992)."

- "Page 3, line 3-4: Change a sea ice model to several sea ice models?"
  No. Here the sea ice model is refered to LIM2 sea ice model. The same sea ice model is used for all the simulations included in this study.

- "Page 6, line 12: Were three of the 11 stations omitted from the analysis because they were on lakes?"
  Yes. We inserted "The remaining three sites are on lakes (not included in our simulations)." in the revised version.

- "Page 6, line 16 and elsewhere: The paper would be much easier to read if the full names (not acronyms) were used for the station locations."
  Changed as suggested. We use full names in both table 2 and texts now in the revised version. Acronyms are now used only in figure 1 to keep it concise.

- "Page 8, line 10: The 3 sites with poor agreement between simulations and observations are in areas with significant concentrations of old ice, while the sites with reasonable agreement are in areas without (see Canadian Ice Service (2011)). Is this the basic reason for the poor agreement at the 3 sites?"
  Yes. We added as suggested. "The sites where the model produced much thicker ice are likely where significant concentration of old ice exists (CIS, 2011)."

- “Page 8, line 11: I suggest adding a plot of the seasonal cycles of the models and observations (as in Howell et al 2016, Figure 8). This would make it easier to visualize the asymmetric seasonal cycles and summarize the differences in amplitude etc. between the various models.”
  Added as suggested as fig 3.

- “Page 8, line 21: too thick sea ice. What would be a realistic sea ice thickness, based on the literature, given that there are significant concentrations of old ice in the area?”
  We have revised the texts to “At Eureka, Alert and Alert LT1 sites (Fig. 2 and 3, e, f, and g), there are clear differences between the simulated ice thickness and the observations (2 m at Alert/Alert LT1 and 1 m at Eureka). Note neither ANHA4 or ANHA12 has the capability to resolve the difference between Alert and Alert LT1, thus, the same simulated values are shown on the figure for both sites. The differences between simulations and observations could be an initial value problem, particularly at Eureka (Fig. 2g). However, given high concentrations of old ice are at these sites, observations represent the immobile level first-year ice only. Thus, the model and the observations may not be representing the same type of ice.

- “Page 10, line 6-7: The meaning isnt clear. Thus, it is likely due to another physical process such as advection from surrounding areas (?)”
  Changed as suggested.

- “Page 17: I suggest reversing the order of Figure 8 and 9, so that they are in the same order as in the text.”
  Changed as suggested.

Answer to minor comments:

- “Page 1, Line 21: overturning”
  Corrected.

- “Page 2, line 17: there are still”
  Corrected.

- “Page 2, line 30: evaluated the”
  Corrected.

- “Page 4; Table 1: subcycling (?)”
  Corrected.

- “Page 6, lines 16 and Table 2: Change Carol to Coral.”
  Corrected.

- “Page 8, line 19: Add (Fig. 2c and d).”
  Added as suggested.
- “Page 8, line 20: Change MEU to WEU.”
  Corrected to full name “Eureka”.
- “Page 8, line 24: green line (add space)”
  Corrected.
- “Page 8, line 34: Add .”
  Corrected.
- “Page 10, line 21: just south of the site YRB (?)”
  Changed to “just to the west of the site Resolute”.
- “Page 12, line 4: spatial”
  Corrected.
- “Page 16, line 9: supports the notion that (?)”
  Changed as suggested.
- “Page 19, line 4: constraints”
  Corrected.

Thermodynamic and ~~Dynamic Ice Thickness Changes~~ dynamic ice thickness contributions in the Canadian Arctic Archipelago in NEMO-LIM2 ~~Numerical Simulations~~numerical simulations

Xianmin Hu[1,+], Jingfan Sun[1,++], Ting On Chan[1,+++], and Paul G. Myers[1]

[1]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, T6G 2E3, Canada
[+]now at Bedford Institute of Oceanography, Fisheries and Oceans Canada, Dartmouth, Nova Scotia, Canada
[++]summer intern from Zhejiang University, 38 Zheda Road, Hangzhou, China, 310027
[+++]now at Skytech Solutions Ltd., Canada

Correspondence to: Xianmin Hu(xianmin@ualberta.ca)

Abstract. Sea ice thickness evolution within the Canadian Arctic Archipelago (CAA) is of great interest to science, as well as local communities and their economy. In this study, based on the NEMO numerical frame work including the LIM2 sea ice module, simulations at both $1/4°$ and $1/12°$ horizontal resolution were conducted from 2002 to 2016. The model captures well the general spatial distribution of ice thickness in the CAA region, with very thick sea ice ($\sim 4m$ and thicker) in the northern CAA, thick sea ice ($2.5m$ to $3m$) in the west-central Parry Channel and M'Clintock Channel, and thin ($< 2m$) ice (in winter months) on the east side of CAA (e.g., eastern Parry Channel, Baffin Islands coast) and ~~water~~ in the channels in southern areas. Even though the configurations still have resolution limitations in resolving the exact observation sites, simulated ice thickness compares ~~well~~ reasonably (seasonal cycle and amplitudes) with weekly Environment and Climate Change Canada (ECCC) New Icethickness Program data at ~~nearby sites except in the north~~first-year landfast ice sites except at the northern sites with high-concentrations of old ice. At $1/4°$ to $1/12°$ scale, model resolution does not play a significant role in the sea ice simulation except to improve local dynamics because of better coastline representation. Sea ice growth is decomposed into thermodynamic and dynamic (including all non-thermodynamic processes in the model) contributions to study the ice thickness evolution. Relatively smaller thermodynamic contribution to ice growth between December and the following April is found in the thick and very thick ice regions, with larger contributions in the thin ice covered region. Wavelet analysis of the hourly simulated ice fields at two sites clearly shows the thermodynamic contribution ~~have~~ has seasonal and diurnal cycles while only the seasonal cycle is significant for the total ice thickness. High frequency changes are found in both fields during the sea ice melting and formation process, particularly in the melting season. No significant variation in winter maximum ice volume is found in the northern CAA and Baffin Bay while a decline ($r^2 \approx 0.6, p < 0.01$) is simulated in Parry Channel region. The two main contributors (thermodynamic growth and lateral transport) balance each other with large inter-annual variability, but further quantitative evaluation is required.

1 Introduction

The Canadian Arctic Archipelago (CAA), the complex network of shallow-water channels adjacent to the Arctic ice pack, has been a scientific research hot spot for a long time. Scientifically, it is an important pathway delivering cold fresh Arctic water downstream (e.g., Prinsenberg and Hamilton, 2005; Melling et al., 2008; Dickson et al., 2007; Peterson et al., 2012), that eventually feeds the North Atlantic Ocean, where the watermass formation and ocean dynamics play a key role in the large scale meridional overturing overturning circulation (MOC) and global climate variability (e.g., Rhein et al., 2011; Hátún et al., 2005; Marshall et al., 2001; Vellinga and Wood, 2002). Economically, under the context that Northern Hemisphere sea ice cover has been declining dramatically (e.g., Parkinson et al., 1999; Serreze et al., 2007; Parkinson and Cavalieri, 2008; Stroeve et al., 2008; Comiso especially since 2007, shipping through the CAA , via the Northwest Passage (NWP), is of particular interest to commercial transport between Europe and Asia because of the great distance savings compared to the current route through the Panama Canal (e.g., Howell et al., 2008; Pizzolato et al., 2016, 2014). This has been a hot topic under the context that Northern Hemisphere sea ice cover has been declining dramatically (e.g., Parkinson et al., 1999; Serreze et al., 2007; Parkinson and Cavalieri, 2008; especially after 2007. Besides the harsh weather and other security safety issues (e.g., icebergs), the biggest concern for the opening of the using the NWP is still the condition of sea ice, especially high concentrations of thick multiyear ice (MYI) (Melling, 2002; Howell et al., 2008; Haas and Howell, 2015).

Lietaer et al. (2008) estimated about 10% of the total Northern Hemisphere sea ice volume is stored within the CAA. Sea ice within the CAA region is a combination of both first-year ice (FYI) and MYI. MYI is both locally formed and imported from the Arctic Ocean, and normally located in the central-west Parry Channel and the northern CAA (e.g., Melling, 2002; Howell et al., 2008, 2013). Since the late 1970s, the ice free season has extended by about one week per decade (Howell et al., 2009), with a statistically significant decrease of 8.7% per decade in the September FYI cover. Reduction in the September MYI cover is also found (to be -6.4% per decade) but until 2008 (Howell et al., 2009) . But this trend was not “yet statistically significant” due to the inflow of MYI from the Arctic Ocean mainly via the Queen Elizabeth Islands (QEI) gates in August to September (Howell et al., 2009, 2013) . (Howell et al., 2009) . With extended data in recent years (until 2016), Mudryk et al. (2017) showed that the summer MYI decline rate has almost doubled. Even though the Arctic Ocean ice pack also extends to the CAA region through M‘Clure Strait, the net sea ice flux is small and usually leads to an outflow from the CAA (Kwok, 2006; Agnew et al., 2008; Howell et al., 2013).

Although there is increasing demand for sea ice thickness information within this region, there is are still very limited records available (Haas and Howell, 2015). Melling (2002) analyzed drill-hole data measured in winters during 1971–1980 within the Sverdrup Basin (the marine area between Parry Channel and QEI gates, see Fig. 1), and found sea ice in this region is landfast (100% concentration without motion) for more than half of the year (from October-November to late July) with a mean late winter thickness of 3.4 m. Sub-regional means of the ice thickness can reach 5.5 m, but very thick multiyear ice was found to be less common, which is likely due to the melting caused by tidally enhanced oceanic heat flux in this region (Melling, 2002). The seasonal export transport of the old ice from the Sverdrup Basin down to the south was known in the past (Bailey, 1957) , to occur (Bailey, 1957) . which helps to create another major region with severe MYI condition conditions in the CAA, the central Parry Channel and M'Clintock Channel (see Fig. 1 for the location). Based on two airborne electromagnetic (AEM) ice thickness surveys conducted in May 2011 and April 2015, Haas and Howell (2015) estimated the ice thickness to be 2 to 3 m in this region with MYI thicker than 3 m on average. This supports the general spatial distribution of ice thickness within the CAA, thicker in the north and relatively thinner in the south.

Observations were not only limited in time but also in spatial coverage, thus, numerical simulations are required to better understand the ice distribution and variability in the CAA (e.g., Dumas et al., 2006; Sou and Flato, 2009; Hu and Myers, 2014). Dumas et al. (2006) evaluated ~~of~~ the simulated ice thickness at CAA meteorological stations but with a uncoupled one dimensional (1D) sea ice model (Flato and Brown, 1996). The variability and trends of landfast ice thickness within the CAA were systematically studied by a recent paper from Howell et al. (2016) based on historical records at observed sites (Cambridge Bay, Resolute, Eureka and Alert) and numerical model simulations over the 1957–2014 period. They found statistically significant thinning at the sites except at Resolute, and ~~this downward trend is mostly associated with the changes in snow depth~~ the detrended inter-annual variability is high (negative) correlated with snow depth due to the insulating effect of the snow (Brown and Cote, 1992) . Although some of the numerical simulations used in Howell et al. (2016) produced a reasonable seasonal cycle, generally, these simulations overestimated ice thickness and did not do a good job in capturing the trend. In addition, the lack of horizontal resolution in these models were also pointed out in Howell et al. (2016).

In this paper, we ~~will~~ focus on the simulated CAA sea ice thickness over recent years (2002–2016)~~, and address~~ . First, to evaluate the skill of a ~~sea ice model, including but not limited to those mentioned in Howell et al. (2016) . To be more specific, this paper will discuss~~ numerical model in simulating sea ice thickness, comparisons are done between the simulations and landfast ice thickness at several sites in the CAA. Two features of the simulations will then be discussed: 1) the relative importance of thermodynamic and dynamic processes in sea ice growth/melting in simulating the possible variability of sea ice and ocean surface fields in the CAA; 2) high frequency changes in ice growth/melting processes. This paper starts with a brief description of the numerical simulations and observational data used in this study. Then the evaluation of simulated ice thickness in the CAA region is presented in section 3.1. The spatial distribution~~and~~ , temporal evolution (at selected sites) of thermodynamic and dynamic ice thickness ~~change are discussed in section 3.2. Section 3.3 focuses on~~ contributions, as well as the high frequency (up to diurnal cycle) variability in ~~ice growth/melting processes.~~ the two components, are studies in section 3.2. Ice volume budgets in the northern CAA, Parry Channel and Baffin Bay are discussed in section 3.3. Concluding remarks and ~~a discussion~~ discussions are given in section 4.

