Interactive comment on "Investigating future changes in the volume budget of the Arctic sea ice in a coupled climate model" by Ann Keen and Ed Blockley

Anonymous Referee #1
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We thank the reviewer for reading our manuscript, and for his/her comments. Our updated responses are included below in blue text. The page numbers refer to the 'tracked-changes' section of this document, showing the alterations from the original version of the manuscript.

Summary
The authors investigate changes in the Arctic sea-ice volume during the 21st century.
To do so, they use the Earth System Model HadGEM2-ES and output variables that describe
the different components of the ice volume budget, i.e. basal melting and growth,
top melting, snowfall, frazil ice formation, and ice advection. The effects of these processes
on the ice volume can directly be quantified as they can be transformed into
meters of ice thickness. Therefore the ice volume budget can be closed. The method
enables a thorough analysis of the evolution of the sea-ice volume budget during the
21st century. The authors find that the sea-ice loss is mainly driven by a decrease in
basal growth over the 21st century in the decadal mean. However, by investigating the
seasonal cycle, they show that different processes are at work depending on the time
of the year. Finally, another important result of the study is that the changes in the
processes do not depend on the forcing of the scenario but rather on the sea-ice area
that is still present.
As there is still a high spread in climate model projections, this topic is interesting and
could bring more insight into differences in ice volume budget evolution in different
models. This method could be used for comparison between CMIP6 models, if these
provide the needed variables, as suggested by the SIMIP protocol. Therefore, the topic
is of relevance in the current context of sea-ice and climate research. The manuscript
is well written but I would appreciate if the authors would clarify some points. I also
have some additional suggestions.

Thematic comments
#1 In the end of the introduction, it is not clear to the reader what precisely is the
scope of the study and what is new about it. It is clear that the authors will describe
the evolution of the sea-ice volume budget, in a similar way to Holland et al. (2010),
with the method of Keen et al. (2013). However, it is not clear if the scope of the
manuscript is to introduce the method for further application (as is suggested in the
conclusion) or to draw conclusions from the ice volume budget evolution to improve the
understanding of changes in the Arctic climate system as a whole. I would appreciate
if the authors make this point very clear in the beginning. It is difficult to follow the story
of the manuscript otherwise. The authors write on page 5: "although here we are also
able to include individual components [. . .] volume budget". I suggest including this
information in the introduction as it is a strong statement about what makes this study
special.

We intend the scope of the manuscript to be both the introduction of the method, illustrated by the application to the HadGEM2-ES model, and the investigation of the impact of the forcing scenario on the budget changes.

The abstract (p9) and introduction (p10-12) have been updated to clarify this, and the statement from p5 of the original manuscript has been incorporated into the revised introduction.

#2 The reference period is chosen as the years 1960-79. I would like the authors to comment why they chose this period and not the period 1960-1989 (as usually used in studies for IPCC assessment reports) or the period 1950-79 (to have at least 30 years).
I find this period rather short to be a reference period. I wonder if they have tried other reference periods? And if yes, do they yield different results?

We have also considered changes w.r.t the 30 year period 1960-89, and the results and conclusions are almost identical. All the relevant figures have now been updated to use the longer reference period, and the text has been updated as appropriate. Some of the numbers quoted in the text have changed very slightly

#3 P4 L22-24: I do not understand why Eq. 1 should result in an ice volume that has to be converted back to effective ice thickness. As far as I understood, Eq. 1 gives thicknesses directly. I would appreciate if the authors could clarify this.

Apologies, this was incorrect and this paragraph has been modified (p13 L8-10).

#4 P4 L30: Can the authors explain the especially steep decline of the winter sea-ice cover from 2080 onwards in the RCP8.5 scenario with their results? I would guess it has to do with the increase in water temperature inhibiting the formation of a winter sea-ice cover (see Bathiany et al. 2016). I would find interesting to hear if the authors have another explanation. It would be worth mentioning in the manuscript as well. On the same note, I would suggest that the greater decline in basal ice growth (P9 L26) is linked to the greater decline in ice area in RCP8.5 stated earlier in the manuscript. Maybe these two could be linked to make a statement about the processes at work here.

Yes, it is most likely that the steeper decline in winter ice cover towards the end of the 21st century in RCP8.5 is associated with the warming ocean surface: certainly the DJF ocean top level temperature increases more rapidly towards the end of the integration. This is now mentioned in the text (p13 L18-21 and p20 L24-27)

#5 P7 L4: The lateral melting is not explicitly modeled. Do the authors have an idea of how important this term is? I could imagine that it is an important term in summer, as a component of the sea-ice albedo feedback.

In a 'present day' (year 2000) long equilibrium run of our latest (CMIP6) model HadGEM3 GC3.1, the lateral melting term is important in the mean budget of the Arctic sea ice during JJA, when it is at most about 14% of the ocean to ice heat flux. It may become more important in a warming climate, and while this is outside the scope of this manuscript it will be possible to investigate this using data from CMIP6 scenario runs once they are available.
HadGEM2-ES does include an adjustment [*] to the ocean to ice heat flux when the ice concentration drops below 0.05, to provide a crude representation of increased lateral melting of small ice floes in the marginal ice zone.
[*] The heat flux is scaled by 0.05/ice_area so that the grid box integral of the flux becomes independent of the ice area
.

In the revised manuscript we have now mentioned the lateral melting in the discussion (p22 L21-24)

#6 P7 L19-22: Holland found large differences between CMIP3 models. I would like the authors to comment on the implications of their findings for these differences or differences between CMIP5 models. In any case, I suggest moving this paragraph to

the discussion in the end of the manuscript.

The point we intended to make here was that given Holland et al found that CMIP3 models did not even agree on the relative role of melt and growth in the ice decline, we might also expect considerable inter-model differences when we can break these terms down further for the CMIP6 models. We now mention this is the discussion (p23 L10-12)

#7 P8 L29: The authors write that the extra top melting is enhanced by reductions in the surface albedo. Do they infer this directly from the model simulation? I wonder if maybe longwave radiation also has an influence on surface melting (see e.g. Notz and Stroeve, 2016), for example through clouds and water vapor? I would like the authors to comment on that.

Yes the LW also has an impact on the extra melting. We have added some extra text to show the relative magnitude of the SW and LW changes, and the albedo changes (p18 L10-21)

#8 P9 L2: I am not convinced that the in-situ warming of the ocean is only a consequence of the ice cover retreat in your model. Could it not also partly be due to a higher advection of oceanic heat from lower latitudes, as stated for example in Burgard and Notz, 2017? I would like the authors to comment on that.

Yes, the advection of oceanic heat from lower latitudes does also play a role, and as shown in Burgard and Notz it is the main driver for the long term warming of the Arctic Ocean. However a seasonal analysis of the Arctic Ocean budget for HadGEM2-ES shows that during the spring (MAM) and summer (JJA), when large increases in the basal melting are seen, atmospheric surface fluxes are the major driver of warming, especially for the upper ocean. We have added this to the updated manuscript (p18, L31-34)

#9 The conclusion from Fig. 9 and Fig. 10 is that the changes in components of the ice volume budget are independent of the forcing and dependent on the remaining sea-ice area. I agree that this relationship is very clear. However, can the authors be sure that it is not rather dependent on the temperature? Several studies showed that the sea-ice area depends linearly on the air temperature (e.g. Winton, 2011; Mahlstein and Knutti, 2012) and cumulated CO2 emissions (Notz and Stroeve, 2016). It might be worth having a look at these relationships as well to get a larger picture and maybe a stronger conclusion.

Yes, there is a linear relationship between anomalies in the ice area and the near-surface air temperature in HadGEM2-ES, which holds for all the forcing scenarios considered here. We did consider plotting Fig 9 and Fig 10 using temperature instead of ice area. The main reason that we decided not to was because we felt that the changes in the budget terms and the changes in ice area were more directly and closely linked (eg smaller basal growth term in the ice budget because the growth is occurring over a smaller area). We agree that it would be advantageous to widen the discussion to include these relationships as well and have mentioned this in the discussion (p22 L32 – p15 L5)

#10 The last paragraph of the conclusion is somewhat unclear and is not very strong. This is not an advantage for the manuscript. I would suggest discussing a little more what makes this study special and what are its implications for future research. It is still not clear enough for me.

We have re-written this section (p23 L6-14) to make it clearer.

Writing comments

#11 The Section 2.2 about model integration is interesting but I think there are too many details. The effect of the different CO_2 pathways on the temperature is what is important for the study. This effect can be seen well in Fig. 1. I therefore suggest that the authors leave in the reference to Moss et al. (2010) but that they leave out the bullet point list and the sentence "Fig. 1A of Caesar et al. [. . .] scenarios."

This text has now been removed (p12 L25 – p5 L1)

#12 I suggest writing down the exact limits for the study area in an appendix/supporting information. This might be useful for the comparison with future studies.

As it is a single sentence, we have added this information to the caption for figure 2 (p31)

#13 Section 3.1, P5-6: The bullet point list makes the text well readable. To keep consistent, maybe the authors could add some numbers to the three first points. There, the results are described qualitatively in contrast to the three last points, where they are described quantitatively.

We have now added some numbers to the first three points so that this section has a consistent format. (p14 L16, L23 and L28-29)

#14 The transition between Section 3 and Section 4 is quite abrupt. I would suggest working on a more logical transition.

Yes, agreed, we have added some text to improve this (p16 L1-3)

#15 In section 4.1., Fig. 5B is cited instead of Fig. 5A and vice versa. I suggest reading through this section carefully again.

Thank you, and apologies for this. This has now been corrected (p16 L13-28)

#16 In section 4.2., the reader is pointed to several different figures while the rest of the manuscript is very structured (one paragraph = one figure description). In this case, it is helpful for the message to look at the different figures. However, I find difficult to follow the story from P9 L1 to P9 L22. I suggest to try reformulating the message in a clearer way.

This section has been re-structured, so that the three budget components shown in figure 7c are discussed separately (p17 L22 – p20 L15). We have also added an extra pane to figure 7 to show the anomalies in the ice area (p41)

#17 P10 L26-27: The processes changing at the ice surface are listed and then "basal melting" is mentioned. Why?

This was intended to refer to processes acting over the remaining ice, and the sentence how now been corrected (p21 L32 – p22 L1)

Technical comments
P1 L9-13: These two sentences are long and contain too much information. Reformulating might clarify the message.

This has been rewritten using shorter sentences. (p9, L12-14)

P3 L3: I suggest removing "for use in IPCC AR5". I think readers know the aim of CMIP5.

Yes, done at p11 L19.

P3 L9: West et al., 2017 is cited. In the references, it is marked as "in prep.". I think they can therefore not be cited it in this context then.
This work is now under review in The Cryosphere Discuss: the reference has been updated accordingly (p27 L18-20)

P3 L12: Replace "as that used" by "as the one used"
Done (p11 L28)

P4 L6: Remove comma after the Moss et al., 2010 reference
P4 L15-16: The sentence is long. I suggest cutting after "scenario)" and starting the next sentence with "Fig.1".
Done (p13 L2)

P6 L25: The sentence is too long. I suggest stopping after "loss" and starting the next sentence with "The ice decline arises"
Done (p15 L19-20)

P6 L27: Add "seen in Fig. 3b" after "thickness".
Done (p15 L21)

P6 L29: The sentence is long. I suggest stopping after "line." and starting next sentence with "During"
Done (p7 L23)

P7 L8: Replace "and also how the seasonal cycle changes" by "and the changes in seasonal cycle".
Done (p16 L7-8)
P7 L27: "s" missing after 2040
P8 L 24-26: This sentence is too long. I suggest reformulating it to clarify the message.
Section 4.2 has been re-written, and this sentence is no longer there.

P8 L31-32: Can the authors reformulate this sentence? I do not understand it.
Section 4.2 has been re-written, and this sentence is no longer there.

P9 L9: add "process" between "this" and "that"
Section 4.2 has been re-written, and this sentence is no longer there.

P11 L2: I suggest changing "and reduced basal growth during autumn/early winter" to "and in autumn/early winter due to reduced basal growth".
Done (p22, L9)

P11 L15-18: This sentence is too long and unclear. I suggest reformulating it to clarify the message.
Much of section 5 has been re-written, and this sentence is no longer there.

Figures
Fig. 1: I suggest marking or shading the reference period In the caption, replace "HadGEM2ES" by "HadGEM2-ES"

Done (p29)

Fig. 6: Have the authors looked into the period 2080-2099? Are the changes still
similar? If not, would they bring additional information for the study?

Having looked again at this later period we have now added an extra pane to figure 6 to show the seasonal cycle for 2080-89 (p39), and this is referred to in sections 4.1 and 4.2.

Fig. 7: Add in the caption for (b) that this is 2010-2019.
Done (p41)

Fig. 9: 1960-79 instead of 1960-9
Updated to 1960-89 (p45)

References
Arctic is written "arctic" in most of your references. I suggest reading through them carefully again.
The references have been checked and updated.

Interactive comment on "Investigating future changes in the volume budget of the Arctic sea ice in a coupled climate model" by Ann Keen and Ed Blockley

Anonymous Referee #2

Received and published: 11 December 2017

We thank the reviewer for reading our manuscript, and for his/her comments. Our updated responses are included below in blue text. The page numbers refer to the 'tracked-changes' section of this document, showing the alterations from the original version of the manuscript.

General Comments

In this work the authors decompose in the coupled climate model HadGEM2-ES the global Arctic sea ice volume budget over the late 20th and 21st century into its main components – top melt, basal growth, basal melt, frazil ice formation, advection, snowfall less sublimation.

In many ways this study appears as a follow up study of the earlier Keen et al., 2013 paper - see section 5 on 'modelled heat budget of the Arctic snow and ice' but instead of taking a local (per unit ice area) analysis here the authors present a global perspective that presents the advantage of explaining the mechanisms that control sea ice volume decline at the Arctic basin scale.