2 Method and Data

2.1 Numerical model setup

In this study, the coupled ocean sea ice model, the Nucleus for European Modeling of the Ocean (NEMO, available at https://www.nemo-ocean.eu) version 3.4 (Madec and the NEMO team, 2008), is utilized to conduct the numerical simulations. The model domain covers the Arctic and the Northern Hemisphere Atlantic (ANHA) with two open boundaries, one close to Bering Strait in the Pacific Ocean and the other one at 20°S across the Atlantic Ocean (Fig. 1, inset). The model mesh is extracted from the the global tripolar grid, ORCA (Drakkar Group, 2007) with two different horizontal resolutions, 1/4° (hereafter ANHA4) and 1/12° (hereafter ANHA12). The highest horizontal resolution is $\sim 2\,km$ for ANHA12 and $\sim 6\,km$ for ANHA4 in Coronation Gulf–Dease Strait region, which is near the artificial pole over northern Canada (Fig. 1), and the lowest resolution is $\sim 9\,km$ for ANHA12 and $\sim 28\,km$ for ANHA4 at the equator. In the vertical, there are 50 geopotential levels with high resolution focused in the upper ocean. Layer thickness smoothly transitions from $\sim 1m$ at surface (22 levels for the top $100\,m$) to $458\,m$ at the last level.

The sea ice module used here is the Louvain la-neauve Ice Model Version 2 (LIM2) with an elastic-viscous-plastic (EVP) rheology (Hunke and Dukowicz, 1997), including both thermodynamic and dynamic components (Fichefet and Maqueda, 1997). It is based on a three-layer (one snow layer and two ice layers of equal thickness) model proposed by Semtner Jr (1976) with two ice thickness categories (mean thickness and open water). The sea ice module is coupled to the ocean module every model step. The elastic time scale is tuned small enough to damp the elastic wave in the EVP approach (see Table 1), based on the discussions in Hunke and Dukowicz (1997). Note that recent studies (e.g., Lemieux et al., 2012; Bouillon et al., 2013; Williams et al., 2017) s that more iterations are needed to reach a viscous-plastic (VP) solution. Without doing that, the divergence field will be affected, i.e., being noisy (Dupont, 2017) . Thus, to what degree it will impact the final averaged ice thickness will vary in space. Such an investigation in the CAA is beyond the scope of this study. A no-slip boundary condition is applied for sea ice in the simulations, which means the ice can have zero velocity along the coast. However, it should be noted that the sea ice module used in this study does not include a representation of landfast ice (e.g., Lemieux et al., 2016), which may negatively impact the sea ice simulation where landfast ice exists.

Table 1. Sea ice module parameters used in our simulations

parameter	ANHA4	ANHA12
time step (seconds)	1080	180
~~subsycling~~ subcycling iterations	150	120
timescale of elastic wave (seconds)	320	60

Two simulations, ANHA4-CGRF and ANHA12-CGRF, are integrated from January 1st 2002 to December 31 2016. The initial conditions, including three dimensional (3D) ocean fields (temperature, salinity, zonal velocity and meridional velocity) as well as two dimensional (2D) sea surface height (SSH) and sea ice fields (concentration and thickness) are taken from

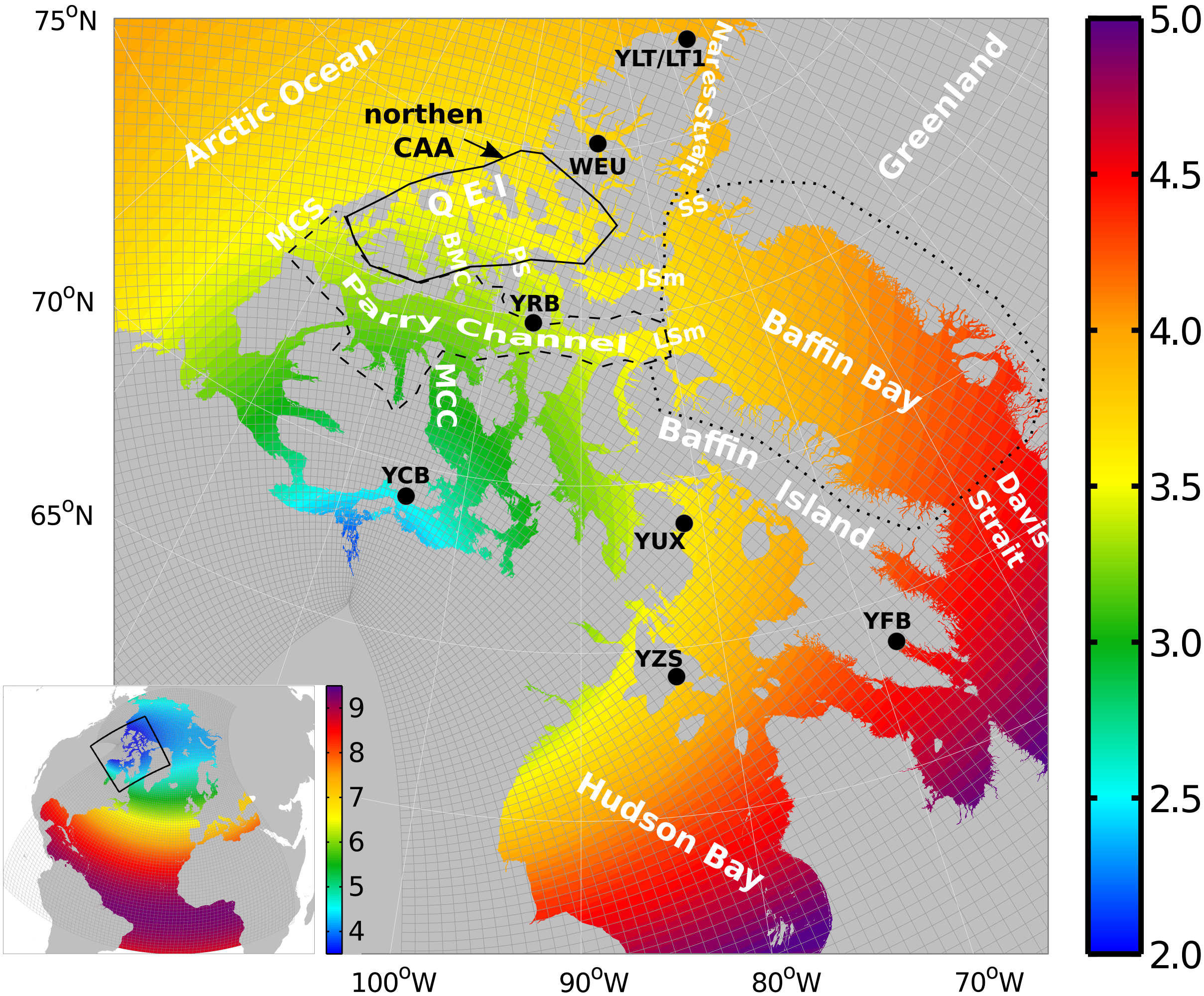

Figure 1. ANHA12 (inset) model mesh (every 10th grid point) and horizontal resolution (colours, unit: kilometers) in the Canadian Arctic Archipelago (QEI: Queen Elizabeth Islands; MCS: M'Clure Strait; MCC: M'Clintock Channel; BMC: Byam Martin Channel; PS: Penny Strait; JSm: Jones Sound Mouth; LSm: Lancaster Sound Mouth; SS: Smith Sound) and Hudson Bay region (thick black box highlighted in the inset). Note the colour scale is different from that used in the inset). Ice thickness observation sites (see table 2 for the detailsYZS: Coral Harbour, YUX: Hall Beach; YFB: Iqaluit; YCB: Cambridge Bay; YRB: Resolute; WEU: Eureka; YLT: Alert; LT1: Alert LT1) are shown with black circles on the map. Detailed location information of observation sites is available in table 2.

from the Global Ocean Reanalysis and Simulations (GLORYS2v3) produced by Mercator Ocean (Masina et al., 2015). Open boundary conditions (temperature, salinity and horizontal ocean velocities) are derived from the monthly GLORYS2v3 product as well. At the surface, the model is driven with high temporal (hourly) and spatial resolution ($33\,km$) atmospheric forcing data provided by Canadian Meteorological Centre (CMC) Global Deterministic Prediction System (GDPS) ReForecasts (CGRF) dataset (Smith et al., 2014), including 10 m wind, 2 m air temperature and humidity, downwelling and longwave radiation flux, and total precipitation. These forcing fields are linearly interpolated onto the model grid. Inter-annual monthly $1° \times 1°$ river discharge data from Dai et al. (2009) as well as Greenland meltwater ($5\,km \times 5\,km$) provided by Bamber et al. (2012) is carefully (volume conserved) remapped onto the model grid.

With the same setting as ANHA4-CGRF but driven with the inter-annual atmospheric forcings from the Coordinated Ocean-ice Reference Experiments version 2 (CORE-II) (Large and Yeager, 2009), another ANHA4 simulation, ANHA4-CORE, integrated from January 1st 2002 to December 31 2009, is also conducted to study the sensitivity of the sea ice simulation to the atmospheric forcings. The CORE-II provides fields at various temporal resolutions, a) 6-hourly 10-m surface wind, 10-m air temperature and specific humidity; b) daily downward longwave and shortwave radiation; c) monthly total precipitation and snowfall.

No temperature or salinity restoring is applied in any of the simulations used in this study. Without such ~~constrains~~ constraints the model evolves freely in time to help understand better the limitations of the physical processes represented by the model.

~~Monthly ice thickness at $1/4°$ resolution from the GLORYS2v3 product with sea ice assimilation is also utilized in this study to better understand the initial condition issue.~~

2.2 Environment and Climate Change Canada New Arctic Ice Thickness Program

To evaluate the performance of the model in terms of ice thickness, simulated ice thickness is compared to the observed landfast ice data from Environment and Climate Change Canada (ECCC) New Icethickness Program (hereafter ECCC thickness). The new ECCC thickness program, the second stage of the Original Ice Thickness Program Collection used in Dumas et al. (2006), started in the fall of 2002 , and continued to the present at only 11 stations (including sites ~~in~~ on lakes). Measurements were conducted weekly at approximately the same location close to shore between freeze-up and break-up ~~period~~ (when the ice was safe to walk on) with a special auger kit or a hot wire ice thickness gauge. Note the measurement represents the immobile level first-year (seasonal) ice of uniform thickness that forms close to shore, however, simulated ice thickness, e.g., due to resolution, generally, is an estimation of the mean state of different types of ice (e.g., first-year level ice, young ice and old ice).

Data is made available to the public by Environment and Climate Change Canada under the Open Government License (Canada) on http://open.canada.ca/data/en/dataset. Eight coastal sites, ~~Carol Harbour(YZS)~~Coral Harbour, Hall Beach~~(YUX), Iqaluit(YFB)~~, Iqaluit, Cambridge Bay~~(YCB), Resolute(YRB), Eureka(WEU), Alert YLT (YLT)~~, Resolute, Eureka, Alert and Alert LT1~~(LT1)~~, were used in this study. The remaining three sites are on lakes (not included in our simulations). The detailed location information of each site can be found in Fig. 1 and Table2.

Unlike the 1D model used in Dumas et al. (2006), which can be applied at the exact location where the measurements were carried out, three dimensional (3D) models usually have horizontal resolution issues in resolving the observation sites, even with the high resolution ANHA12 configuration used in this study. Interpolation is needed to do the comparison between simulated fields and observations. This is also mentioned in Howell et al. (2016). To interpolate simulated fields onto the nearest water point (x_k, y_k) of each observation site (x_{obs}, y_{obs}), we utilized a modified inverse distance weighting (IDW) method (eq. (1)) proposed by Renka (1988):

Table 2. ECCC ice thickness station locations (only sites used in this study)

site	longitude	latitude
Carol Harbour (YZS) Coral Harbour	$83.153°W$	$64.130°N$
Hall Beach (YUX)	$81.230°W$	$68.780°N$
Iqaluit (YFB)	$68.517°W$	$63.726°N$
Cambridge Bay (YCB)	$105.06°W$	$69.113°N$
Resolute Bay (YRB)	$94.884°W$	$74.684°N$
Eureka (WEU)	$85.942°W$	$79.986°N$
Alert LT1 (LT1)	$62.593°W$	$82.602°N$
Alert YLT (YLT)	$62.420°W$	$82.753°N$

$$f_i = [\frac{R_w - d_k}{R_w\, d_k}]^2 \tag{1a}$$

$$w_i = \frac{f_i}{\sum_{i=1}^{N} f_i} \tag{1b}$$

$$Q_{target} = \sum_{i=1}^{N} Q_i\, w_i \tag{1c}$$

where R_w is the influence radius about point (x_k, y_k), d_k is the distance from point (x_k, y_k) to each neighboring point (x_i, y_i), f_i is the inverse distance function, w_i is the weight function on each neighboring point (x_i, y_i), N is the number of neighboring points within R_w, Q_i is variable value on each neighboring point and Q_{target} is the final result. In practice, nine neighboring points, including point (x_k, y_k), were considered in the calculatedcalculation. As R_w is set to the maximum value of d_k and land points should be excluded, eventually up to eight effective points are used in our interpolation process.

2.3 Wavelet analysis

Constrained by sampling frequency in observations and atmospheric forcing data, very few modelling studies have ever studied ice thickness variations on a time scale shorter than monthly. Using a 1D thermodynamic sea ice model, Hanesiak et al. (1999) found the hourly atmospheric forcing, which resolves the diurnal cycle, can produce more realistic results in terms of sea ice melting processes (i.e., simulated breakup dates, open water duration and snow ablation) compared to the non-diurnal-resolved forcing (e.g., daily). The significant differences is caused by the nonlinearities in surface energy balance that affects the snow depth, albedo and surface temperature (Hanesiak et al., 1999) . Thus, in this study, more realistic sea ice melting and freezing processes are expected, given that the CGRF dataset provides hourly surface atmospheric forcing fields. Hourly simulated sea ice fields (ice thickness, thermodynamic ice production) are saved from the ANHA12-CGRF simulation between 2008 and 2016 to further study the high frequency processes in ice thickness evolution. Wavelet analysis (Torrence and Compo, 1998) is utilized to show both the periods of the ice thickness variation and their temporal evolution. The wavelet toolbox is accessible from http://paos.colorado.edu/research/wavelets, and a bias correction discussed in Veleda et al. (2012) is also included in our analysis.

3 Results

In this section, first, the ice thickness reproduction ability within the CAA of the NEMO LIM2 configurations used in this study ~~will be~~ is examined via comparisons with the ECCC thickness. ~~Then~~ After that, the detailed thermodynamic and dynamic ice thickness changes, both the spatial distribution and temporal evolution at ~~select~~ selected sites (Cambridge Bay and Resolute~~Bay~~), based on the simulation outputs will be presented. Then ~~,~~ follows the high frequency ice growth/melting processes ~~resolved by the simulation will be studied~~at Cambridge Bay and Resolute. Ice volume balance, focusing on the thermodynamics contribution and lateral transport, in the northern CAA, Parry Channel and Baffin Bay will also be included at the end.

3.1 Ice thickness comparison

Figure 2 shows the ice thickness comparison with observations. In general, both ANHA4-CGRF (blue lines) and ANHA12-CGRF (red lines) simulations produce similar seasonal and inter-annual variations in ice thickness, which compare reasonably well at some sites (i.e., ~~YCB, YZS, YUX, YRB,YFB~~Cambridge Bay, Coral Harbour, Hall Beach, Resolute and Iqaluit) but not at the rest (~~WEU, YLT,~~ Eureka, Alert and Alert LT1). The sites where the model produced much thicker ice are likely where significant concentration of old ice exists (CIS, 2011) . Although the observations are missing in the sea ice melting season, an asymmetric seasonal cycle (a shorter faster melting period follows a relatively longer slow growth period), is evidenced by the available data, and reproduced by the simulations. This is clearly shown in the ice thickness seasonal cycle plot (Fig. 3). Taking account of the model resolution, the interpolated simulated ice thickness reflects actually the variability some distance off the coast rather than the exact observation locations. The geographic location differences, which is also related to model resolution, could also lead to discrepancies in the comparisons here. Thus, if the model can capture the seasonal cycle (e.g., multiple data points in both ice growth and melting seasons), the model is likely capable of simulating the process.

At ~~YFB~~Iqaluit, the model does a good job in most years during the initial ice growth period but failed to catch the ~~very~~ thick sea ice in the next April and May (Fig. 3), particularly in 2014, 2015 and 2016 (Fig. 2h). This could be a local atmospheric forcing field bias, or a model resolution issue, i.e., the measurements captured very localized extremes beyond the ability of model to resolve. Similar behavior happens at ~~YZS, YUX.~~ Coral Harbour and Hall Beach (Fig. 2c and d). Further investigation is needed.

At ~~WEU, YLT and~~ Eureka, Alert and Alert LT1 sites (Fig. 2 and 3, e, f, and g), there ~~is a clear initial value issue~~ are clear differences between the simulated ice thickness and the observations ($\sim 2m$ at ~~YLT~~Alert/Alert LT1 and $\sim 1m$ at ~~MEU)that leads to too thick sea ice in the simulations. Note that~~ Eureka). Note neither ANHA4 or ANHA12 has the capability to resolve the difference between ~~YLT and~~ Alert and Alert LT1, thus, the same simulated values are shown on the figure for both ~~YLT and LT1. At YLT~~sites. The differences between simulations and observations could be an initial value problem, particularly at Eureka (Fig. 2g). However, given high concentrations of old ice are at these sites, observations represent the immobile level first-year ice only. Thus, the model and the observations may not be representing the some type of ice. At Alert/Alert LT1, both ANHA4-CGRF (blue line) and ANHA12-CGRF (red line) show similar inter-annual trends to that in GLORYS2v3

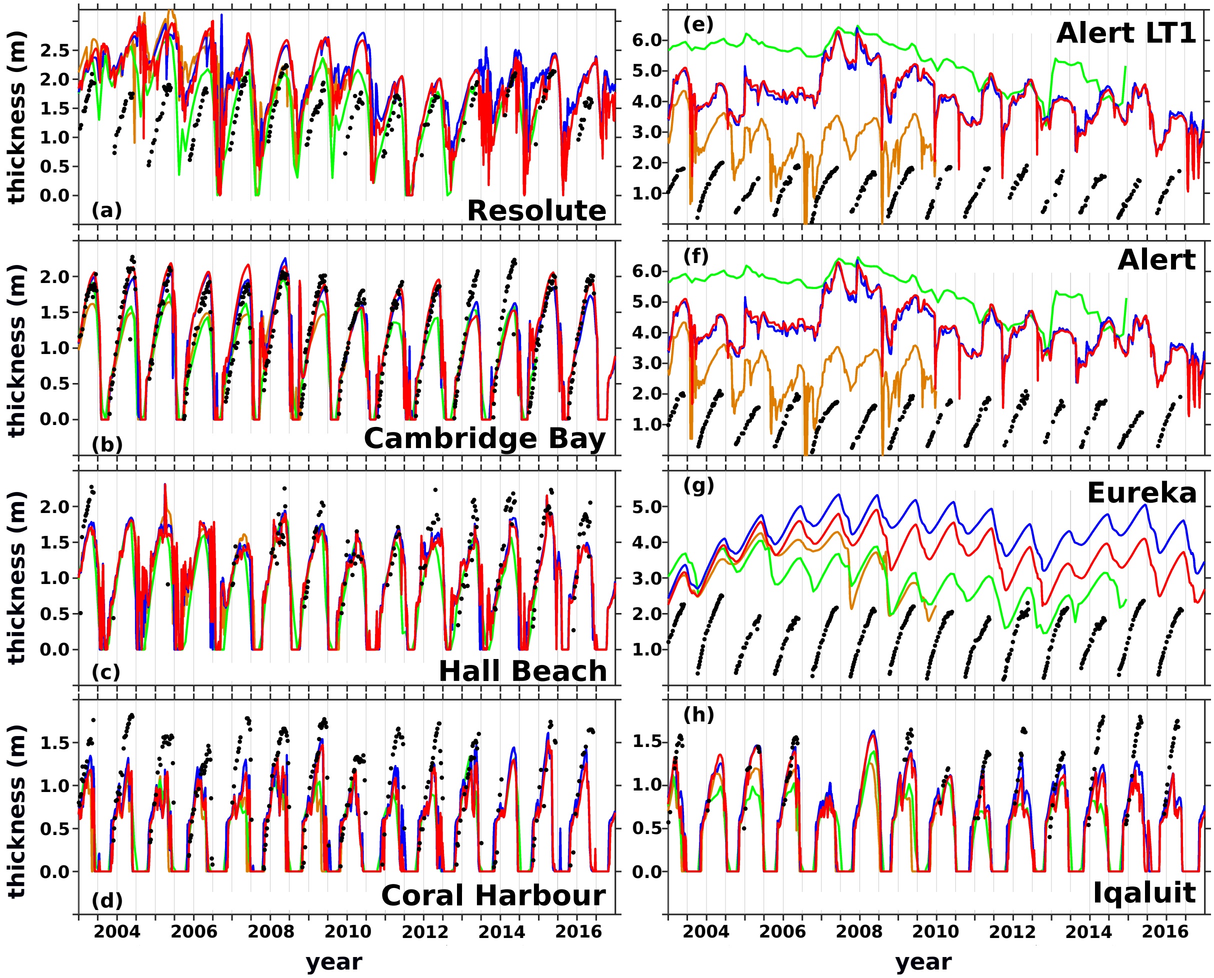

Figure 2. Simulated ice thickness at each selected ECCC thickness site (figure 1 and table 2, unit: meters) from January 2003 to December 2016 (orange: ANHA4-CORE simulation; green: GLORYS2v3 product; blue: ANHA4-CGRF simulation; red: ANHA12-CGRF simulation) against weekly ECCC observations (black dots). Note the GLORYS2v3 product is a monthly mean field while the rest of the simulations use 5-day averages. Different y-axis scales are used.

(which extends back to 1993, ~~greenline~~green line), meaning it is likely a pure initial value problem rather than the model equilibrium issue mentioned in Howell et al. (2016). In addition, the seasonal cycle is not clear in the GLORYS2v3 product. The issue is also present in some years, i.e., 2005–2007, in the ANHA4-CGRF and ANHA12-CGRF simulations. ANHA4-CORE (orange line) is generally improved compared with the observations in both the amplitude and seasonal cycle. However, this improvement was achieved by accident, and is related to a snow depth issue in this simulation (more details will be in the discussion session). Thus, it does not indicate that CORE-II forcing is performing better than other atmospheric forcing datasets in this region. The equilibrium issue, i.e., ice thickness ~~keep~~ keeping increasing, might happen at ~~WEU~~ Eureka in our

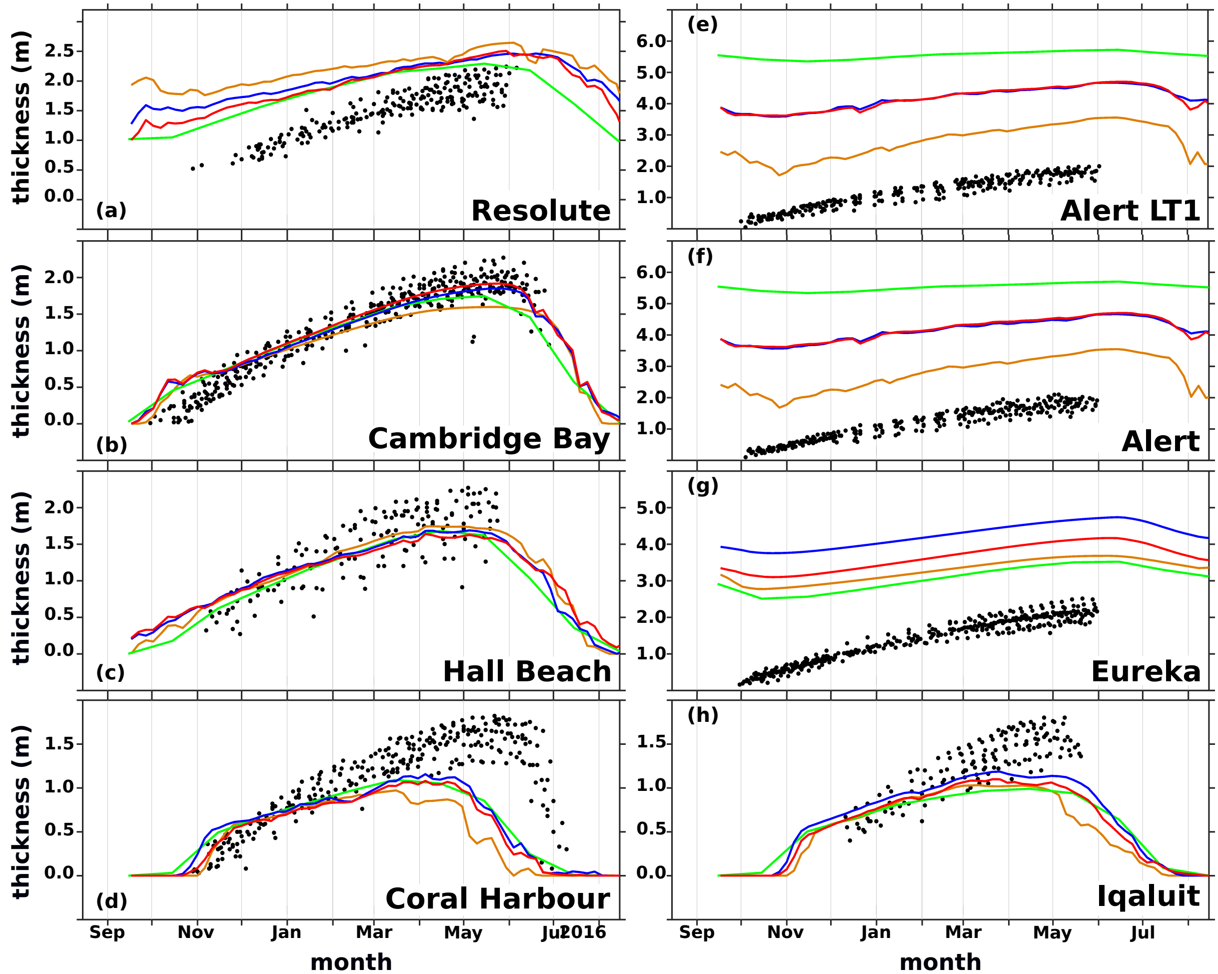

Figure 3. Similar to Fig. 2 but for ice thickness seasonal cycle (starting from September 17 to the next September 12, averaged over 2003 to 2016; ANHA4-CORE ends by 2009). Note observations are not averaged over time because the sampling time is different from year to year).

simulations with either CGRF or CORE-II forcing. The upward trend over 2005 to 2007 is also present in the observations but is missing in the GLORYS2v3 although GLORYS2v3 has a small thickness (which is likely due to data assimilation in GLORYS2v3 or an atmospheric forcing issue in 2005). Its trend does not reflect the real change/variability.