The main results of this study are:

- To present a detailed methodology of how to analyse the HadGEM2-ES Arctic sea ice volume budget components at the basin scale - To characterise and rank in order of importance the different terms controlling the seasonal and inter-annual sea ice growth (and melt) - To show that the changes in the volume budget are a function of the sea ice cover and not of the speed at which the sea ice retreats

My overall impression is that there is nothing fundamentally wrong with this paper but that at the same time that it does not contribute to any significant advances in the field.

We feel that the type of study outlined here is now necessary in order to understand inter-model differences in projected future ice decline: we need to consider changes in the underlying processes as well as looking at how the ice state changes. We also feel that there are a number of novel aspects to our study, some of which are summarised below. However we recognise from this review, and from comments from reviewer 1, that we were clear enough about the scope and interest of the study in the original version of the manuscript.

To remedy this we have updated the Abstract, Introduction and Summary and Discussion to better clarify the scope of the study, and the novel aspects.

I encourage the authors to explore one of the following possible extensions of their work in order to give it a wider audience:

- Explore impact of sea ice physics even at a simple level. Comparing results with results from HadGEM1 analyzed in Keen et al., 2013 could be informative. While it would be difficult to separate the impact of the different physics in the two models on the total volume budget it would show how model developments modify our understanding of the drivers of sea ice decline

We have applied the same analysis to HadGEM1, but the sea ice physics in these two models is essentially the same, so this comparison would not show the impact of different sea ice physics. The two models showed very similar budget change, with the main differences being due to different rates of ice decline. While we *are* interested in the impact of the ice decline in the changing budget, we felt this was better illustrated using one model and a range of different forcing scenarios.

. - Compare the model results with other climate models.
In that sense the reader would get a better sense of inter-model variability. The authors suggest that their methodology is appropriate to analyse other models. Why not do it?

This will be possible using the diagnostics from CMIP6 models, and we plan to do this once the data is available.

- If these options appear too ambitious the authors may at least consider improving the quality of the figures and explain in greater details how the decompositions presented in those figures help explain the future evolution of the sea ice cover and its role in the climate as a whole. For example what can we learn about the changing climate based on seasonal changes in the different terms in the volume budget. Similarly what do the figures 9 and 10 on the changes of effective thickness as a function of sea ice area tells us about climate change in the Arctic and beyond.

We have expanded the discussion in section 4.2 (p17-20) to include more about the processes in the wider climate and their impact on the declining sea ice. In the Summary and Discussion we now link the changes shown in figures 9 and 10 with global changes in near-surface temperature and cumulative CO_2 emissions (p22 L31 – p23 L5)

Summary of changes made to manuscript

- We have updated the abstract and introduction to clarify the scope and novel features of this study.

- We have re-structured section 4.2 so that is it clearer, and have provided more information about processes in the wider Arctic that contribute to the changes in the volume budget components.

- We have updated all the figures to use a longer reference period, and added an extra pane to each of figures 6 and 7.

- We have updated the Summary and discussion to clarify the novel features of our work, and the implications for future research.

Investigating future changes in the volume budget of the Arctic sea ice in a coupled climate model

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Abstract. We ~~consider the~~present a method for analysing changes in the modelled volume budget of the Arctic sea ice ~~in the~~ as the ice declines during the 21st century. We apply the method to the CMIP5 global coupled model HadGEM2-ES, ~~and~~ to evaluate how the budget components evolve ~~during the 21st century~~ under a range of different forcing scenarios. As the climate warms and the ice cover declines, the ~~Arctic~~ sea ice processes that change the most in HadGEM2-ES are summer

10 melting at the top surface of the ice due to increased net downward radiation, and basal melting due to extra heat from the warming ocean. ~~However,~~There is also extra basal ice formation due to the ~~declining ice cover affects how much~~thinning ice. The impact ~~of~~ these changes ~~have~~ on the ~~ice~~ volume budget~~, where~~ is affected by the declining ice cover. For example, as the autumn ice cover declines the volume of ice formed by basal growth declines as there is a reduced area over which this ice growth can occur. As a result, the biggest contribution to Arctic ice decline in HadGEM2-ES is the reduction in the total

15 amount of basal ice ~~formation~~growth during the autumn and early winter. ~~This highlights the importance of taking the declining ice area into account when evaluating projected changes in the sea ice budget, especially if comparing models with very different rates of decline.~~

Changes in the volume budget during the 21st century have a distinctive seasonal cycle, with processes contributing to ice decline occurring in May/June and September to November. During July and August the total amount of sea ice melt

20 decreases, again due to the reducing ice cover.

The choice of forcing scenario affects the rate of ice decline and the timing and magnitude of changes in the volume budget components~~, but for~~. For the HadGEM2-ES model and for the range of scenarios considered for CMIP5, the mean changes in the volume budget depend strongly on the evolving ice area, and are independent of the speed at which the ice cover declines.

25

1 Introduction

30 Arctic September sea ice cover has declined at a rate of over 13% per decade since satellite observations began (Serreze and Stroeve, 2015), and the ice that remains is becoming thinner (Kwok and Rothrock, 2009), younger (Maslanik et al, 2011),

and faster moving (Rampal et al, 2009, Spreen et al, 2011). The ice cover is projected to reduce further as greenhouse gas concentrations continue to increase (Stroeve et al, 2012). These changes have implications both within the Arctic itself, for example for shipping (Melia et al, 2016), and local ecology (Post et al, 2013), and also for the wider climate system via large scale circulation changes that have been linked to the reducing Arctic ice cover (Francis et al 2009, Overland and Wang,

5 2010). As the sea ice interacts directly with both the atmosphere and the ocean, it is influenced by changes in both, and as such can be seen as an integrator of wider changes within the Arctic region.

Hence there is much interest in how the decline in Arctic sea ice will continue in the future, both in terms of the predictability of ice cover in a given year, and in terms of the manner and timing of the transition to a seasonally ice-free Arctic. Global coupled models are arguably the best tool we have for making future projections of the Arctic sea ice, but

10 generate a wide spread of projections of future ice decline (Stroeve et al 2012). There are many factors potentially contributing to this spread, including sea ice model formulation, forcing from atmosphere and ocean model components, uncertainty in forcing scenarios, and internal model variability. A number of studies have attempted to decrease the spread of plausible future projections by sub-selecting models based on their ability to simulate current day sea ice (Wang and Overland, 2009), or past observed changes (Massonnet et al, 2012). More recent work has focussed on the role of internal

15 model variability (Jahn et al, 2016), and the extent to which it is realistic to expect modelled ice decline to closely match the observed decline (Notz, 2015).

Given the inherent uncertainties in predicting future changes in 'integrated' quantities like ice cover and volume, it is becoming increasingly clear that it is also necessary to consider, compare and evaluate the underlying processes causing ice growth and decline, and how they are likely to change in a warming world. Holland et al (2010) evaluated the annual mean

20 changes in ice growth, melt and divergence during the 21st century for a range of models submitted to the CMIP3 model archive, finding considerable variation in the magnitude and relative importance of changes in the budget components. For this 2010 study, the budget components were derived from model monthly ice thickness and velocity from the CMIP3 data archive. However, for individual models a more detailed decomposition is often possible (eg Keen et al, 2013), and for CMIP6 models a wide range of budget components should be available for intercomparison (Notz et al, 2016). In addition,

25 new process-based observational datasets are becoming available to help understand whether the modelled ice state arises for the right reasons (Holland and Kimura, 2016, Uotila et al, 2014).

In this study weIn this study we introduce a method for analysing how the modelled volume budget of the Arctic sea ice (and overlying snow) changes during the 21st century. We use a CMIP5 model for which the budget components are already

30 available as model output. The data required for this decomposition forms part of the CMIP6 SIMIP data request, and so for the next generation of climate models this method can also be used for model inter-comparison. We consider the processes contributing to 21st century changes in the volume of the Arctic sea ice and overlying snow in the Met Office Hadley Centre Earth system model HadGEM2-ES (Martin et al. 2011; Collins et al. 2011), which was one of the models submitted to the IPCC AR5 assessment. We consider a volume budget decomposition similar to that previously used by Keen et al (2013) for

the HadGEM1 model, to identify how the components of the budget change during the 21ˢᵗ century under a range of future emissions scenarios, and which components play the most important role in the decline in ice volume. CMIP5 model HadGEM2-ES (Martin et al. 2011; Collins et al. 2011). We use a similar budget formulation to Holland et al (2010), so that components of the volume budget are expressed in terms of their impact on the mean ice thickness over a defined domain of the Arctic. The data available to Holland et al (2010) only allowed a decomposition between advective, melt and freeze processes, and only considered the annual mean changes. Here we are able to decompose the budget further into individual processes causing ice growth and loss, and we also consider the seasonal cycle of the volume budget. The application of the method allows us to investigate how the volume budget for HadGEM2-ES evolves during the 21ˢᵗ century, and to identify the dominant processes contributing to the decline in ice volume. We also evaluate how the declining ice area impacts the changes in the volume budget, and consider how key budget changes relate to wider changes in the Arctic and beyond. As HadGEM2-ES projections are available for a range of different 21ˢᵗ century forcing scenarios, we also evaluate the impact of forcing scenario on the evolving volume budget.

In summary, the scope of this work is to introduce our method of analysing the volume budget of the Arctic sea ice, and to use the method to learn about 21ˢᵗ century changes in the HadGEM2-ES model. In Sect. 2 we describe the model and the forcing scenarios used. In Sect. 3 we describe the mean volume budget for this model, and in Sect. 4 we investigate how this changes during the 21ˢᵗ century for a range of forcing scenarios. In Sect. 5 we summarise and discuss our findings.

2 Model description and integrations used

2.1 Model description

HadGEM2-ES is a coupled atmosphere-ocean model that was submitted to CMIP5 for use in IPCC AR5. The model includes interactive atmosphere and ocean carbon cycles, dynamic vegetation, and tropospheric chemistry (Martin et al. 2011; Collins et al. 2011). HadGEM2-ES is considered to have a good depiction of present-day global cloud characteristics (Jiang et al, 2012) and the best model depiction of Arctic cloud and surface radiative forcing (English et al 2015). The mean Arctic ice extent lies within 20% of observed values at all time of year, although September extent is biased low and the magnitude of the seasonal cycle is too large, consistent with biases in winter net surface LW and summer net surface SW (West et al, 2017 2018)

The horizontal resolution of the atmosphere component is 1.25° latitude by 1.875° longitude, with 38 vertical levels. The ocean component is 1° by 1° outside the tropics, increasing to 0.33° latitude by 1° longitude at the equator, and has 40 vertical levels. The sea ice formulation within HadGEM2-ES is essentially the same as that the one used in HadGEM1 (McLaren et al., 2006), with three updates as follows:

- The bare sea ice albedo was increased from 0.57 to 0.61, together with a correction to sea-ice albedo during surface melt.

11

- Heat fluxes passed from the atmosphere to the ocean/seaice model are regridded taking the ice concentration into consideration.
- Sea ice velocities are combined with ocean currents to create a "surface velocity" field for use in the atmosphere model.

5 Some of the sea ice calculations take place within the atmosphere component, where the sea ice surface temperature and the top melting and diffusive heat fluxes are computed using the zero-layer thermodynamics scheme described by Semtner (1976). In this scheme the sea ice has no heat capacity, and the ice and any overlying snow are treated as one layer with an effective thickness h_e defined as

$$h_e = h + (\kappa_i/\kappa_s)h_s, \qquad\qquad (1)$$

10 where h is the ice thickness, κ_i and κ_s are the (constant) thermal conductivities of ice and snow, and h_s is the snow depth. The albedo of the sea ice is a function of surface temperature (Curry et al, 2001), allowing the radiative impact of melt ponds to be represented in a simple way.

The growth and melt of ice is calculated within the ocean component, and the ocean to ice heat flux is calculated following McPhee (1992). There is a sub-gridscale ice thickness distribution (Thorndike et al, 1975), with 5 thickness categories plus
15 open water, and the thermodynamic transfer of ice between categories is calculated using a linear remapping scheme (Lipscomb, 2001). Ice velocities are calculated following the elastic-viscous-plastic (EVP) model of Hunke and Dukowicz (1997), using the Hibler (1979) formulation for ice strength. The amount of ridging is determined following the approach used in the CICE model (Lipscomb and Hunke, 2004). For a fuller description of the HadGEM1 sea ice component, see McLaren et al (2006).

20 **2.2 Model integrations**

The integrations used here are described in Jones et al (2011), and include an ensemble of 4 historical simulations (Hist) using observed forcing from 1860 to 2005, and initialised from the model state at 50 year intervals of a pre-industrial control integration. Four different climate forcing scenarios developed for the IPCC Fifth Assessment Report (AR5) (Moss et al, 2010), were then run from the end of each of these historical simulations:

25 - Representative Concentration Pathway (RCP) 2.6: A low emissions scenario, with CO_2 concentration levelling off, and then starting to decline towards the end of the century.
- RCP4.5: A medium forcing scenario, in which the forcing stabilises during the latter part of the 21st century.
- RCP6.0: Another medium forcing scenario, but in this case the forcing continues to increase throughout the 21st century.
30 - RCP8.5: A strong forcing scenario, with ongoing increases in CO_2 concentration throughout (and beyond) the 21st century.

~~Figure 1a of Caesar et al (2012) shows the prescribed CO_2 concentrations for each of these scenarios~~. Here we consider the period 1960 to 2099 (comprising part of the historical period, followed by the scenario~~), and~~). Fig. 1 shows the global temperature anomalies for these HadGEM2-ES integrations w.r.t. a reference period taken as the years 1960-~~79~~89. There is little divergence in the global temperature response before the middle of the 21st century, but by 2100 the temperature

5 increase relative to 1960-~~79~~89 ranges from less than 2 degrees for RCP2.6 to nearly ~~6~~5.5 degrees for RCP8.5.