At ~~YCB~~Cambridge Bay, simulations (red and blue lines in Fig. 2b) with CGRF forcing show very good agreement with the observations except during the winters of 2013 and 2014. Considering the horizontal resolution of our simulations is not capable of resolving the inner bay at ~~the~~ Cambridge Bay, the match in ice thickness between the simulation and observations indicates the variation of ice thickness within the inner Bay might be small. Both ANHA4-CORE and GLORYS2v3 simulations underestimated the maximum values in winters by $\sim 0.5\,m$. This indicates CGRF ~~forcings~~ forcing might provide more realistic surface inputs in this region.

At ~~YRB~~Resolute, it is more complicated (Fig. 2a). Prior to the significant sea ice melting in 2007, none of the simulations show ice free conditions in this region in summer. GLORYS2v3 shows relatively thinner ice in summer months but it is still $0.5\,m$ to $1.5\,m$ thick. It could be the initial value problem. However, high frequently variations even in winter in the ANHA simulations suggest that the ice growth process is not dominated by a smoothly changing physical process (e.g., air temperature). Thus, it is likely due to ~~the physical process (e.g.,~~ another physical process such as advection from surrounding areas~~)~~. This will be discussed more in the following section. Post 2007, the seasonal cycle in the sea ice field is more distinct, although ice free summer conditions do not happen every year. After 2010, simulations produce winter sea ice thickness much close to the observations.

3.2 Thermodynamic and dynamic ice thickness change

In the real world, both the thermodynamic and dynamic ice thickness processes are coupled together (occurring at the same time). However, with the assistance of numerical model, the two processes can be decoupled (shown in equation (2)) to better understand the relative importance of each process.

$$\Delta H_{total} = \Delta H_{thermal} + \Delta H_{dynamic} \qquad (2)$$

where ΔH_{total} is the total ice thickness change over a specific time interval; $\Delta H_{thermal}$ is the ice thickness change due to vertical heat fluxes (through the atmosphere-ice-ocean interfaces); $\Delta H_{dynamic}$ is the ice thickness change due to dynamic processes. In practice, a simple approach is utilized to compute the two terms on the right side. $\Delta H_{thermal}$ is calculated based on the model thermal ice production. $\Delta H_{dynamic}$ is taken as the residual from the ΔH_{total}.

3.2.1 Spatial distribution

Here we focus on ice growth process between December and April of the following year. Figure 4a and 4b show the simulated ice thickness in ANHA12 at the beginning of December and at the end of April, respectively. Geographically, at the end of April, a) very thick sea ice is located in the northern CAA ($\sim 4\,m$ by the end of April) with regional maximum ($> 4.5\,m$) at the openings to the Arctic Ocean. This is consistent with the ICESat and Cryosat-2 estimations (e.g., Laxon et al., 2013; Tilling et al., 2015; Kwok a b) less thick sea ice covers western, and central Parry Channel (just ~~above the site YRB~~to the west of the site Resolute) and M'Clintock Channel with a thickness of $2.5\,m$ to $3\,m$. These values are similar to previous observations from airborne electromagnetic surveys (Haas and Howell, 2015) and satellite (Tilling et al., 2017) . c) relatively thin ice ($< 2\,m$) is mainly in the southern CAA, eastern Parry Channel, coasts of Baffin Islands and within Hudson Bay. Invasion of the Arctic Ocean ice pack through the northern CAA openings and the advection from there into central Parry Channel are clearly shown in the figures, ~~consisted~~ consistent with previous studies (e.g., Melling, 2002; Howell et al., 2008; Haas and Howell, 2015).

During the winter, sea ice grows everywhere in the CAA regions due to the thermodynamic cooling (Fig. 4c). But the total increase over the winter is not evenly distributed in space. Nor is ice growth largest in the north. Large thermodynamic

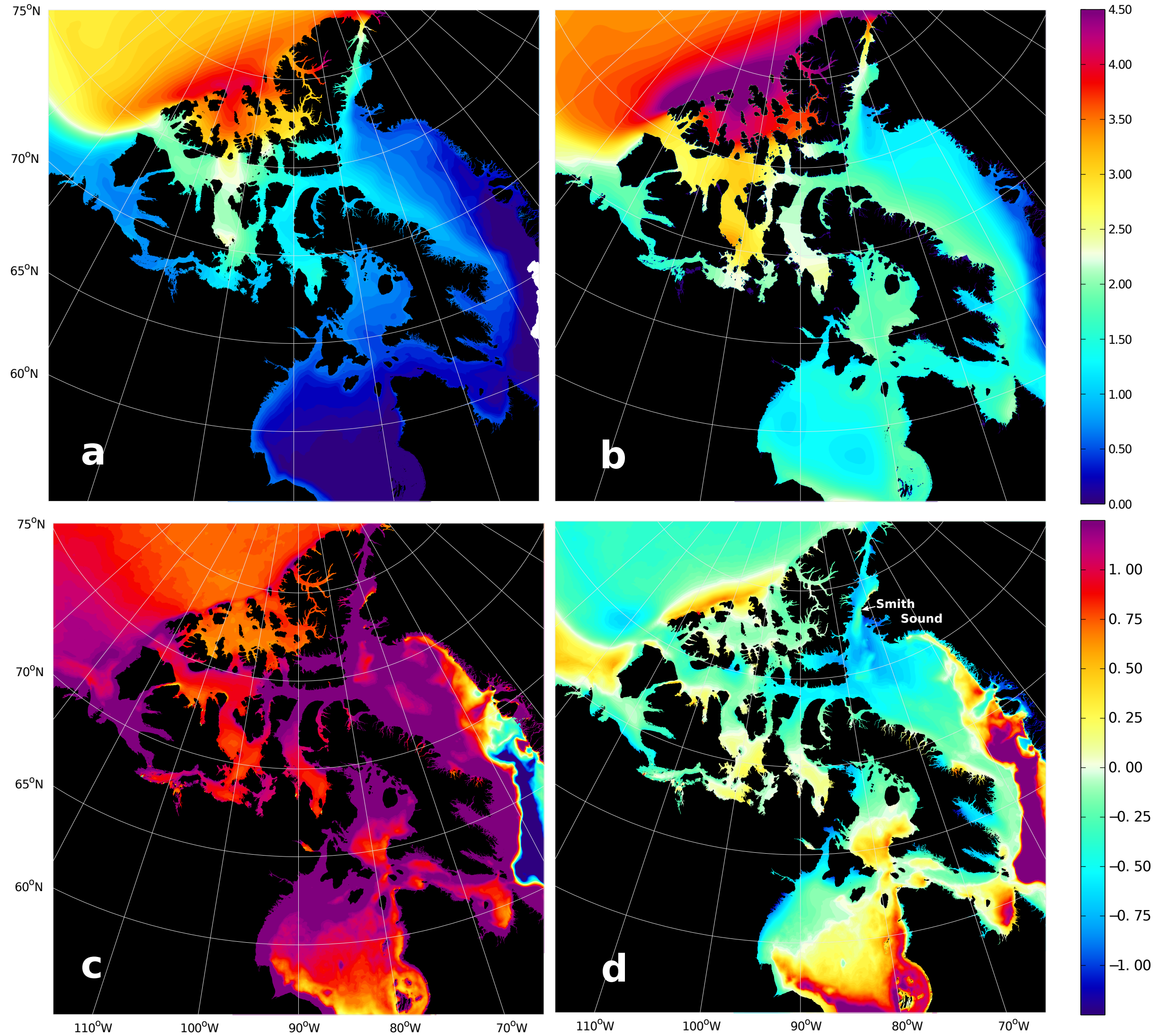

Figure 4. Upper panel shows the thickness (unit: meters) averaged over 2003–2016 at the beginning of December (a) and at end of April (b). Lower panel shows the thermodynamics component (c) and dynamic component ice thickness contribution (unit: meters) between December (a) and the following April (b) averaged over 2003-2015. ANHA12-CGRF simulation is used here.

ice growth is seen in the eastern CAA (eastern Parry Channel, Nares Strait, Baffin Island coast and western Hudson Bay), Amundsen Bay and many coastal regions (e.g., western coast of Banks Island, northern coast of western Parry Channel). Regions covered by thick sea ice (i.e., ~~the~~ northern CAA, west-central Parry Channel and M'Clintock Channel) show less thermodynamic ice growth over the winter. This is particularly true in the northern CAA, likely due to the existence of already thick ice reducing the heat exchange between the ocean and atmosphere.

The dynamic contribution to sea ice thickness is mainly negative (reduces local ice thickness) within the CAA (Fig. 4d). Large positive values (0.4 to $0.7\,m$) are shown along the Arctic Ocean coast off the CAA and within the Beaufort Sea. This is consistent with known sea ice convergence or strong advection of thick ice from upstream regions (Kwok, 2015; Maslanik et al., 2011). Within the northern CAA, west-central Parry Channel and M'Clintock Channel, there is ~ 0.25 $\sim 0.25\,m$ thick ice loss locally due to the dynamics. Note the positive values occurring in the south of M'Clintock Channel, suggesting a net convergence there which contributes to the local ice thickening in winter. In the eastern CAA (e.g., eastern Parry Channel, Nares Strait and northwest corner of Baffin Bay), there are large negative dynamic thickness contributions, implying strong ice advection.

Although the North Water (NOW) Polynya (e.g., Dunbar, 1969; Melling et al., 2001) region is still ice covered by the end of April (Fig. 4b), the spatail spatial distribution of negative dynamic ice thickness (which helps to remove local ice) captures the shape of NOW Polynya well. Weaker advection of sea ice at Smith Sound and to its south, which is likely to be caused by ice jamming, is also simulated by the model.

3.2.2 Seasonal cycle at YCB Cambridge Bay and YRBResolute

Two sites, YCB and YRBCambridge Bay and Resolute, were selected to further study the seasonal cycle of the thermodynamic and dynamic ice thickness changes.