2.3 Evolution of ice area and volume

We focus on changes in the sea ice over the domain shown in Fig. 2, covering the Arctic basin~~,~~ and the Barents Sea. Figure 3 shows how the ice area and ~~the volume of~~mean effective ice ~~and snow~~thickness within this domain declines for each of the model integrations during the period 1960 to 2090. The effective ice ~~volume~~thickness includes the impact of any overlying

10 snow by converting the snow to an equivalent ~~volume~~thickness of ice using Eq. ~~(1). This effective ice volume is expressed as a mean effective ice thickness over the domain, calculated as the ice volume divided by the area of the domain.~~ (1). Hereafter, whenever ice thickness or volume is mentioned it refers to ~~these~~an *effective* ~~values~~value, which includes the overlying snow as well.

The March ice area over the domain declines from a mean value of 9.3 x10^6 km^2 during the 1960-~~79~~89 reference period, to

15 8.4 x10^6 km^2 towards the end of the 21st century (2090-2099) for the RCP2.6 scenario, and 5.2 x10^6 km^2 for the more aggressive RCP8.5 scenario (Fig. 3a). There is little divergence in the response of either the ice area or volume to the different forcing scenarios before about 2050 (Fig. 3), after which the stronger forcing scenarios show a greater loss of winter ice cover, with RCP8.5 showing an especially steep decline from 2080 onwards. This rapid decline in winter ice cover is seen in other climate models as well (Bathiany et al, 2016). It occurs once the summer ice in the Arctic Ocean has gone,

20 and when regions of the central Arctic Ocean no longer fall to the freezing temperature over the winter. The seasonal ice can no longer form at these locations, leading to a rapid drop in the winter ice cover.

The mean March ice thickness over the domain declines from 2.3m during the period 1960 to ~~1979~~1989, to 1.2m during the 2090s for the RCP2.6 scenario, and 0.2m for RCP8.5.

For September, the mean ice area during the 1960-~~79~~89 reference period is 4.~~1~~0 x10^6 km^2, and the mean thickness is

25 1.~~5m~~0m. By the end of the 21st century, all the scenarios have less than 1.0 x10^6 km^2 of ice cover remaining in September, so that the Arctic Basin is virtually ice free.

3 Mean volume budget of the Arctic sea ice

The HadGEM2-ES model output includes sea ice volume tendencies due to thermodynamic and dynamic processes, and terms quantifying the thermodynamic processes acting on the ice and overlying snow. This allows us to construct a budget

30 that balances the diagnosed changes in ice volume over any given period. In Keen et al (2013), the budget terms are expressed in terms of a heat anomaly per unit area of ice (in J m^{-2}). While this formulation enables an understanding of how

the atmospheric and oceanic forcing of the ice is changing as the climate warms, the budget terms expressed this way cannot be summed to balance the changes in the ice volume. Here we ~~express~~start by expressing the budget components in terms of their impact on the average ice thickness over the domain of Fig. 2, so the units are m of ice formed/lost. This is a similar formulation to that used by Holland et al (2010~~), although here we are also able to include individual components of the~~
5   ~~melt/freeze terms, and we also consider the seasonal cycle of the volume budget.~~).

3.1 Mean volume budget for the reference period 1960-~~79~~89

The components of the volume budget that we can diagnose for the HadGEM2-ES model are shown in Fig. 4, both as a decadal mean time series (for the RCP8.5 scenario) and as a mean seasonal cycle for the reference period 1960-~~79~~89. As mentioned above, each component is expressed in terms of its impact on the ice thickness (averaged over the domain): a flux
10 representing heat entering the ice will be shown as a negative value as it causes ice loss. We describe each component in turn:

- Basal ice growth via the diffusive heat flux through the ice and snow (dark green lines) : In HadGEM2-ES, ice growth is dominated by basal ice formation due to the loss of heat via the diffusive heat flux through the ice and snow (Fig. 4a). This term is positive for most of the year (Fig. 4b), representing ice growth at the base of existing
15   ice. The total amount of basal growth increases as ice forms during the autumn, and is a maximum during the winter~~.~~, reaching 29cm of ice growth during December. During the summer, this term can become small and negative (representing ice melt) when the surface temperature rises about the freezing temperature of sea water (Fig. 4b).

- Basal melting due to heat from the ocean (light green lines): The ocean to ice heat flux is a function of the
20   difference in temperature between the top layer of the ocean, and the temperature at the base of the ice (McPhee, 1992). It is maintained through diffusive and advective ocean processes, and melts ice at the bottom surface throughout the year, especially during the summer and autumn (Fig. 4b). This term is small and negative during the winter, increasing in magnitude from April to a maximum of 24cm of ice loss in July, and then declines in magnitude through the late summer and autumn. In HadGEM2-ES this is the largest individual term causing ice
25   melt (Fig. 4a).

- Top melting (dark blue lines): The top melting flux is the sum of the atmospheric turbulent and radiative heat fluxes, resulting in the surface melting of ice or snow. It is zero outside the melting season (Fig. 4b), and negative during the spring and early summer (as it causes ice melt). The amount of top melting peaks in June at 37cm of ice loss. The maximum occurs earlier in the melt season than the basal melting, and then declines more quickly. In
30   HadGEM2-ES there is less ice lost during the year by top melting than by basal melting (Fig. 4a).

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- Advection (orange lines): The net impact of ice advection is to move ice out of the domain (to lower latitudes), and so this appears as a negative term in Fig. 4. There is a small seasonal cycle, with more ice lost by advection during the winter, falling from a monthly maximum of 2.~~8cm~~7cm of ice loss during January, to 0.8cm by August. The amount of ice lost by advection each decade is smaller than the amount lost by either top or basal melting (Fig. 4a).

5
- Frazil ice formation (green/blue lines): This term represents the formation of ice in a grid box when the ocean temperature would otherwise fall below the freezing temperature. It is virtually zero during the summer, and a maximum in autumn (2.5cm of ice formation during November) as the ocean cools and the ice cover increases following its summer minimum. This component is always positive, as it solely represents ice formation.

- Snowfall (less sublimation) (red lines): This represents the snow accumulation due to snowfall, less any loss of ice
10   or snow at the surface due to sublimation. It is positive in all months, a maximum during the winter (1.~~3cm~~2cm of ice formation in December), and virtually zero during the summer melt season.

To summarise, in the decadal mean volume budget for HadGEM2-ES, ice growth is dominated by basal ice formation due to the diffusive heat flux through the snow and ice, which accounts for 85% of the annual mean ice formation during the reference period 1960-~~79, with~~89. There are smaller contributions due to frazil ice growth (7%) and the accumulation of snow (less sublimation) (7%). These processes are offset by melting at the base of the ice due to heat from the ocean (48% of annual mean ice loss~~),~~,), melting at the top of the ice due to atmospheric fluxes (40~~%)~~,%), and ice advection out of the region (12%). The sum of these budget components (black line, Fig. 4a) is much smaller in magnitude than the individual components, representing the near balance between the processes of ice growth and loss~~, with the~~. The ice decline 20 ~~arising~~arises because of the small imbalance between these terms in the warming climate. This budget sum (Fig. 4a) matches the decadal changes in ice thickness seen in Fig. 3b.

The HadGEM2-ES melting season extends from May to September during the 1960-~~79~~89 reference period (Fig. 4b, solid black line~~), and during~~). During this time the melting is initially dominated by melting at the top surface of the ice, with basal melting due to heat from the ocean becoming more important later in the melt season, and continuing into the autumn.
25   During the winter, the dominant term is basal ice growth due to the diffusive heat flux.

Note that ridging is not included in this decomposition, as it does not explicitly affect the ice volume: it changes the spatial distribution of ice within a grid box, but not the volume of the ice. That is not to say that the ridging is unimportant, merely that it has a null direct impact on the volume budget. In addition, lateral melting is not explicitly modelled in HadGEM2-ES and so does not appear in this decomposition, ~~and~~although for low ice concentrations there is an adjustment to the ocean to
30   ice heat flux to provide a crude representation of lateral ice melt of small ice floes. Finally, as we are considering the combined budget of the ice and overlying snow there is no snow-ice formation term.

To summarise, in this section we have defined and quantified the mean volume budget for HadGEM2-ES during the reference period 1960-89, and identified the most important processes. Next, we will examine how this budget changes during the subsequent decades as greenhouse gas concentrations increase.

5 **4 Changes in the volume budget of the Arctic sea ice**

Here we consider how the components in the volume budget change relative to the reference period 1960-7989 discussed abovein Sect. 3, both in terms of their decadal evolution during the 21st century, and also howthe changes in the seasonal cycle changes. Initially we focus on the strongest forcing scenario RCP8.5, and then we consider the impact of the different forcing scenarios on the changes.

10 **4.1 ResultsBudget changes for the RCP8.5 forcing scenario**

Figure 5 shows how the components of the volume budget change relative to the reference period 1960-7989 for the RCP8.5 scenario. As the ice starts to decline, the ice loss initially results from a mean reduction in basal ice formation due to the diffusive heat flux through the ice (dark green line, Fig. 5b5a), and extra melting at the base of the ice due to heat from the ocean (light green line). There is also a reduction in the accumulation of falling snow on the ice (red line). These changes are

15 shown as negative values in Fig. 5, representing less ice growth (or more ice loss) relative to 1960-7989. Offsetting these are a reduction in melting at the top surface of the ice due to atmospheric fluxes (dark blue line), reduced loss by advection (orange line), and more frazil ice formation (green/blue line).

~~These changes are similar to the response Holland et al (2010) found for our CMIP3 model HadGEM1 (their Fig. 7l), where the volume decline was due to reductions in ice growth, offset by (smaller) decreases in ice melt and advective ice loss. This~~

20 ~~is not the case for all models though: Holland et al found that the CMIP3 models overall show a large model to model differences in the 21st-century budget changes.~~

As the run progresses, the majority of these changes become more pronounced as the ice cover declines, the exceptions being the basal melting and the frazil ice formation (Fig. 5a5b). The amount of frazil ice formation initially increases (Fig. 5b5a), then after 2010 it begin to decrease, until by the 2050s there is less frazil ice formation than during 1960-7989 (Fig.

25 5ab). The total amount of basal melting initially increases relative to 1960-7989 (Fig. 5ba), and then decreases from 2010 onwards, until by the 20402040s there is less basal melt than there was during 1960-7989 (Fig. 5a5b). In each case the reversal in sign is due to alterations in the balance between opposing changes that occur at different times of year, and is most easily understood by looking at changes in the seasonal cycles of the budget components (Fig. 6)

—The budget changes causing extra net ice loss relative to 1960-7989 occur at two distinct times of year: during May/June,

30 and again during September-November (black line, Fig. 6a). These are partially offset by the changes occurring at other times of year, most notably during July and August.

Early in the melt season (May/June) there is extra ice loss due to top and basal ice melt, and also due to reduced basal ice growth (Fig. 6a). During July and August there is less top melting and no extra basal melting, and so less net ice melt relative to the reference period. During the autumn, there is reduced basal ice formation, which becomes the largest budget change resulting in ice loss.

5   The changes shown in Fig. 6a are for the decade 2010-2019. Later in the integration (2040 49, Fig. 6b), changes in the budget components show broadly the same seasonal pattern as for the earlier decade, althoughand the magnitude of the changes relative to 1960 79 has increased89 increases as the ice area declines. The (Figs. 6b and 6c). During the 2040s (Fig. 6b), the most notable differences are that by the 2040s the amount of basal melt in the late summer has reduced relative to the reference period, and that there is now no net change in the amount of ice loss during June. Then towards the end of the
10   21st century (Fig. 6c), the reduction in the amount of basal ice growth extends into the winter months, and during June there is a reduction in the volume of ice lost by surface melting.

The amount of ice lost by advection is reduced at all times of year, and to a greater extent during the winter (orange line, Fig. 6). This is consistent with the reducing ice volume – there is less ice that can move out of the basin. In fact by the 2070s2060s (not shown), there is virtually no advective ice loss during August and September, consistent with the Arctic
15   basin being almost completely free of ice by the end of the summer (Fig. 3).

There is reduced frazil ice formation in the autumn during the 2040s (Fig. 6b), and an increase in the winter months (November to March). The autumn change is consistent with warmer temperatures delaying the freeze-up, and the winter change is consistent with decreased ice cover exposing a larger area of ocean where frazil ice can form. During the following decades, as the ocean surface continues to warm, the reduction in frazil ice formation continues later into the winter months
20   (Fig. 6c).

4.2 Impact of the declining ice area on the volume budget

The Having described how the volume budget evolves during the 21st century, we now consider the processes contributing to these changes. As the climate warms, the processes causing ice formation and loss will change accordingly. As the ice cover declines, the impact of these process changes on the volume budget of the different processes acting on the ice and snow is
25   strongly influencedwill be modified by changes in the ice area, and how it changes in response to the forcing scenario. . For example the ice cover in , suppose partway through the 21st century the amount of basal melting per unit area of the ice during September and October reduceshas doubled compared to the reference period. If the September ice cover has reduced by half over the same period then the volume budget will show no net change in the total amount of basal melt that month. As the ice cover declines more quickly in response toduring the forcing scenariolate summer and autumn than at other times
30   of year (Fig. 7a), reducing theFigs. 7a and 7b), we might expect the evolving ice cover at this time of year to have the greatest impact on the volume budget of changes occurring then. So while some of the changes in the budget components are clearly consistent with a warming climate: for example the extra top and basal melting and reduced basal ice growth during the spring (Fig. 6), others have a less intuitive impact on the budget due to the declining ice cover.