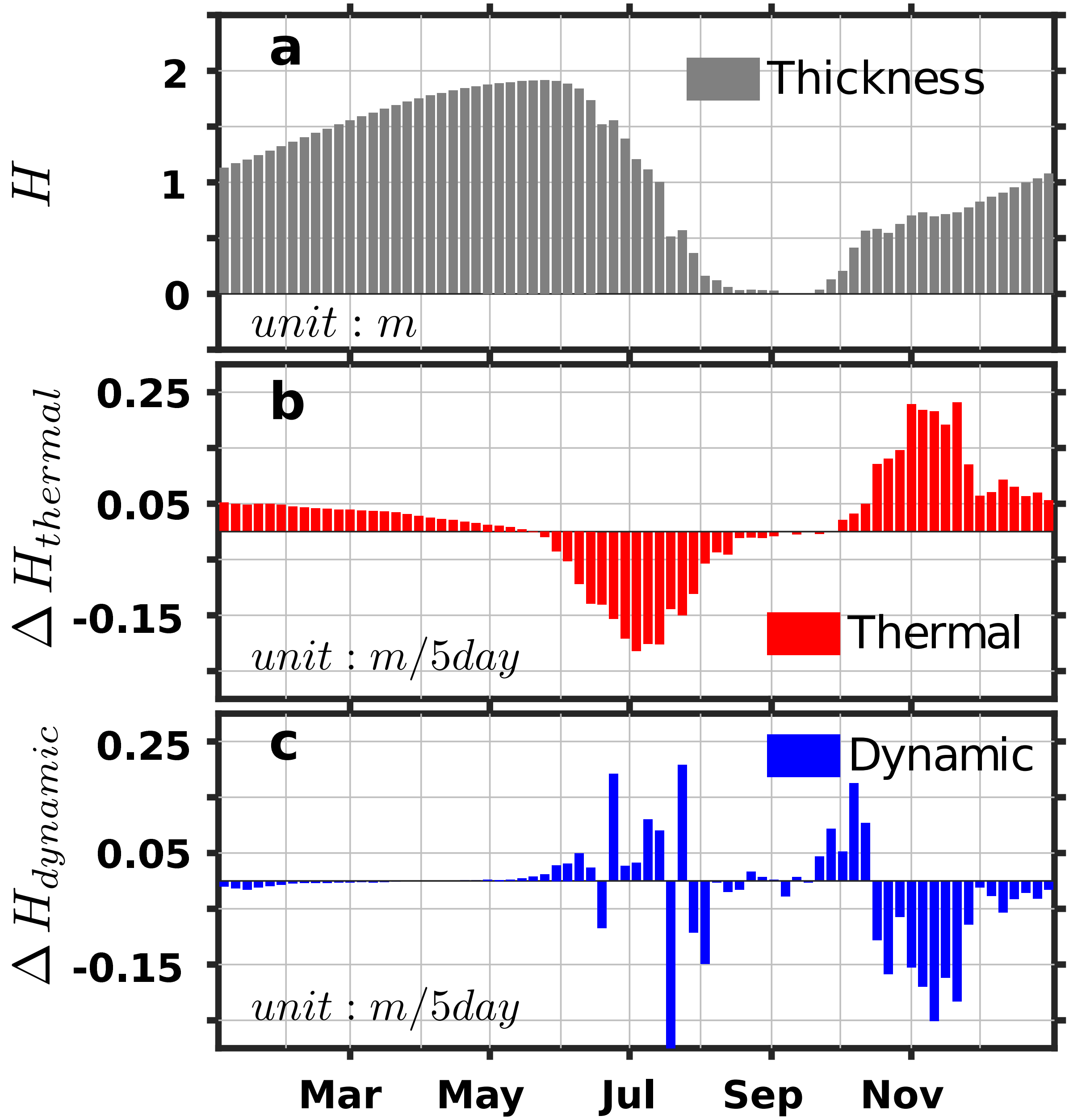

Figure 5. Seasonal cycle (averaged over 2003 to 2016) of ice thickness (a, unit:meters), dynamic (b) and thermodynamic (c) ice thickness changes (unit: meters per 5-day) at ~~YCB~~ Cambridge Bay from the ANHA12-CGRF simulation. Note each x-grid line indicates the beginning of each month.

Figure 5 shows the seasonal cycle of ice thickness, 5-day $\Delta H_{dynamic}$ and $\Delta H_{thermal}$ averaged between 2003 and 2016 at ~~YCB~~Cambridge Bay. Sea ice reaches its maximal thickness ($\sim 2\,m$) in late May with ice free conditions for about two months (August and September). As the sea ice starts to form (October and November), both thermodynamics (e.g., due to cold temperature) and dynamics (e.g., local advection) play a role in the production of the ice thickness although with opposite contributions (Fig. 5b and c). Starting from December through to the end of the next May, it is almost a pure thermodynamic process that controls the ice thickness change. Note the thermodynamic ice production is not constant in time, it is about three times larger in the first period ($\sim 0.03 m\,per\,day$) than in the later period ($\sim 0.01\,m\,per\,day$). The steady thermodynamic growth in the second period contributes to about half of the total ice thickness. During the ice melting period (June and July), the thermodynamics is the major player as well (Fig. 5c).

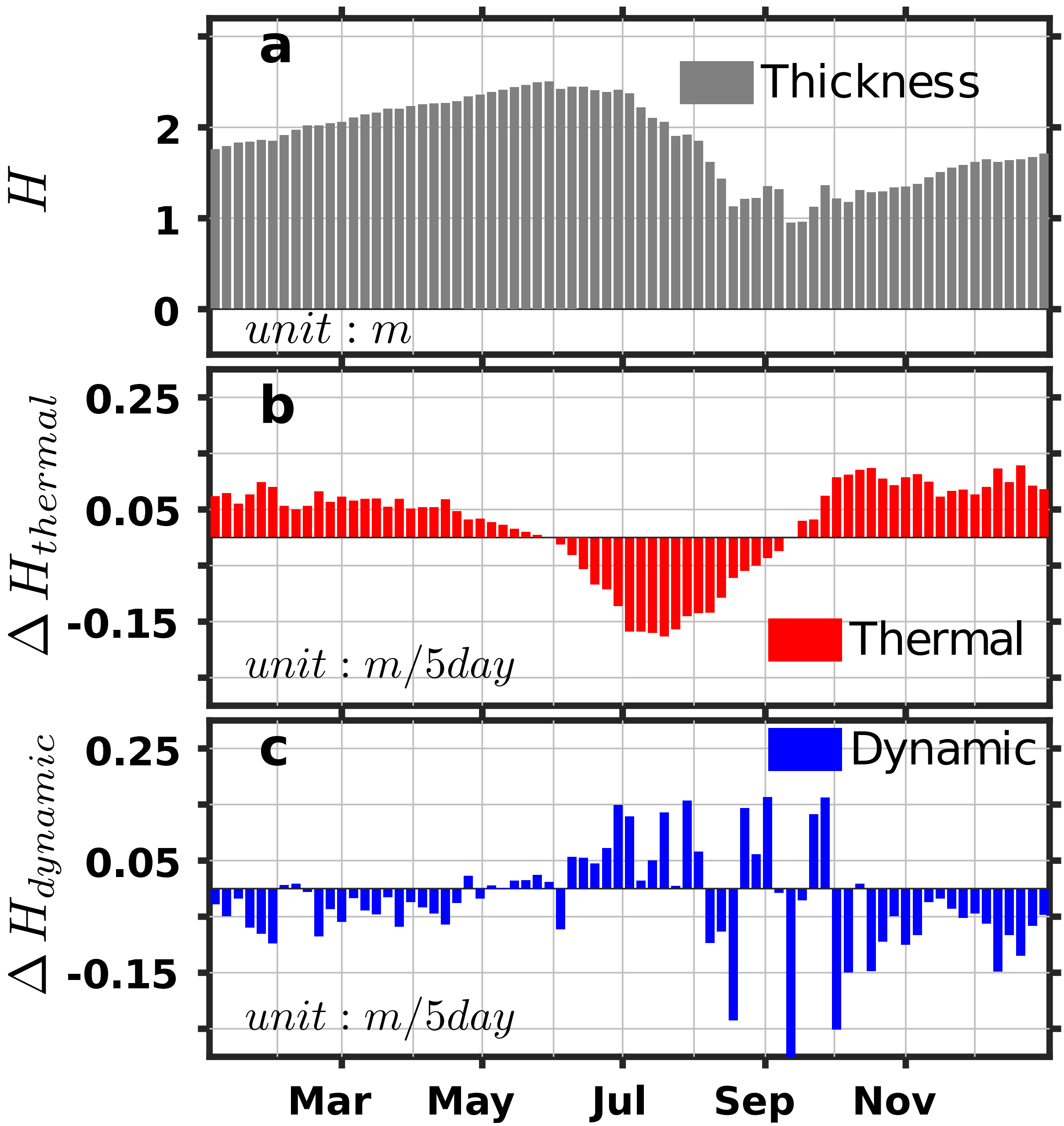

Figure 6. Same as Fig. 5 but at ~~YRB~~Resolute.

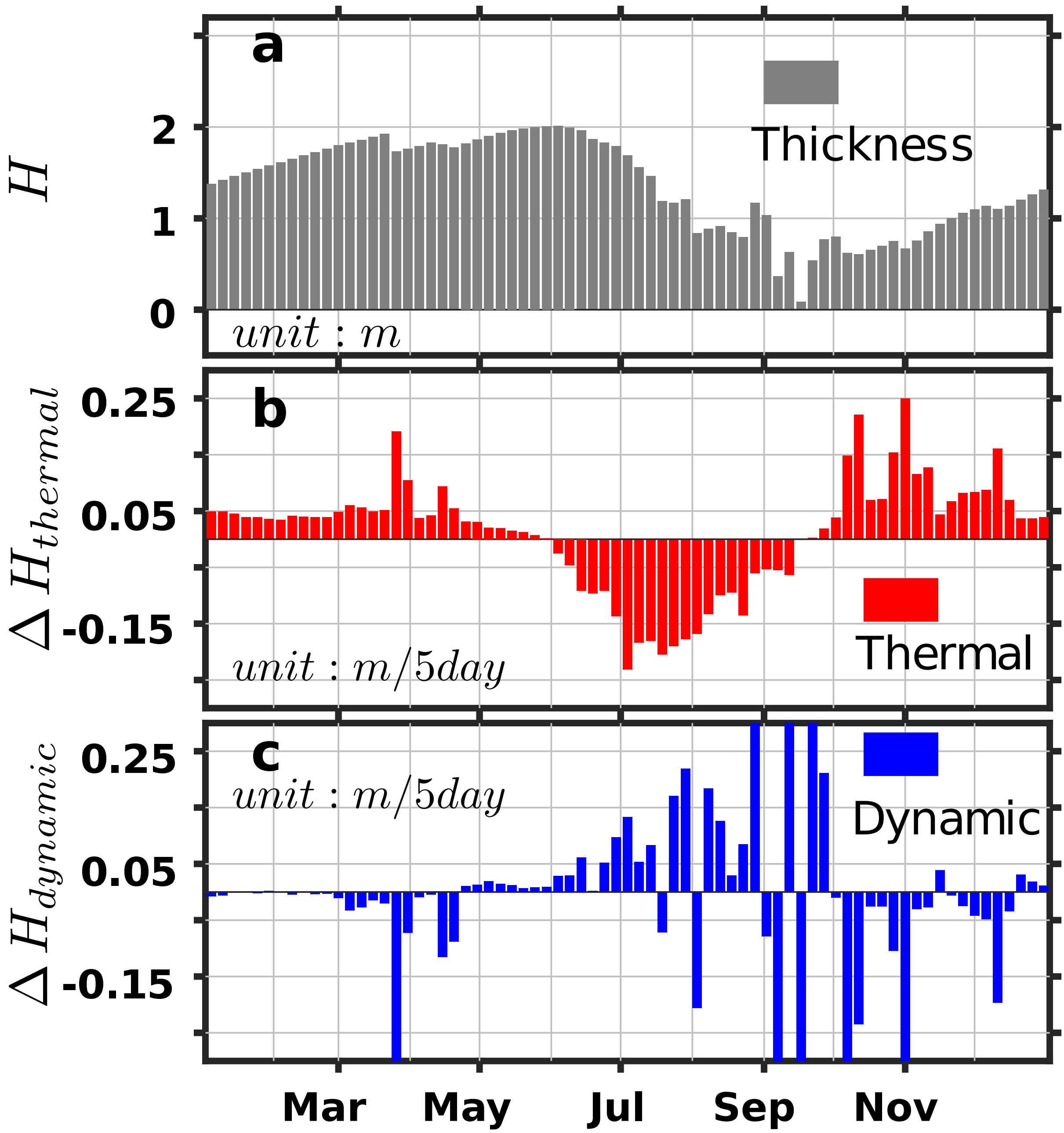

Figure 7. Same as Fig. 6 but only ~~considered~~ considering 2012 for ANHA12-CGRF.

At ~~YRB~~Resolute, on average, there is no ice free period ($\sim 2.5\,m$ at the end of May and $\sim 1\,m$ in August and September) (Fig. 6a), albeit with large inter-annual variability (Fig. 2a). For example, in 2012, there is an ice free period in the mid of September (Fig. 7a). The freeze-up date is about half a month earlier at ~~YRB~~ Resolute than that at ~~YCB~~Cambridge Bay. The ice production is a little ~~bit higher~~ larger at the beginning (October to December), $\sim 0.02\,m\,per\,day$, than later (6b), $\sim 0.01\,m\,per\,day$, but the difference is not as noticeable as at ~~YCB~~ Cambridge Bay (Fig. 5b). The relatively faster thermal growth lasts longer at ~~YRB~~ Resolute than that at ~~YCB~~Cambridge Bay, likely due to local advection. These features are also applicable to a specific year, e.g., 2012 (Fig. 7). The non-thermodynamic contribution is more significant than at ~~YRB~~ Resolute (Fig. 5c) but basically plays a negative role, i.e., slowing ice thickness increase during the winter season. Similarly to ~~YCB~~Cambridge Bay, the thermodynamics is the dominant factor melting the sea ice, with a melting peak in July. During the melting season, more ice can be advected to ~~YRB~~ Resolute and melts later locally (Fig. 6c) than that at ~~YCB~~ Cambridge (Fig. 5c).

3.3 ~~High frequency thermodynamic processes during ice formation and melting~~

3.2.1 High frequency thermodynamic processes during ice formation and melting at Cambridge Bay and Resolute

~~Constrained by sampling frequency in observations and atmospheric forcing data, very few modelling studies have ever studied ice thickness variations on a time scale shorter than monthly. Using a 1D thermodynamic sea ice model, Hanesiak et al. (1999) found the hourly atmospheric forcing, which resolves the diurnal cycle, can produce more realistic results in terms of sea ice melting processes (i.e., simulated breakup dates, open water duration and snow ablation) compared to the non-diurnal-resolved forcing (e.g., daily). The significant differences is caused by the nonlinearities in surface energy balance that affects the snow depth, albedo and surface temperature (Hanesiak et al., 1999) . Thus, in this study, more realistic sea ice melting and freezing processes are expected, given that the CGRF dataset provides hourly surface atmospheric forcing fields. Hourly simulated sea ice fields (ice thickness, thermodynamic ice production) are saved from the ANHA12-CGRF simulation between 2008 and 2016 to further study the high frequency processes in ice thickness evolution. Wavelet analysis (Torrence and Compo, 1998) is utilized to show both the periods of the ice thickness variation and their temporal evolution, The wavelet toolbox is accessible from http://paos.colorado.edu/research/wavelets, and a bias correction discussed in Veleda et al. (2012) is also included in our analysis.~~

Figure 8 shows the wavelet spectrum (a and c) and the global wavelet spectrum (b and d) of the ice thickness (a and b) and ice thermodynamic production (c and d) at ~~YCB~~Cambridge Bay. The thermodynamic ice production was converted to $m\,per\,day$ and normalized based on its standard deviation before performing the wavelet. The ~~season~~ seasonal cycle dominates the variability in all the years throughout the ~~simulation~~ analysis period (2008 to 2016), which is also shown in the global wavelet spectrum (Fig. 8b). High frequency oscillations down to a period of a week are significant before and after the ice free period (Fig. 8a). This supports the notion that the ECCC weekly sampling frequency is good enough during the ice break-up and freeze-up periods. The high frequency ice thickness variation is associated with the diurnal cycle in the thermal ice production (Fig. 8c). The wavelet of the non-thermodynamic ice production has some oscillations at roughly weekly scale, but it is not significant every year in both the break-up and freeze-up periods (not shown). The weekly oscillations in the the dynamic ice

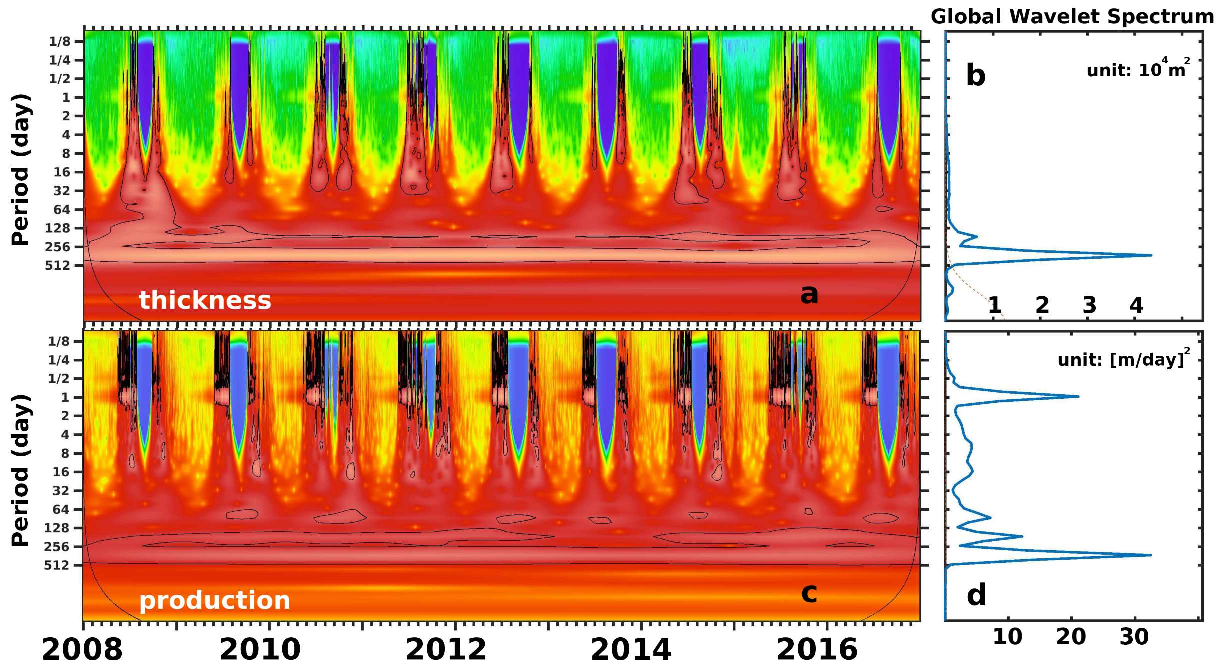

Figure 8. Wavelet spectrum (left, black contours highlight the significant oscillations at a confidence level of 95%) and global power spectrum (right) of ANHA12 hourly ice thickness (upper panel) and thermodynamic ice production (lower panel) at ~~YCB~~Cambridge Bay

production is likely caused by the interaction between the dynamic and thermodynamic processes rather than dynamic process itself. Figure 10 shows an example of the thermal ice production during the 2012 break-up season. The diurnal cycle also exists before the break-up but its amplitude is nearly zero. Thus, it is not significant in the wavelet spectrum (Fig. 8c). Similar results are achieved with the wavelet analysis of the ice fields at ~~YRB~~ Resolute (Fig. 9).

The thermal ice production diurnal oscillation also shows asymmetric features. For example, in 2012 (Figure 10 and 11), it can reach a melting rate of $0.1 \sim 0.15\,m\,per\,day$ ($0.04 \sim 0.1\,m\,per\,day$) during the day but will fall back to a freezing rate of $0.01 \sim 0.03\,m\,per\,day$ ($< 0.01\,m\,per\,day$) at ~~YCB (YRB~~Cambridge Bay (Resolute). This asymmetric feature is also seen on the season scale, more noticeable during the ice melting period than the freezing period (Figure 8c and 9c).

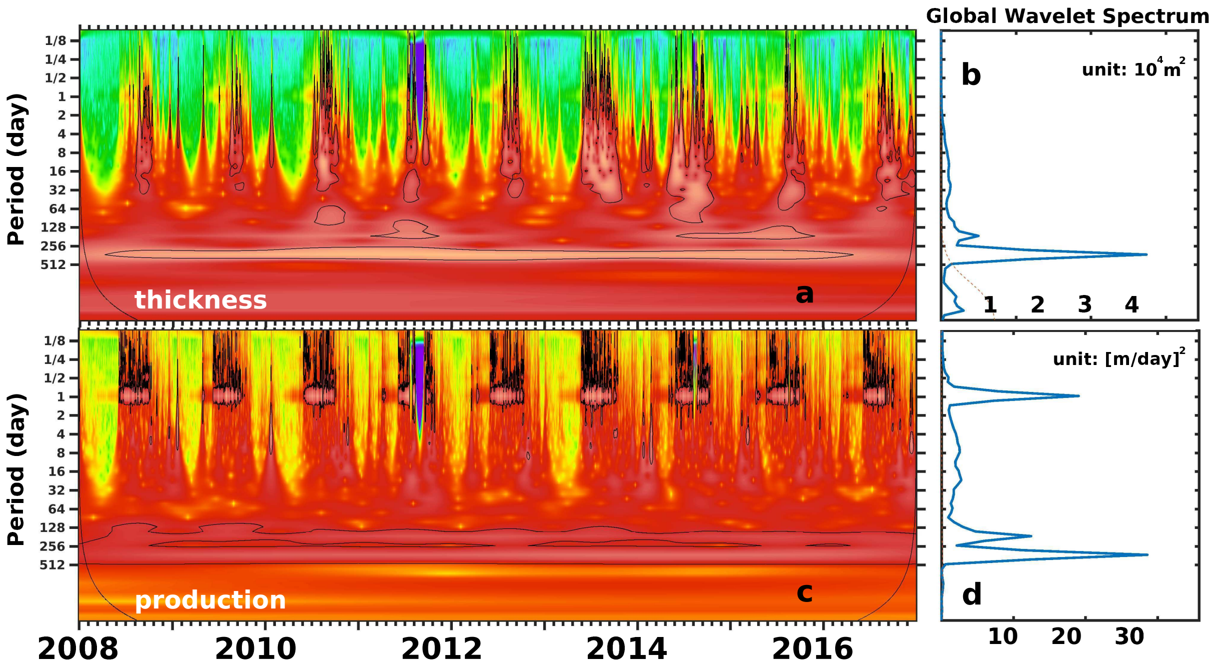

Figure 9. Same as Fig. 8 but at Resolute

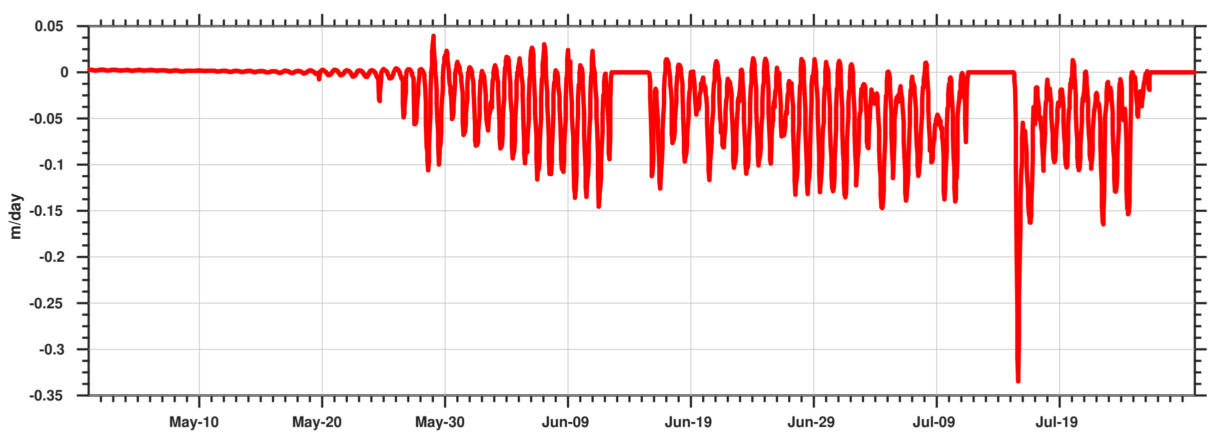

Figure 10. Diurnal cycle of thermodynamic ice production (unit: m/day) during the break-up season at ~~YCB~~Cambridge Bay.