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. In Fig. ~~7b~~7c, the dominant budget components ~~have been~~are weighted by the ice area to show how they change per unit area of ice. ~~During the decade 2010-19 there is more melting at the ice surface during May/June relative to 1960-79: the warmer atmosphere leads to extra melting, enhanced by reductions in the surface albedo. For the remainder of the melt season there is no extra surface melt, partly because by July the surface temperature is already close to the melting~~

5 ~~temperature during 1960-79, and hence there is little scope for further reductions in albedo. So during July and August the reduced ice area means that there is a smaller volume of ice lost by surface melt in 2010-19 (and later decades) relative to 1960-79 (Fig. 6).~~ during the decade 2010-19. Using this decade as an example, we consider each of these processes in turn to see how it changes as the climate warms, and how the declining ice area affects its impact on the volume budget.

Top melting

10 During May and June there is more melting at the surface of the remaining ice during 2010-19 than there was during the reference period 1960-89. At other times of year there is little change in the amount of surface melting (Fig. 7c). The changes in top melting are primarily driven by changes in the surface SW and LW fluxes. Over the entire Arctic region considered here, approximately 74% of the mean increase in the net downward radiative flux at the ice and ocean surface during May is due to changes in SW radiation. The incoming SW decreases, partly due to the increased CO_2 and water vapour in the

15 atmosphere, but predominantly due to changes in the impact of cloud (71%). The outgoing SW decreases partly because there is less incoming SW, but predominantly because of the reduced surface albedo (67%). In common with other CMIP5 models, incoming LW increases due to the higher levels of CO_2 in the atmosphere (Notz and Stroeve, 2016) found a robust linear relationship between incoming non-shortwave fluxes and cumulative CO_2 emissions for CMIP5 models). Cloud modifies the amount of LW reaching the surface, but there is little change in the overall impact of cloud on downward LW as

20 CO_2 increases. Outgoing LW also increases as the surface temperature warms, and the balance is an increase in net downward LW.

The impact of the top melting changes on the volume budget is modified by the associated changes in the ice area (Fig. 6a). ~~There is~~In the 2010s, during May and June the extra melt over the remaining ice dominates, leading to a net loss of ice in the volume budget. During July and August there is no extra melting over the remaining ice, and as the ice area has reduced

25 this means a smaller volume of ice had melted compared to the reference period. This appears as a net gain of ice in the volume budget.

As the model integration continues, the declining ice area has more and more impact on the top melting component of the volume budget. By the 2040s there is a smaller volume of ice melted during June as well as during July and August.

Basal melting

30 As the Arctic Ocean warms, there is more melting at the base of the ice (per unit area) throughout the melt season, especially during July, August and September (Fig. ~~7b),~~7c). Year on year, the warming of the Arctic Ocean in HadGEM2-ES is driven by ocean heat transport from lower latitudes, with a net heat loss due to atmospheric surface fluxes (Burghard and Notz, 2017). During spring and summer, a budget analysis of the upper ocean shows that atmospheric fluxes cause a strong *warming* of the ocean surface, and this is the dominant process warming the upper ocean during the melt season. So the extra

basal melting seen in Fig. 7c is primarily due to the in-situ warming of the ocean surface as the ice cover retreats. ~~In May and June this results in a greater volume of ice loss relative to 1960-79 (Fig.~~

Comparing Fig. 7c and Fig. 6a, we see that in the 2010s the extra melting at the base of the remaining ice during May and June translates into a greater total amount of ice loss in the volume budget. In contrast, during July-September the volume

5 budget for 2010-19 shows no extra ice loss due to basal melt. This is because of the larger reduction in ice area compared to 1960-89 at this time of year (Fig. 7b). The extra basal melting over the remaining ice in 2010-19 cannot compensate for the impact of the reduced ice cover, and so the volume budget shows no extra ice loss during July-September. As the model integration continues and the ice cover declines further, its effect on this term in the budget becomes more dominant. By the 2020s the volume budget has *less* basal ice melt compared to the reference period during August (illustrated in Fig. 6b), and

10 by the 2050s this is the case for July and September as well (illustrated in Fig. 6c).

These contrasting seasonal changes explain the evolution of the decadal changes shown in Fig. 5. Until the 2020s, the impact of the extra basal melting over the remaining ice dominates, and the decadal budget shows a net ice loss due to basal melt (w.r.t. the reference period).~~6a). However due to the reduced ice area in the 2010s compared to the 1960s and 70s, the volume of ice lost by basal melt in the late summer is almost the same in each of the two time periods (Fig. 6a).~~ Later in the

15 integration, ~~as the ice cover reduces further, there is less volume loss by basal melting in the late summer (Fig. 6b). This explains why the net impact of the ocean to ice heat flux changes sign during the model integrations (Fig. 5): the decadal timeseries initially only shows the impact of the extra basal melting that occurs during the spring, as there is little change at other times of year. As the forcing scenario progresses, the budget contribution due to reduced basal melting during the late summer starts to play a role, and towards the end of the 21st-century it is this that dominates the decadal mean basal melt~~

20 ~~term~~the impact of the declining ice area dominates, and the decadal budget shows a net ice *gain* due to changes in basal melt.

~~Compared~~Basal ice growth

From October through to ~~1960-79~~March, there is ~~more~~extra ice growth at the base of the remaining ice during the ~~autumn and winter, and less during~~2010s w.r.t. the ~~late summer for the decade 2010-19~~reference period (Fig. ~~7b).~~7c). Between May and September, there is reduced ice growth compared to the reference period. The diffusive heat flux causing the basal

25 ~~melt~~growth is a function of ~~both~~the surface temperature and the ice thickness.~~In September the warmer~~: colder surface temperatures ~~in 2010-19 dominate, meaning reduced basal ice formation where there is still ice. There~~or thinner ice result in more ice growth. At lower surface temperatures there is a stronger dependence on the ice thickness~~at cooler temperatures, and~~, so that from October onwards ~~the fact that the ice is thinner in 2010-19 than during 1960-79 mean~~there is more diffusive heat loss to the atmosphere, and more basal ice formation~~at~~. Between May and September the ~~base (Fig. 7b).~~

30 ~~However,~~impact of the ~~reductions in~~warmer atmosphere and ice ~~area during August, September and October mean that despite the extra~~surface dominates, resulting in a smaller diffusive heat flux and less ice growth over the remaining ice~~, a smaller volume of ice is formed at this time of year during 2010-19 than during 1960-79 (Fig. 6a).~~.

Again, the impact of these process changes on the volume budget depends on the declining ice area. Within the volume budget, the largest changes due to basal growth occur during September, October and November (Fig. 7a). During

19

September, the reduced ice area in the 2010s amplifies the impact of the reduced basal ice growth on the volume budget. During October and November, although there is *more* basal ice growth over the remaining area of ice during the 2010s, the impact of the declining ice area dominates so that the total volume of ice grown is reduced compared to the reference period to give a net ice loss. By the 2080s, the sharp decline in winter ice cover seen in Fig. 3a results in the net ice loss due to

5   changes in basal growth extending into the winter (Fig. 6c).

In summary, for the HadGEM2-ES model ~~the Arctic decline up to the 2020s for the RCP8.5 scenario is a result of reduced~~ there is increased melting at the top and bottom surfaces of the Arctic sea ice in the spring and summer as the climate warms in response to the RCP8.5 forcing scenario. As the ice thins, there is increased basal ice growth. In the volume budget, the

10   impact of these changes is affected by the declining ice area. Until the 2020s the ice volume budget shows ice loss due to reduced amounts of basal ice formation and extra basal melting~~,~~. These decreases in ice volume are offset by ~~reductions in melting~~less ice being melted at the top surface ~~of the ice~~, and reduced advective ice loss. Later in the 21st century the total amount of basal melting decreases due to the shrinking ice area in the ~~later~~late summer, so that in the volume budget the basal melt term ~~also offsets the reductions~~changes sign to represent a net gain in ~~basal~~ ice ~~growth.~~ volume relative to the

15   reference period (Fig. 6b).

4.3 Impact of forcing scenario

We now consider how the volume budget changes for the other forcing scenarios. Figure 8 shows changes in basal growth (relative to the reference period) for each of the four scenarios. All the scenarios show a decline in basal ice growth, with the

20   more aggressive scenarios showing a greater decline. For the latter half of the 21st century there is a clear difference in response between RCP2.6, RCP4.5/6.0, and RCP8.5. For RCP2.6 the amount of basal ice growth levels off towards the end of the 21st century, consistent with the stabilisation of the ice area and volume in this scenario (Fig. 3), whereas for RCP6.0 the amount of basal growth continues to decline throughout the 21st century, albeit to a lesser extent than for the stronger RCP8.5 scenario (Fig. 8). The steep decline in the amount of basal ice growth in RCP8.5 during the latter part of the 21st

25   century is due to the sharply declining winter ice cover at this time. As previously mentioned, areas of the Arctic Ocean become too warm for ice to form during the winter months, thus reducing the area over which basal ice formation can occur. There is also an associated sharp reduction in frazil ice formation at this time (not shown).

A similar picture emerges for the other budget components (not shown): the signals of change for each scenario are broadly the same as already described for RCP8.5, although the exact timing and magnitude of the changes depends on the strength

30   of the forcing.

By plotting the decadal response in each budget component as a function of decadal mean ice area rather than time (Fig. 9), we see that they each follow a common trajectory independent of the forcing scenario. Note that the plots in Fig 9 have

different scales, as the intention here is to show the trajectory of each component, rather than their relative magnitudes. Hence, changes in the volume budget components are independent of the speed at which the ice retreats, at least for the HadGEM2-ES model, and for the range of IPCC scenarios considered here. Figure 9 also confirms that the changes in the volume budget components are, as previously discussed, strongly dependent on the ice area.

5   Compared to the thermodynamic budget components, the changes due to advection are relatively small in relation to the inter-decadal variability of the control integration. By the end of the 21st century, the ratio between the response for scenario RCP8.5 and the variability in the control run is 6.8 for the advective term, whereas for the other budget terms this ratio ranges from 21.7 to 34.9.

We note that for most of the budget components the relationship with the ice area is non-linear. For example, when the
10   annual mean ice area has reduced to approximately 6.5 x10^6 km^2, the anomaly w.r.t 1960-~~79~~89 in the total amount of frazil ice formation and basal melting changes sign, and the slope in the response of the basal ice formation steepens. This corresponds to the stage at which the Arctic basin first becomes seasonally ice-free, as shown in Fig. 10 where the budget components from Fig. 9 are plotted against the appropriate (10 year mean) September ice area. As the Arctic becomes seasonally ice-free, processes that were initially dominant in the ice volume budget during late summer/early autumn have a
15   reduced impact on the decadal mean budget.

Although not shown here, the seasonal cycle of anomalies in the volume budget is also related to the remaining ice cover, and independent of the speed at which the ice retreated. For example, if we choose a decade for each of the scenarios with matching mean ice cover and over plot the anomalies they are very similar.

~~So in~~In summary, while the strength of the forcing scenario affects the magnitude and timing of the modelled decline in ice
20   ~~cover~~area during the 21st century, for HadGEM2-ES the changes in the volume budget at any chosen time during the scenario depend on the remaining ice cover, and are independent of the speed at which the ice retreated.

5 Summary and discussion

~~We have investigated decadal changes in the seasonal cycle of~~We have presented a method for investigating changes in the volume budget of the Arctic sea ice as the ice declines due to increasing greenhouse gas forcing. Our approach is distinct
25   from previous work as we are able to include terms representing the individual processes causing ice growth and loss, and we consider the seasonal cycle of changes to show the (sometimes opposing) changes at different times of year. The budget is constructed so that the sum of the budget terms balances the changes in the ice volume. This mean that the declining ice cover has to be taken into account when summing the terms, so that changes in the budget depend both on changes in processes and changes in ice cover. To help distinguish between the two, we also evaluate how the dominant processes in the
30   budget change locally over the remaining ice cover.

The method has been used to investigate changes in the volume budget of the AR5 climate model HadGEM2-ES during the 21st century for a range of IPCC forcing scenarios. For this model, over the remaining ice the processes that change most ~~at~~

~~*the ice surface*~~ as the climate warms are top melting and basal melting during the summer and autumn. Extra top melting occurs during May and June, while basal melting due to extra heat from the warming ocean occurs from May onwards, reaching a peak in August and September. When the declining ice area is taken into account, so that the budget terms can be summed to balance the actual changes in ice volume, we see that the decline in ice volume results primarily from ~~reduced~~a

5 reduction in ice growth, offset by smaller reductions in ice melt and reduced advection to lower latitudes. ~~The~~ Holland and Landrum (2015) have also noted the influence of the ~~evolving~~declining ice area on processes contributing to 21st century changes in the sea ice ~~has also been noted by Holland and Landrum (2015).~~.

The seasonal cycle of the ice volume budget shows net ice loss in the spring and early summer due to extra surface and basal melting and reduced basal ice growth, and ~~reduced basal growth during~~ in autumn/early winter~~,~~ due to reduced basal growth.

10 These changes are partially offset by net ice gain due to reduced ~~amounts of~~ surface melting during July and August as the ice cover declines.

~~The choice of forcing scenario affects the rate of ice decline and the timing of change in the volume budget components, but does not have a strong impact on the changes in the balance between the individual budget components, at least for the HadGEM2-ES model and for the range for forcing scenarios considered for IPCC AR5.~~

15 The budget changes shown here are likely to be dependent on the sea ice physics included in HadGEM2-ES. For example, the fact that the sea ice albedo is a function of surface temperature means that no further albedo reduction are possible once the surface temperature has reached the melting point~~, as happens in July for this model.~~. A different behaviour may be seen in a model including an explicit representation of melt ponds. Also HadGEM2-ES uses zero-layer thermodynamics, which does not model the internal temperature of the ice, and has a constant ice salinity. A model including a multi-layer

20 thermodynamic scheme and prognostic salinity might well show a greater sensitivity to the forcing scenario than we see for HadGEM2-ES. Finally, HadGEM2-ES does not have an explicit representation of lateral melting and so this term does not appear in our budget. Early results from our CMIP6 model HadGEM3 GC3.1 (Williams et al, 2018) show lateral melting to be an important component of the volume budget during June, July and August, with values of up to 14% of the ocean to ice heat flux.