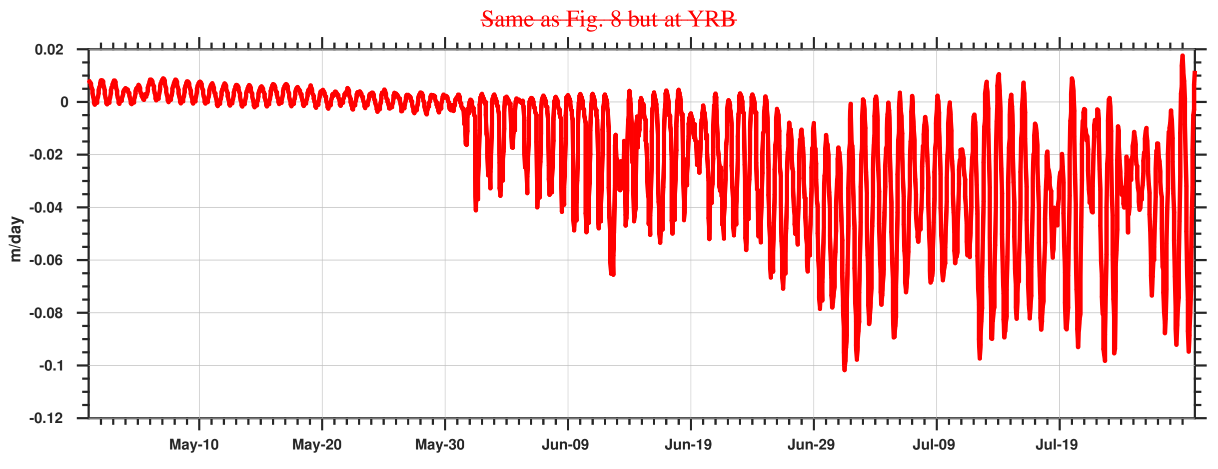

Figure 11. Same as Fig. 10 but at ~~YRB~~Resolute

3.3 Ice volume budget

3.3.1 Northern CAA

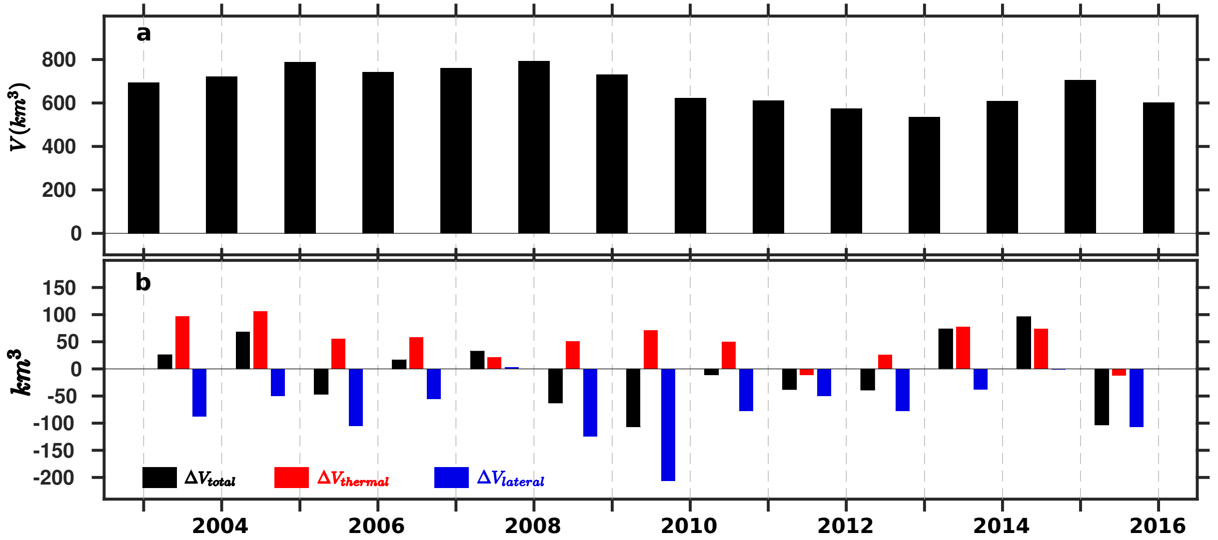

Figure 12. Sea ice volume balance in the northern CAA (location see Fig. 1. a) maximum total ice volume (black bars, unit: km^3) in each seasonal cycle (September 17 to next September 12). b) the net ice volume change (black bars) between two consecutive years, thermodynamic ice volume change (red bars) and lateral ice volume transport (blue bars) in km^3

Fig. 12a shows the maximum total ice volume (referred as "ice volume" hereafter if not mentioned specifically) in the northern CAA (solid black polygon shown in Fig. 1), which is covered by thick ice most of the year. An increase of 14% (from 695 km^3 to 789 km^3) in the ice volume is shown in the first three years. This is similar to the equilibrium problem we see at Eureka (Fig. 2g). During this period, the thermodynamic growth is the main contributor (203 km^3) while the net lateral ice volume transport ($-138\,km^3$ per year) is out of this region (Fig. 12b), particular through Byam Martin Channel (Fig. 13). The sign convention is defined as positive means transport into the northern CAA regions. The ice volume stabilizes at high values for four years until 2008. After that, a shrinkage of about 1/3 (792 km^3 to 535 km^3) in ice volume is simulated over 2008–2013. This reduction is due to large net lateral transport (Fig. 12b), e.g., in 2008 ($-125\,km^3$), 2009 (207 km), and 2012 ($-78\,km^3$). The large lateral transport is not always due to large outflow to the south, e.g., $-102\,km^3$ in 2008 and $-96\,km^3$ in 2010 through Byam Martin Channel and $-48\,km^3$ in 2010 through Penny Strait, but also could be caused by less import (e.g., 8 km^3 in 2012) or even export ($-134\,km^3$ in 2009) through the northern gates (Fig. 13). It also shows that large import of ice through the northern gates is usually accompanied by large export to the south, mainly via Byam Martin Channel but also through Penny Strait in some years, e.g., 2010, 2013 and 2014. Both the thermodynamic and lateral transport (contribution through each major gate as well) experience significant inter-annual variations.

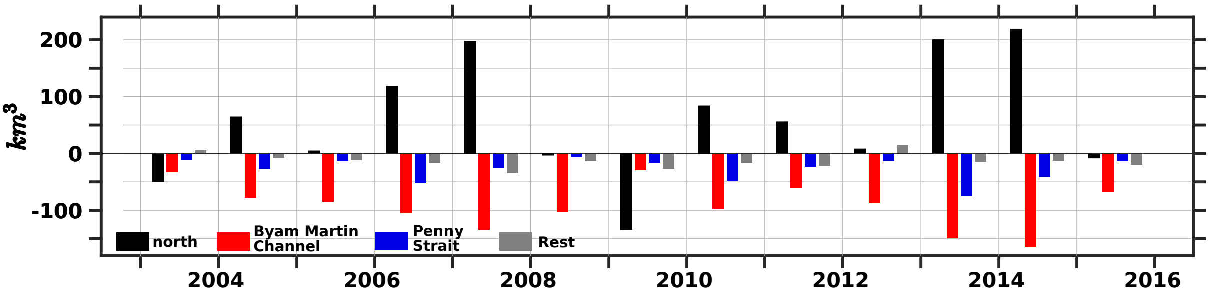

Figure 13. Lateral sea ice volume transport (unit: km^3, black bars: north gates; red bars: Byam Martin Channel; blue bars: Penny Strait; light gray bars: the rest of the lateral gates) in the northern CAA (location see Fig. 1. a) over the same period defined in Fig. 12.

3.3.2 Parry Channel

Parry Channel (dashed black polygon shown in Fig. 1) is the main water channel that connects the Arctic Ocean and Baffin Bay through the CAA (Fig. 1). It starts from M'Clure Strait on the west, running to east by the mouth of Lancaster Sound before entering Baffin Bay. Over the whole simulation, a decrease of $15.2\,km^3$ per year ($r^2 = 0.66$, $p = 0.0004$) in the maximum ice volume is present (Fig. 14a). Even ignoring the initial increase over the first three years (from $554\,km^3$ in 2003 to $665\,km^3$ in 2005), the downward trend similar ($14.6\,km^3$ per year with $r^2 = 0.58$, $p = 0.0065$). However, this decline is not steady but with inter-annual variability. The minima are found in 2012 ($407\,km^3$) and 2013 ($398\,km^3$), which are more than $20\,\%$ lower than the average, $524\,km^3$. Similar to the northern CAA, thermodynamic growth is the main contributor to the ice volume increase from year to year while net lateral transport functions to deplete the sea ice (Fig. 14b).

Large inflows from M'Clure Strait are simulated in the first two years (Fig. 15), but the direction of sea ice flow can switch from year to year (e.g.,$-132\,km^3$ in 2011 and $120\,km^3$ in 2013). The outflow events in 2007 and 2011 are consistent with the ice area flux study in Howell et al. (2013) . As significant inter-annual variability in the amount of this ice volume flux is also present, the over all contribution of ice volume into Parry Channel from M'Clure Strait is small, which also supports the finding in Howell et al. (2013) .

Major sea ice volume exchanges (Fig. 15) occur at Byam Martin Channel (inflow from the north), M'Clintock Channel (outflow to the south) and Lancaster Sound mouth (outflow to Baffin Bay). On average, annual ice volume fluxes through the first two routes nearly cancel each other ($92\,km^3$ vs $94\,km^3$), which indicates a relatively volume conservation due to high concentrations. The averaged sea ice transport at the east end (via Lancaster Sound mouth) is an export into Baffin Bay ($92\,km^3$ per year), which is closed to an early estimation ($102\,km^3$ per year) from Agnew et al. (2008) .

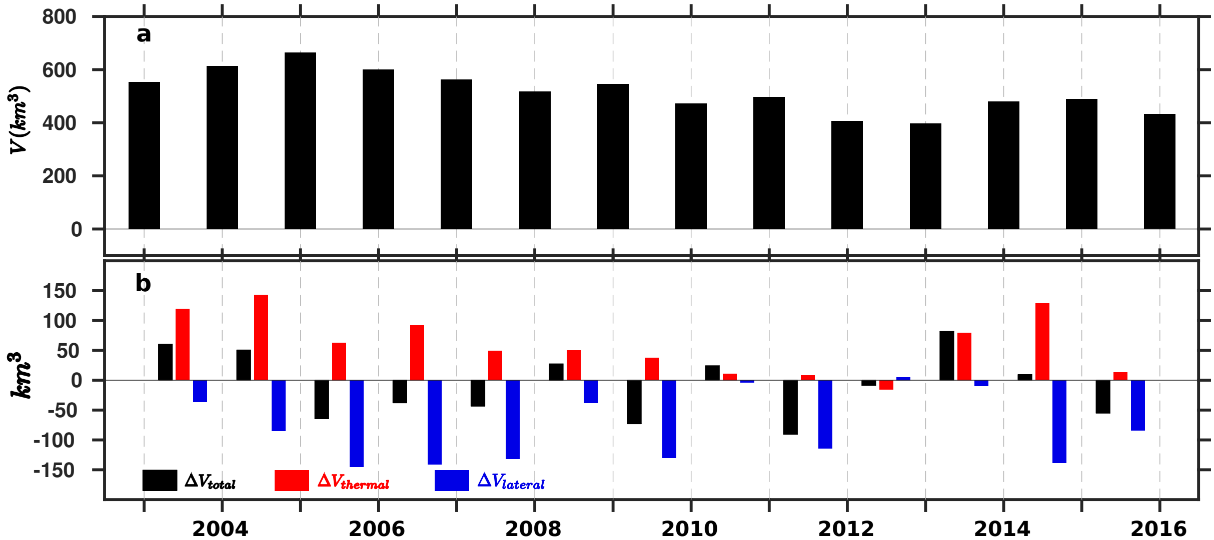

Figure 14. Similar to Fig. 12 but within Parry Channel.

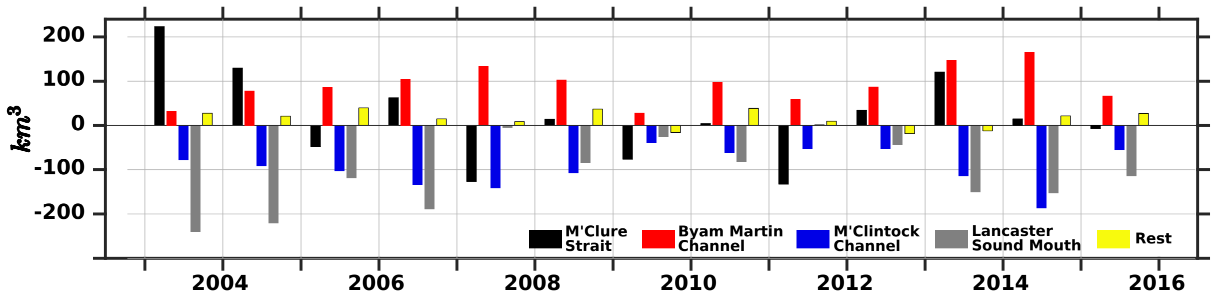

Figure 15. Similar to Fig. 13 but for Parry Channel region (black bars: M'Clure Strait; red bars: Byam Martin Channel; blue bars: M'Clintock Channel; light gray bars: Lancaster Sound Mouth; yellow bars: the rest of the lateral gates).

3.3.3 Baffin Bay

Baffin Bay (dotted black polygon shown in Fig. 1), bounded by Smith Sound in the north, Jones Sound and Lancaster Sound in the west and Davis Strait in the south, $\sim 672 \times 10^3\, km^2$, is covered by seasonal sea ice with an averaged maximum ice volume of $895\, km^3$. No obvious decline is found over the simulation period (Fig. 16a). Although both the local thermodynamic ice growth and lateral ice volume flux show remarkable inter-annual variability (Fig. 16b), the balance between the contributions results in a relatively stable ice volume within the Bay.