25 ~~The methodology used here should be readily applicable to other models, and in particular those with SIMIP diagnostics submitted to the CMIP6 data archive. Our results suggest that while it is useful to consider how budget components change over the ice surface, it is also beneficial to include the impact of the declining ice cover to generate a set of terms that can be summed to balance the actual changes in ice volume, as the different approaches can show a different balance between the budget terms, and the ice area itself affects the impact of each budget term. This will help to distinguish between the impact~~

30 ~~of changing processes acting at the ice surface and the impact of the loss of ice cover. This will be especially important if the CMIP6 models show as wide a spread in projected ice cover over the 21ˢᵗ century as the CMIP3 and CMIP5 models.~~ For HadGEM2-ES we have found a strong (non-linear) relationship between the declining ice area and the evolution of the volume budget components, which holds over the range of forcing scenarios considered for IPCC AR5. In common with other climate models (Stroeve and Notz, 2015), for HadGEM2-ES there is a linear relationship between the Arctic ice area

and the global near-surface temperature. In addition, the CMIP5 models show a linear relationship between Arctic ice area and cumulative CO_2 emissions (Notz and Stroeve, 2016). Hence the relationship found here between the evolving volume budget terms and the ice area indicates there is also a strong connection with the amount of CO_2 emitted, and with the wider climate response to increasing CO_2. If this relationship proves to be robust across models, we may in the future be able to derive strong links between emitted CO_2 and the processes causing ice decline.

For the next generation of climate models, we will be able to establish the extent to which the changes found here for HadGEM2-ES are also seen in other models. The model diagnostics required for this analysis form part of the SIMIP data request for CMIP6 (Notz et al., 2016), and so the method presented here can be utilised as a model inter-comparison tool for the CMIP6 models. This will mean that we can quantify, for each model, not only how the ice declines, but also why. Previous work using a more limited range of model output from CMIP3 models found a large inter-model spread in both the present day ice mass budget, and in the magnitude and relative importance of changes in the ice melt and growth terms over the 21st century (Holland et al, 2010). For CMIP6 models, we will be able to further decompose the ice volume budget and establish whether improvements to the representation of sea ice processes have led to a closer agreement in how the volume budget evolves as the climate warms.

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Global mean near-surface temperature anomalies
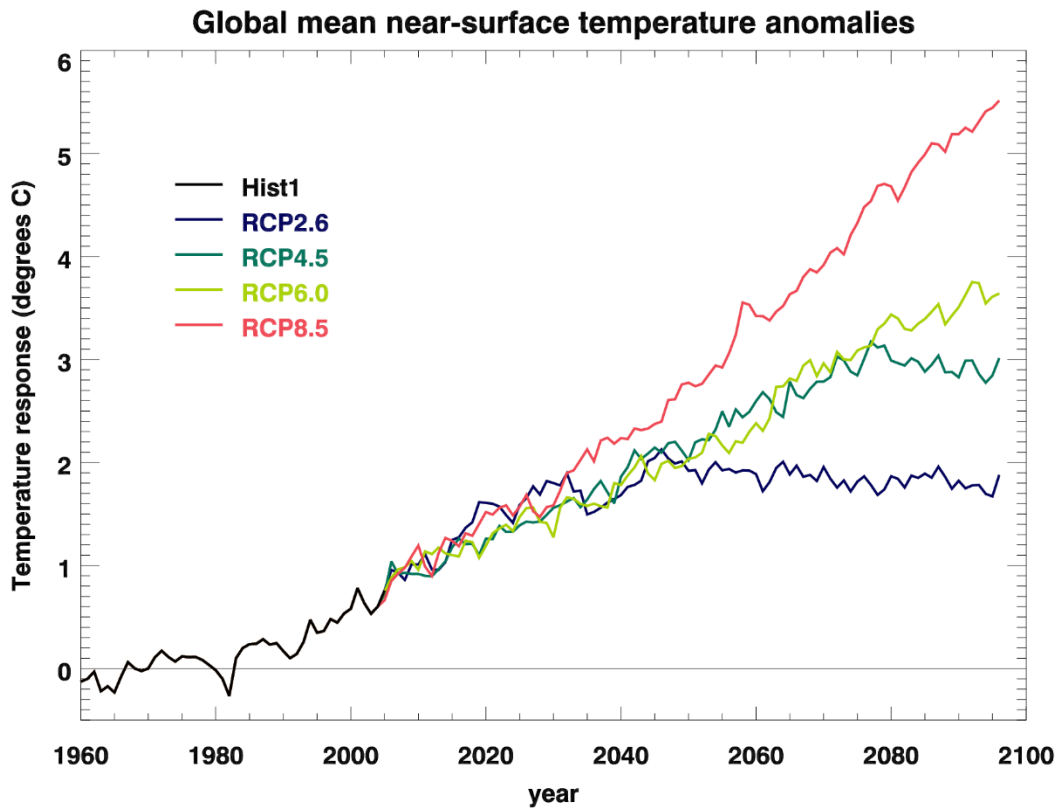
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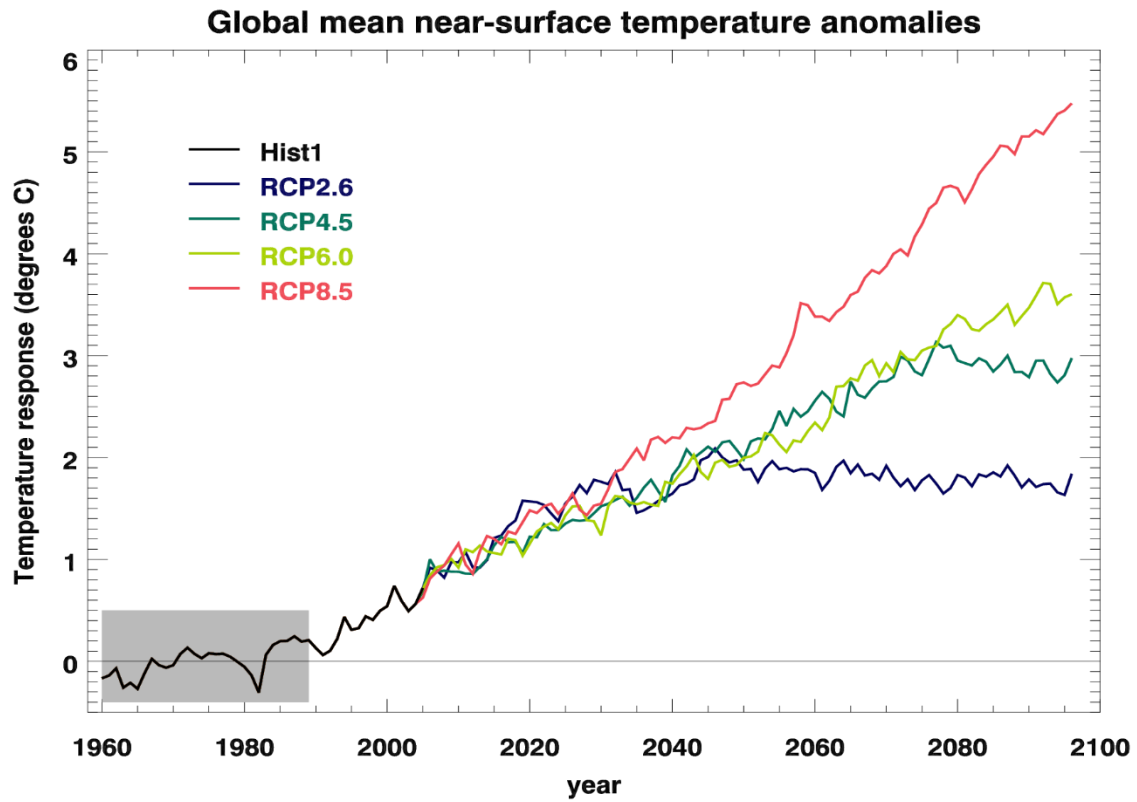
Figure 1: Global mean near-surface air temperature anomalies for ~~HadGEM2ES~~HadGEM2-ES for the IPCC CMIP5 Historical forcing scenario (black), followed by RCP8.5 (red), RCP6.0 (light green), RCP4.5 (dark green), and RCP2.6 (blue); the 1st ensemble member in each case. The shaded region indicates the 1960-89 reference period.

5
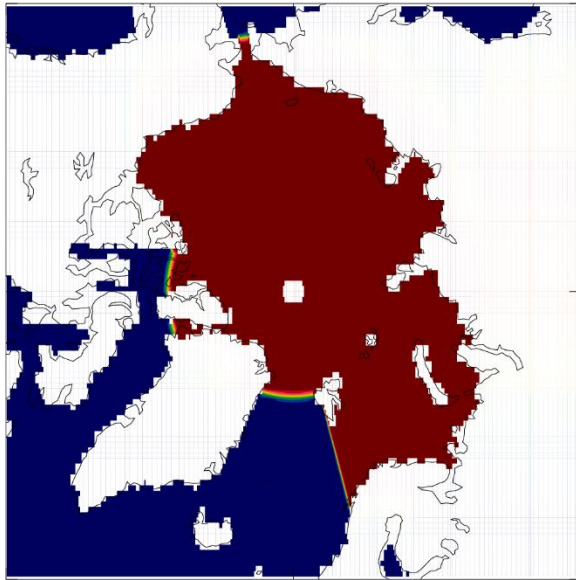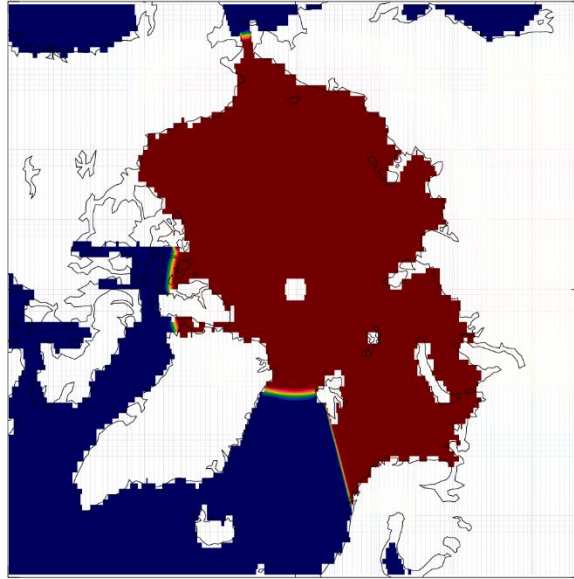
Figure 2: ~~Definition~~The region of the Arctic ~~region~~used in the analysis. For HadGEM2-ES this is formed by masking out all data south of 65N for all latitudes and then the area bounded by 65N to 78N and 90W to 15E.

(a)

(b)
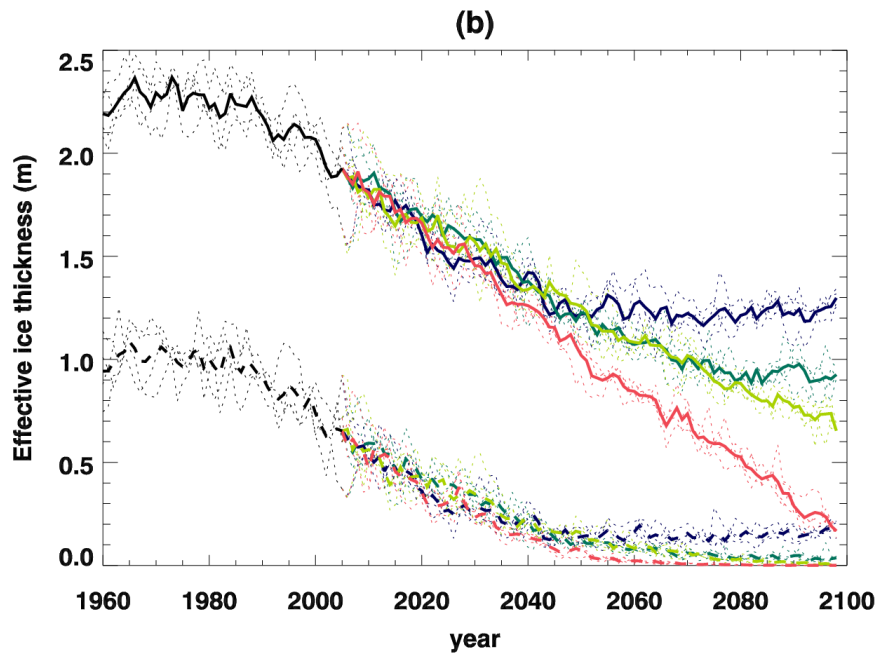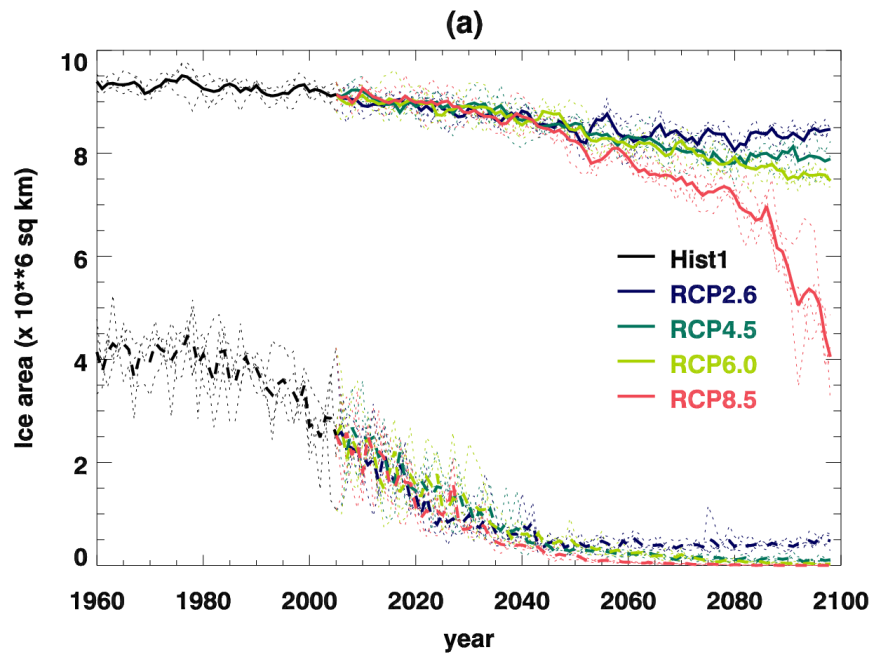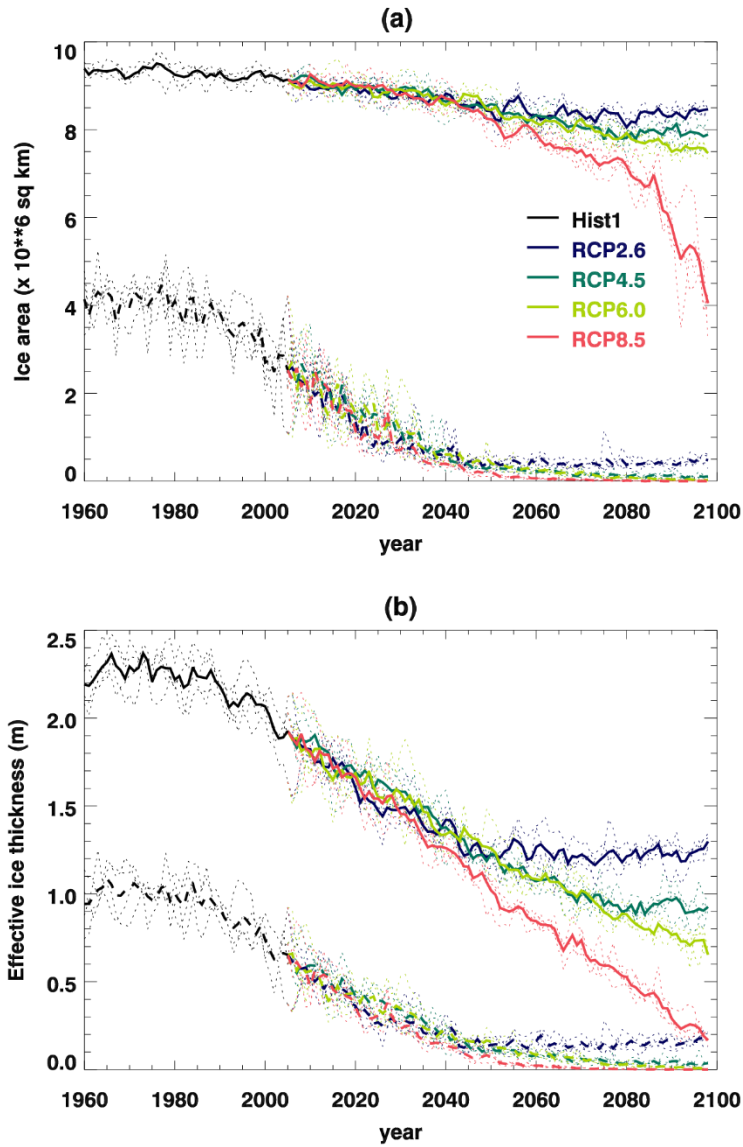
Figure 3: Evolution of (a) the ice area and (b) the mean effective ice thickness for March (solid lines) and September (dash lines) over the region defined in Fig. 2, for each of the HadGEM2-ES integrations. Bold lines show the ensemble means, and dotted lines show the individual ensemble members in each case.

(a)

(b)

legend:
- snowfall & sublim
- top melting
- basal growth
- basal melting
- frazil ice formation
- advection
- total
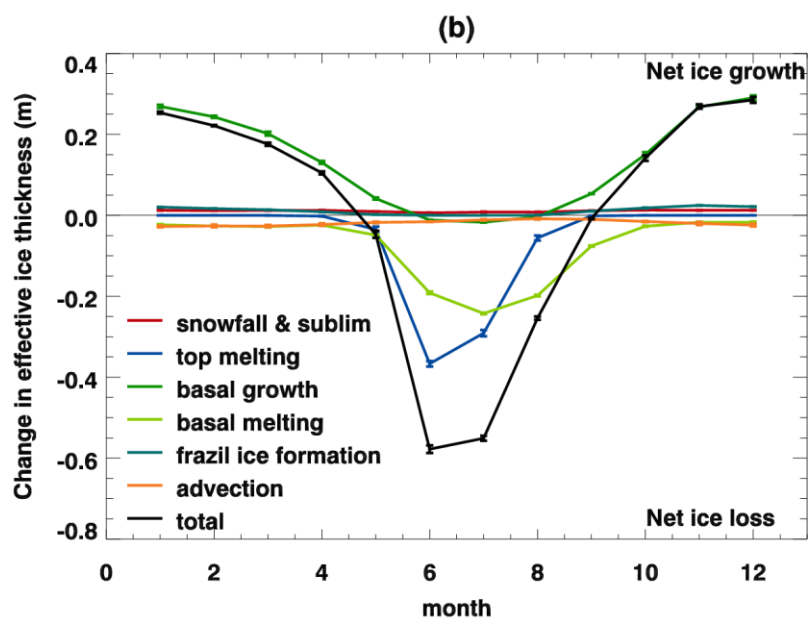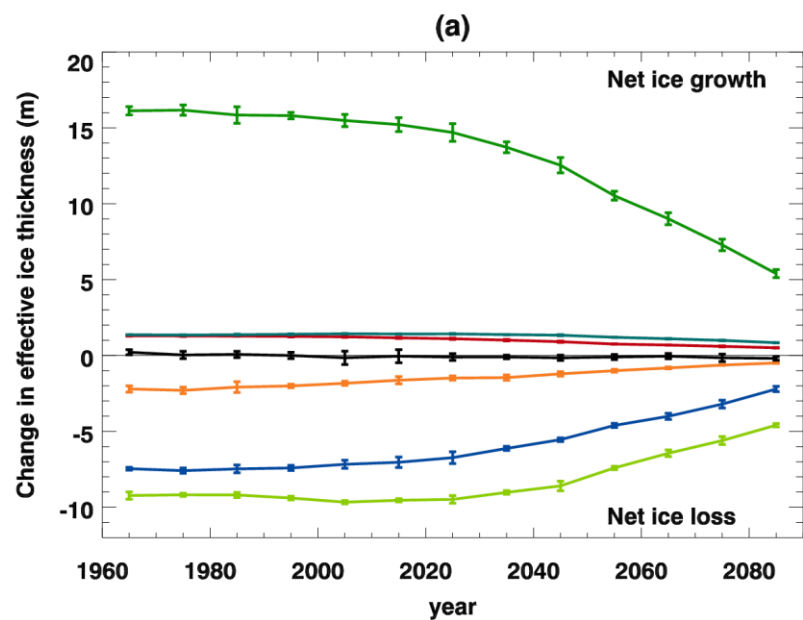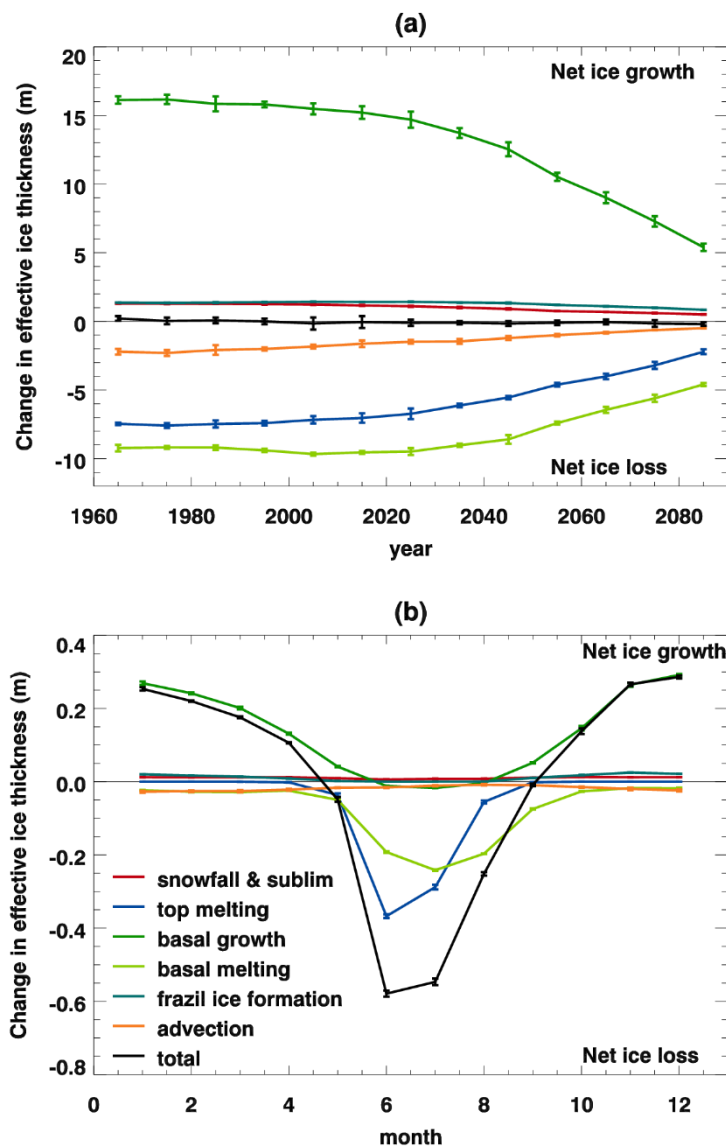
Figure 4: Components of the sea ice volume budget as defined in section 3.1 for the HadGEM2-ES Hist+RCP8.5 integrations, averaged over the region defined in Fig. 2. Values are ensemble means +/- 1 standard deviation, and positive values correspond to net ice growth.

5 (a) Decadal mean timeseries.

(b) Seasonal cycle for the reference period 1960-7989.

(a)

(b)
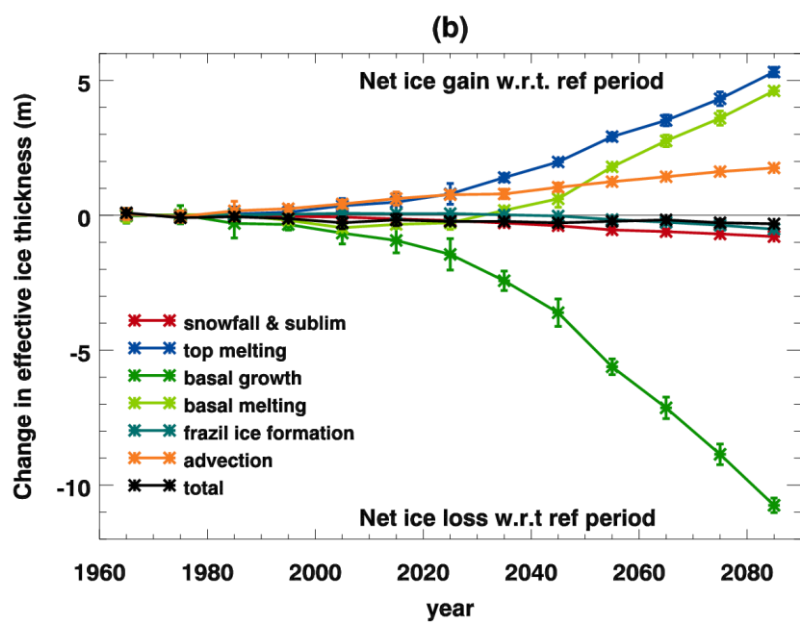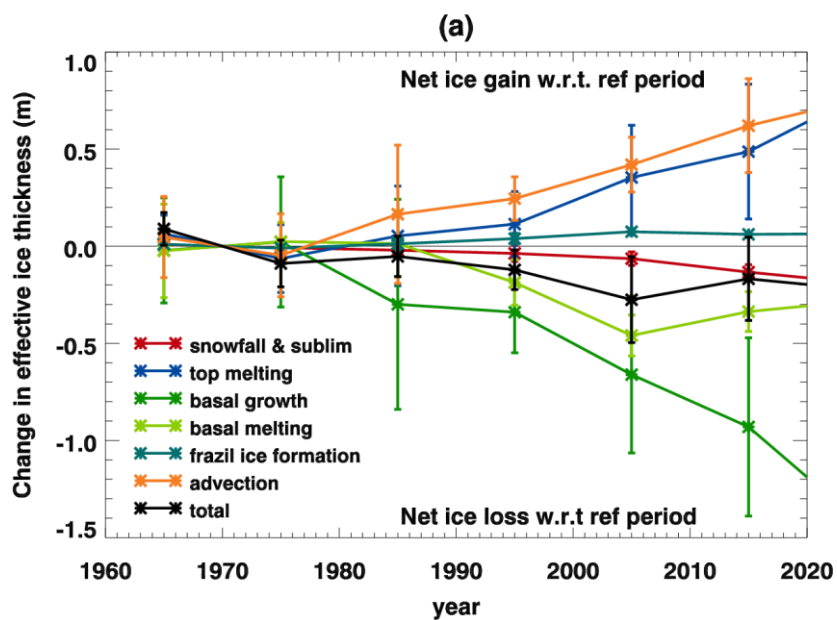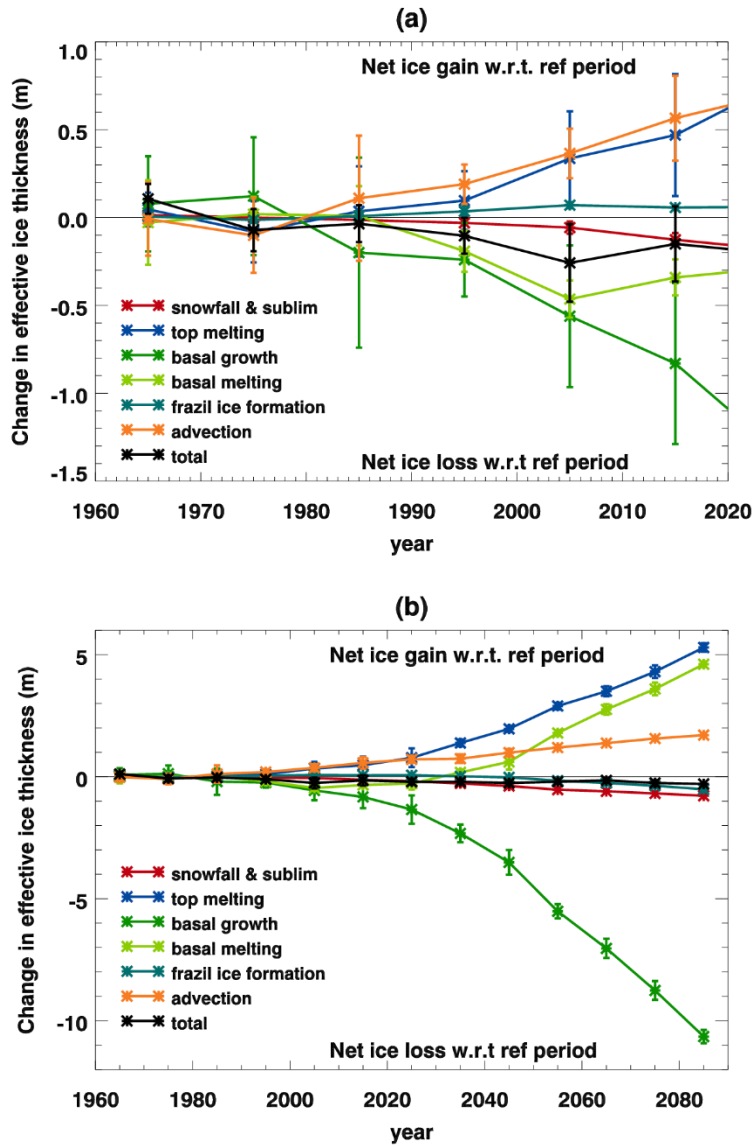
Figure 5: Decadal mean components of the sea ice volume budget as defined in section 3.1 for the HadGEM2-ES Hist+RCP8.5 integrations, averaged over the region defined in Fig. 2 and plotted as differences relative to the mean over the reference period 1960-~~79~~89. Values are ensemble means +/- 1 standard deviation, and positive values correspond to net ice gain w.r.t. the reference period.