Figure 17 shows the lateral ice volume flux is dominated by the inflow from the northern (Smith Sound) and outflow from the south (Davis Strait). On the west side (via Lancaster Sound and Jones Sound), the direction of ice flux is mainly into

Baffin Bay, however, the total amount is much smaller than ice volume flux either via Smith Sound or Davis Strait. This is consistent with other studies (e.g., Tang et al., 2004; Agnew et al., 2008; Sou and Flato, 2009) . The averaged export of ice volume flux through Davis Strait is 702 km^3 per year with a standard deviation of 147 km^3 per year. This number is larger than estimates in Curry et al. (2011) and Curry et al. (2014) , 500 km^3 and 424 km^3 respectively. But they are not very different, taking account of the uncertainties in observations, large inter-annual variability and difference in integration period (Baffin Bay ice volume maximals are used to determine the integration period in this study). It is more comparable to the 530 – 800 km^3 per year estimated by Kwok (2007) . In addition, the low outflow event in 2004 and high outflow event in 2008 agree with Curry et al. (2014) . The inflow of ice flux from Smith Sound is 377 km^3 per year, which is much larger than the long term mean (9 km^3 per year) in a coarse simulation done by (Sou and Flato, 2009) , but closer to their estimate through southern Smith Sound section, i.e., 170 km^3. It indicates sea ice in this region is more dynamic in our simulation (Fig. 4). This dynamic feature is also evidenced in ice motion vector fields derived from enhanced resolution Advanced Microwave Scanning Radiometer (AMSR-E) imagery in Agnew et al. (2008) . Relatively large ice fluxes (e.g., 110 km^3 per year in 1977-1978 and 136 km^3 in 1974-1975) through Smith Sound were also estimated based on satellite images and a mean ice thickness of 2.5 m by Dey (1981) . Another way to estimate the ice flux through Smith Sound is based on the ice flux through the north end of Nares Strait (i.e., Robeson Channel). Note ice flux through Smith Sound usually is larger than the sea ice influx through Nares Strait (Dey, 1981) . (Kwok et al., 2010) estimated the annual mean ice volume flux to 141 km^3 per year over 2003–2008. The large outflow (254 km^3) event in 2007 through Nares Strait reported by (Kwok et al., 2010) is also seen in our simulation (Fig. 17). Both (Sou and Flato, 2009; Terwisscha van Scheltinga et al., 2010) attributed the much-lower-than-observation ice flux through Nares Strait to wind forcing, which does not have enough resolution to resolve the along-strait winds. With a high resolution wind forcing, Rasmussen et al. (2010) was able to reproduce much reasonable ice flux through this narrow channel.

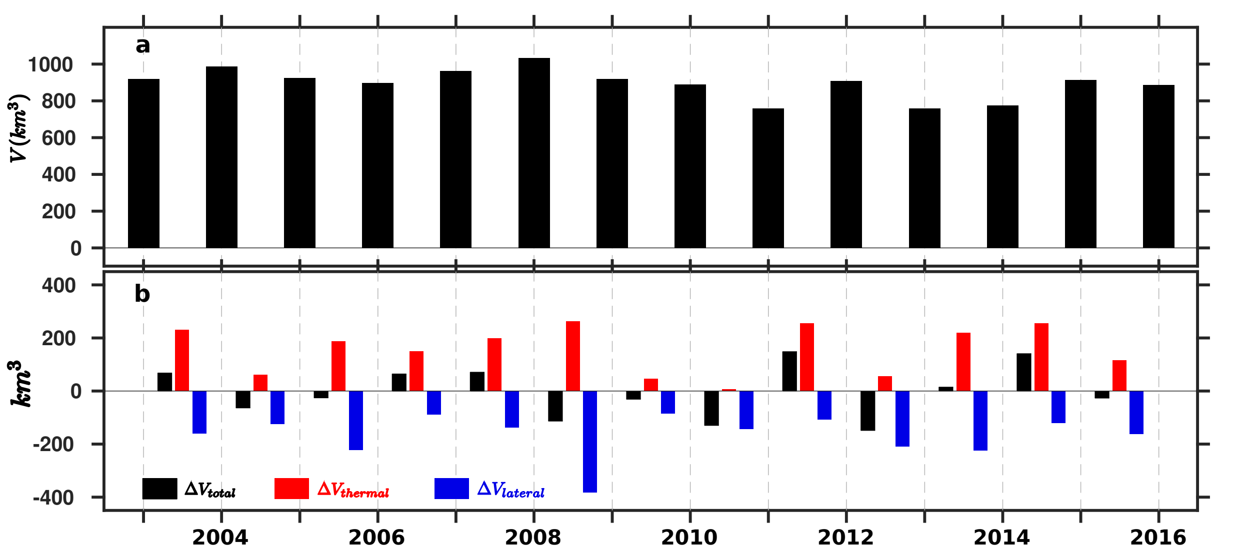

Figure 16. Similar to Fig. 12 but within Baffin Bay.

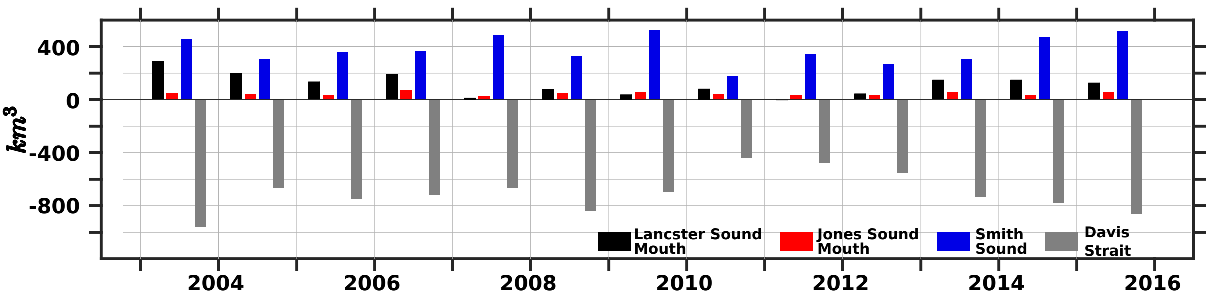

Figure 17. Similar to Fig. 13 but for Baffin Bay (black bars: Lancaster Sound Mouth; red bars: Jones Sound Mouth; blue bars: Smith Sound; light gray bars: Davis Strait).

4 Summary and discussion

Sea ice thickness is simulated within the CAA with a relatively simple (not multi-category) sea ice model, LIM2, with both $1/4°$ and $1/12°$ resolutions from 2002 to 2016. The model can capture the ice thickness asymmetric seasonal cycle and amplitude. Even with the ~~constrains~~ constraints of the resolution, simulated ice thickness still compares reasonably well with the ECCC observations at most sites. Increasing model horizontal resolution does not result in much noticeable change/improvement in sea ice thickness simulation, at least between $1/4°$ and $1/12°$. ANHA12 does show differences at ~~WEU~~ Eureka (Fig. 2g), but this is not related to the sea ice model physics but improvements in the local coastline, and thus the regional circulation and the dynamic component (not shown). In general, the difference is not visible. We expect model resolution to play a big role when it resolves much smaller scale, e.g., sufficient to resolve a ridge/lead. This study focuses on the large scale features, e.g., the simulations can produce reasonable spatial distribution of the thickness (very thick ice in the northern CAA, thick ice in the west-central Parry Channel and thin ice in the eastern and southern regions of CAA). With the help of the numerical model, the ice growth process can be decoupled into thermodynamic and dynamic contributions. Relatively smaller thermodynamic contribution in the winter season is found in the thick ice covered areas, with larger contributions in the thin ice covered regions (which indicates a 1D sea ice model would not be suitable there). We also find the sea thickness can vary quickly (daily to weekly) during the ice melting and formation seasons, due to the diurnal cycle in the thermodynamic ice production. The thermodynamic ice production is not symmetric for the diurnal cycle and on the seasonal scale (more pronounced during the melting period).

The inter-annual variations of the winter maximum ice volume in the northern CAA, Parry Channel and Baffin Bay are controlled by the thermodynamic growth and lateral transport. While both components demonstrate significant inter-annual variabilities, there is no clear trend in the winter maximum ice volume within the northern CAA and Baffin Bay regions but a downward trend ($r^2 \approx 0.6$) in Parry Channel region. In the northern CAA, the lateral transport is mainly through the northern gates and Byam Martin Channel but large ice volume flux could also flow south via Penny Strait when there is large inflow through the northern gates. Ice flow via Byam Martin Channel into Parry Channel is balanced by outflow into M'Clintock Channel on average. Eastward sea ice export through Lancaster Sound mouth is a big term in Parry Channel ice volume budget, but is much smaller than the influx from Smith Sound and outflux through Davis Strait in the ice volume budget of Baffin Bay. These estimates are comparable to limited available studies, however, further evaluations are still in need to confirm the quantities and variations.

Landfast ice exists widely in the CAA (Melling, 2002; Galley et al., 2012; Haas and Howell, 2015; Howell et al., 2016). The sea ice model utilized here does produce zero-motion sea ice (e.g., Fig. 4d), however, more realistic physical parameterizations (e.g., Lemieux et al., 2016) are not applied in our simulations yet. Improvements are expected in both the sea ice thickness and dynamics when including such parameterizations in the future.

Another ice model physics related process is the snow depth at the surface. Both Brown and Cote (1992) , Dumas et al. (2006) and Howell et al. (2016) pointed out that the snow thickness plays a major role in a sea ice thickness simulation. The snowfall data from CORE-II has a monthly resolution, which is possibly too coarse temporally. This leads the snow depth to drop to close to zero quickly during the the first year of the simulation. This never happens with the hourly CGRF forcing, as well as other datasets with daily snowfall (Hayashida, 2017).

A large source of bias is related to the radiation fluxes (shortwave and longwave) at the atmosphere-ocean interface. The CGRF product use the GEWEX correction (more details in Smith et al. (2014)) to minimize the bias in the original output from the atmospheric model. However, it was found that this correction is not needed for years after 2011 (Paquin, 2017). A test run was done to estimate the influence of this correction. A large impact was seen in the Arctic Ocean but not over most of the CAA (not shown) except the north. Without the GEWEX correction, the model tends to simulate thinner ice with a thinner snow depth at the same time, e.g., at WEU Eureka (Fig. 18). The impact is smaller at YLT and YLT1 Alert and Alert LT1 and negligible for the rest of the ECCC sites used in this study. Further investigation is undergoing.

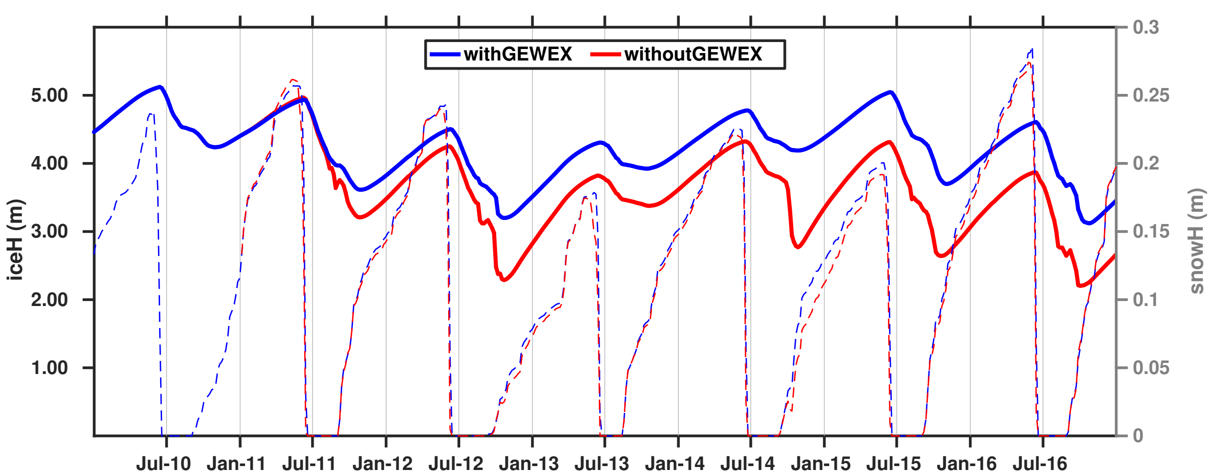

Figure 18. Simulated ice thickness (solid lines, left y-axis, unit: meters) and snow depth (dashed lines, right y-axis, unit: meters) at WEU Eureka in a ANHA4-CGRF simulation with GEWEX (blue) and without GEWEX (red) radiation flux correction

Whitefield et al. (2015) showed the heat flux carried by rivers from land into the ocean plays a role in regional sea ice simulations. Here the river water temperature is assumed to same as the simulated sea surface temperature in the grid cell where the runoff is distributed in the model. Also the salinity of the river water is assumed to be fresh, i.e., its salinity is set to zero. Another factor that may affect the local ice thickness is the tides (Luneva et al., 2015), which is not included in the simulations used in this study as well. All these factors will be considered in the future studies.

Data availability. For access to the model data contact P.G. Myers (pmyers@ualberta.ca)

Competing interests. NONE

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