(a) To 2020 (with ~~expanded~~magnified vertical scale)   (b) To 2090

(a)

(b)
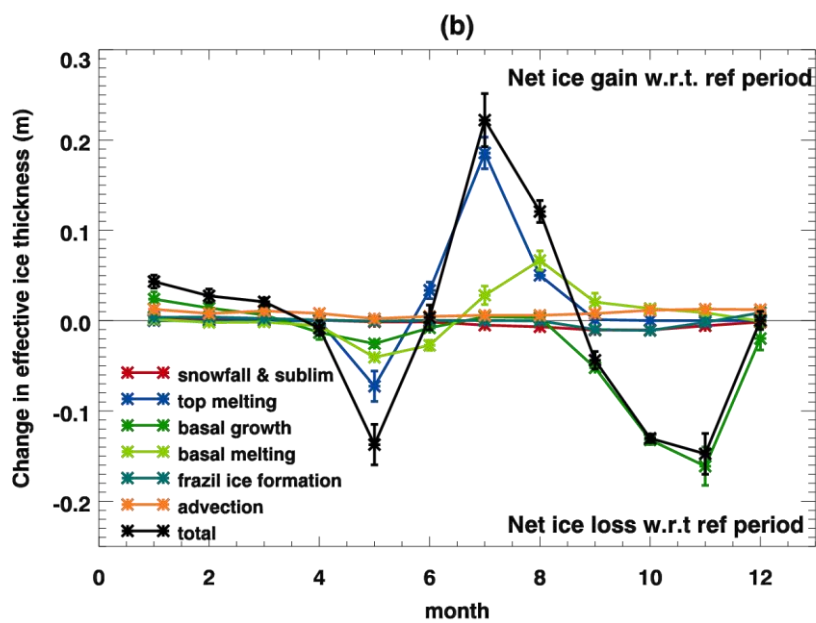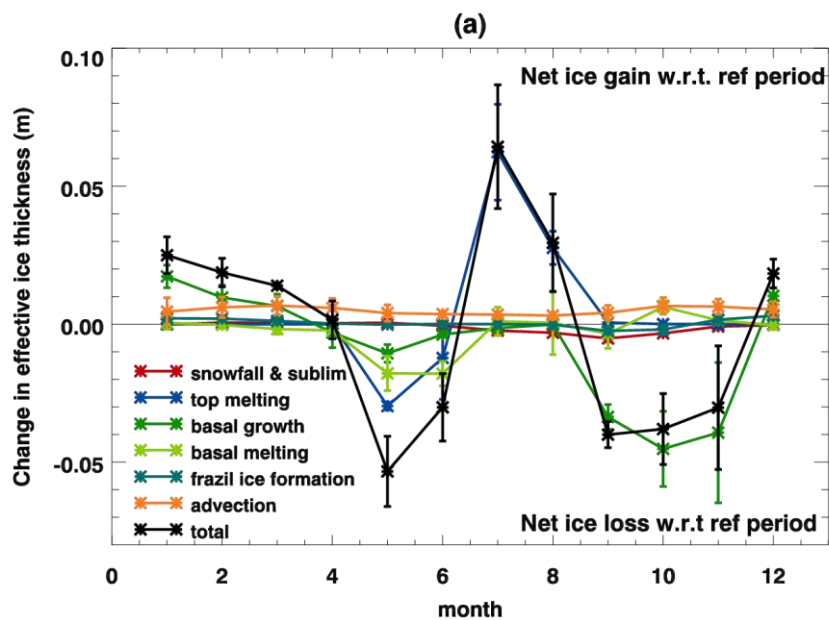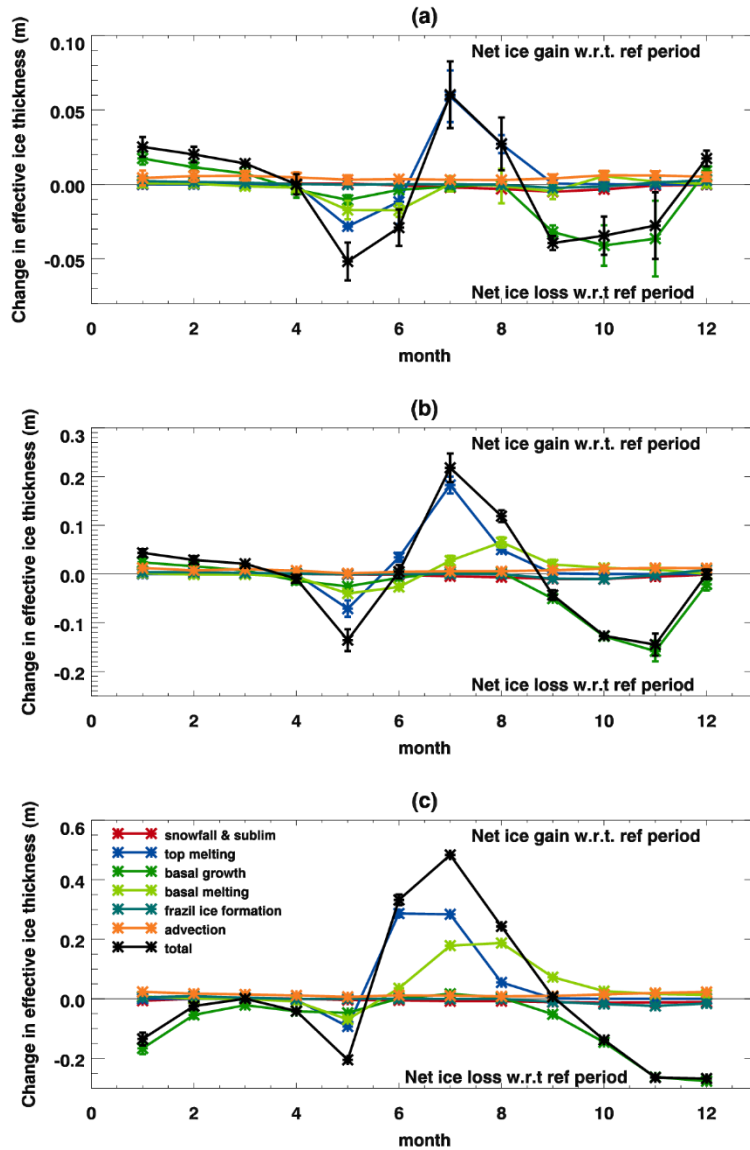
Figure 6: Ensemble mean seasonal cycles of the sea ice volume budget components as defined in section 3.1 for the HadGEM2-ES Hist+RCP8.5 integrations, averaged over the region defined in Fig. 2 and plotted as differences relative to the mean over the reference period 1960-7989. Values are ensemble means +/- 1 standard deviation, and positive values correspond to net ice gain w.r.t. the reference period. (a) 2010-2019 (b) 2040-49. (c) 2080-89. Note that the plots have different vertical scales.

(a)

(b)
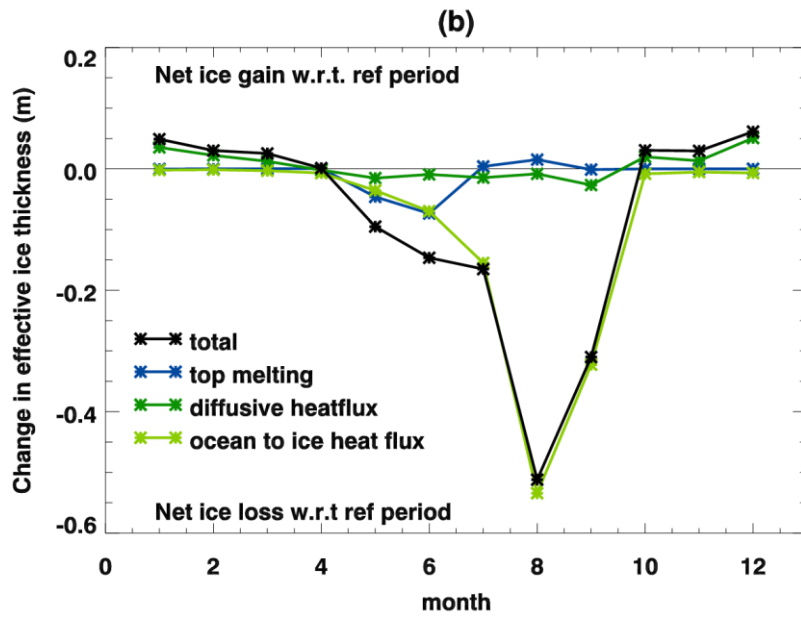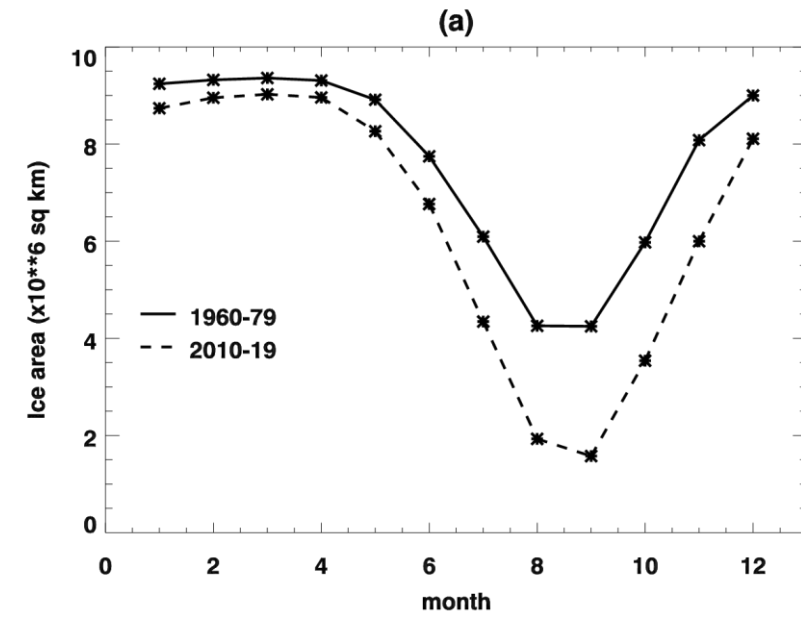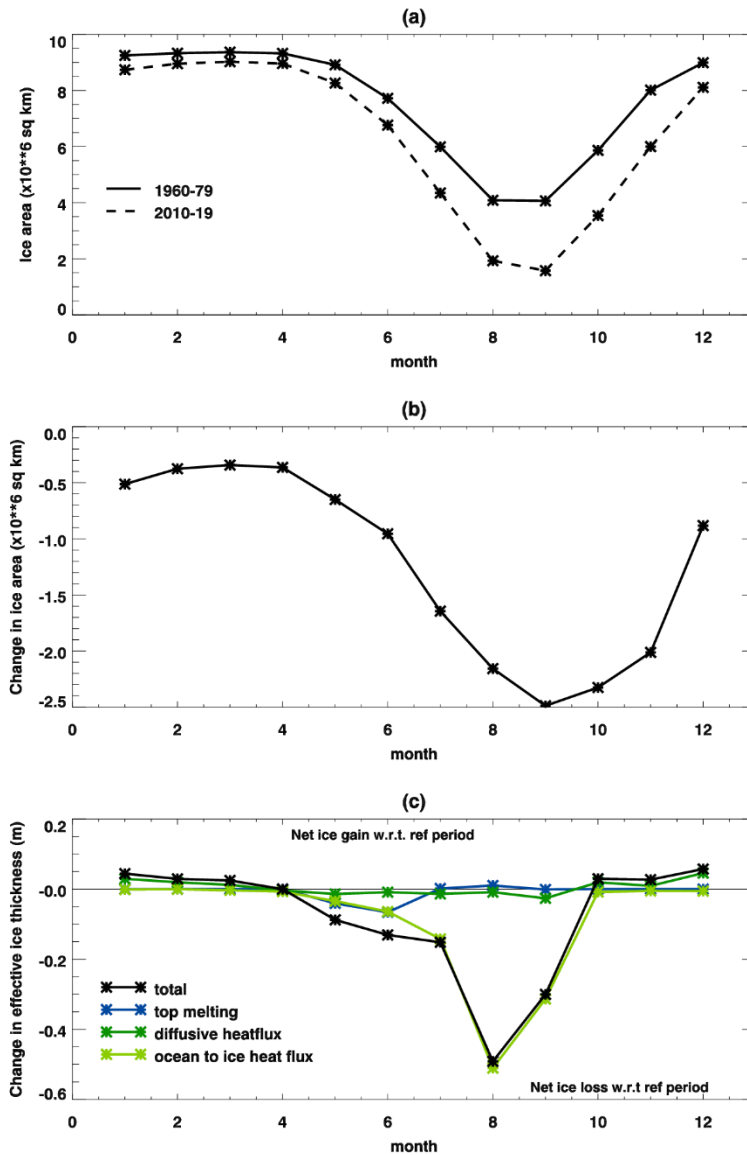
Figure 7: (a) Ice area over the domain defined in Fig. 2 ~~for~~during the reference period 1960-~~79~~89 (solid lines) and ~~for~~ 2010-19 (broken lines) for the HadGEM2-ES Hist1+RCP8.5 scenario. (b) Change in ice area between 1960-89 and 2010-19. (c) Seasonal cycles of changes in selected sea ice volume budget components ~~as defined in section 3.1~~for 2010-19 w.r.t. the reference period 1960-89 for the HadGEM2-ES Hist1+RCP8.5 integration~~,~~. The components are defined in section 3.1. Values are averaged over the region defined in Fig. 2 ~~and plotted as differences relative to the mean over the reference period 1960-79,~~2 and weighted by the ice area in each case, so that the change is per unit area of the remaining ice.
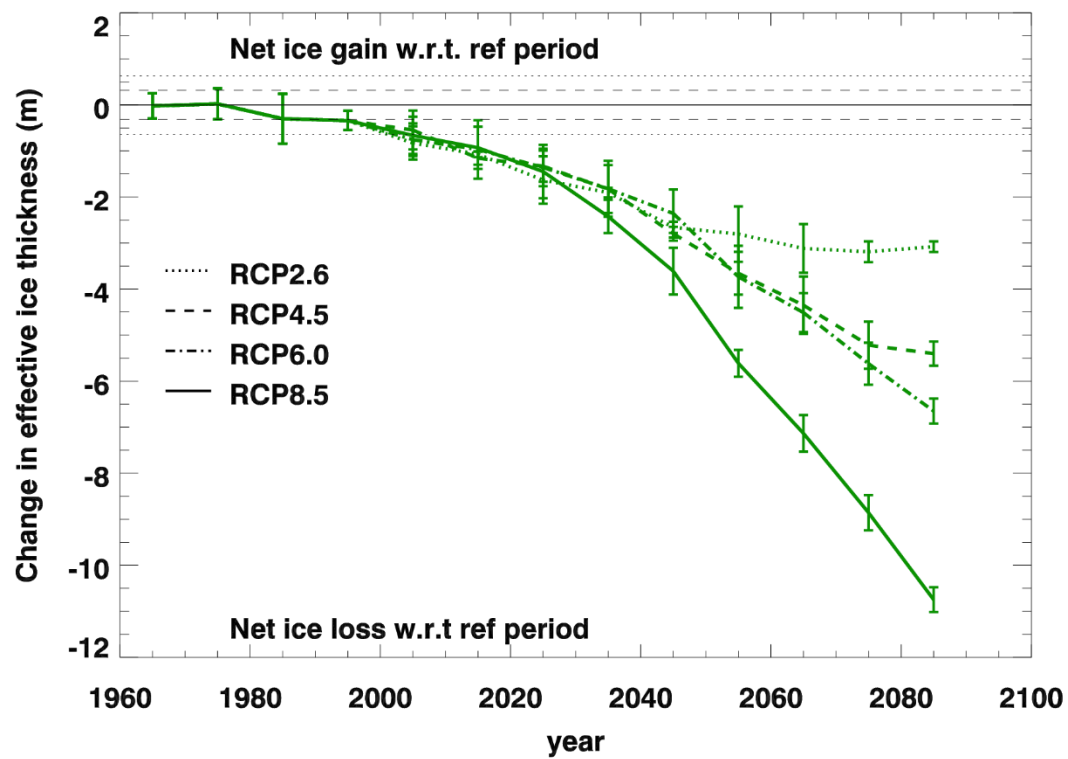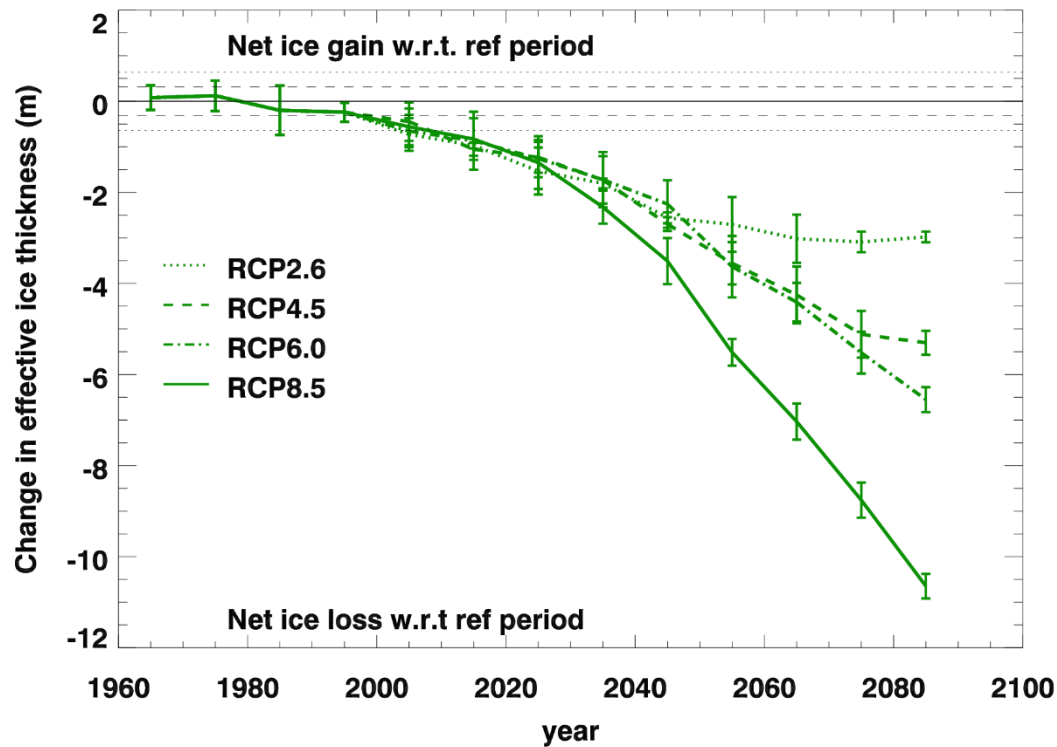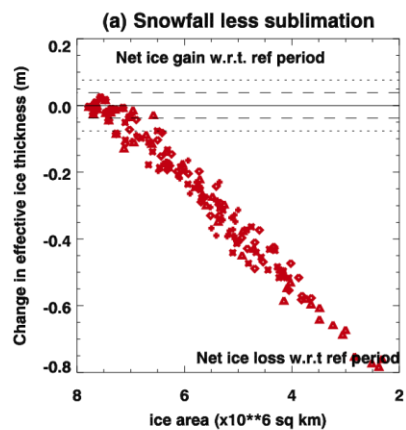
Figure 8: Decadal mean values of the basal growth component of the sea ice volume budget of HadGEM2-ES, plotted as differences relative to the reference period 1960-~~79~~89, for each of the forcing scenarios. Values are ensemble means +/- 1 standard deviation, and positive values correspond to net ice gain w.r.t. the reference period. The ~~dash~~horizontal dashed and ~~dot~~dotted lines show +/- 1 and 2 standard deviations as calculated from 250 years of the HadGEM2-ES pre-industrial control integration.
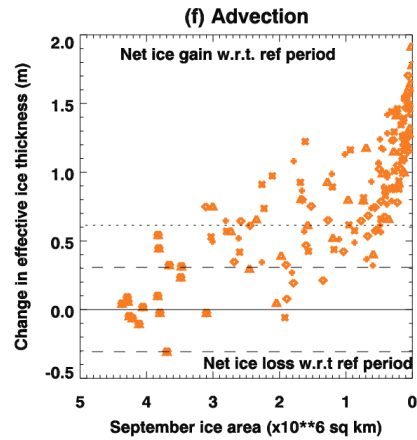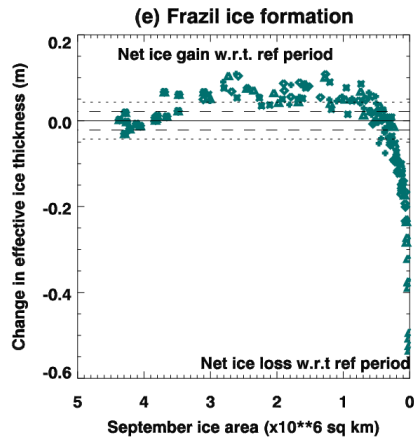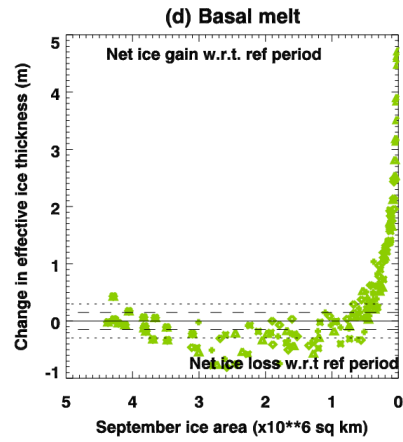
(a) Snowfall less sublimation
(b) Top melt
(c) Basal growth
(d) Basal melt
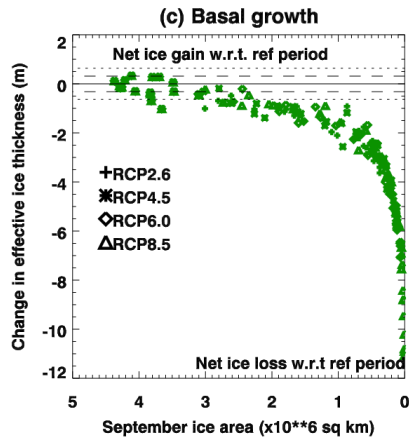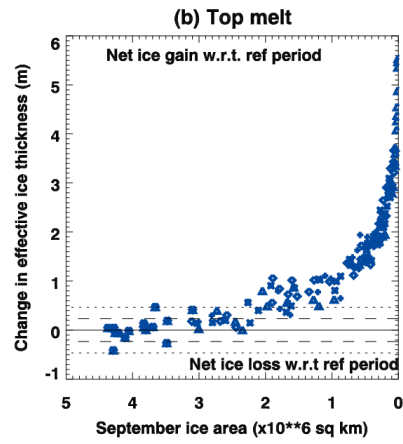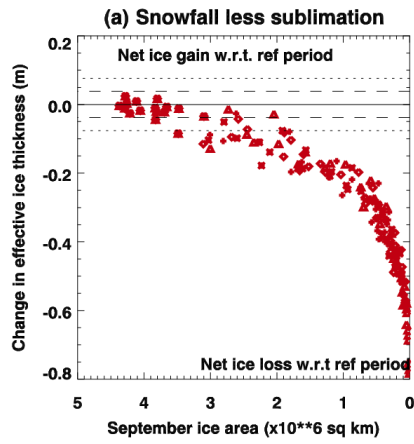(e) Frazil ice formation
(f) Advection

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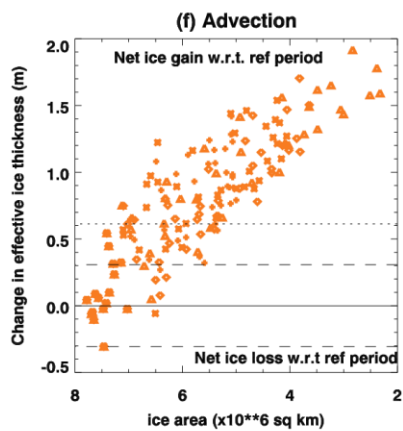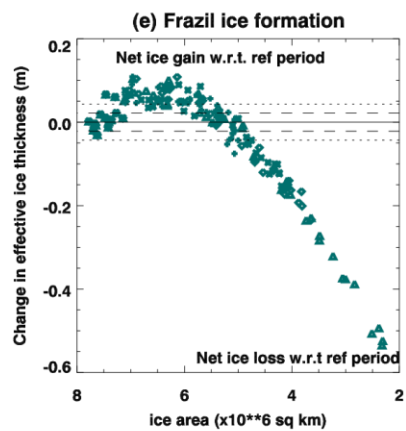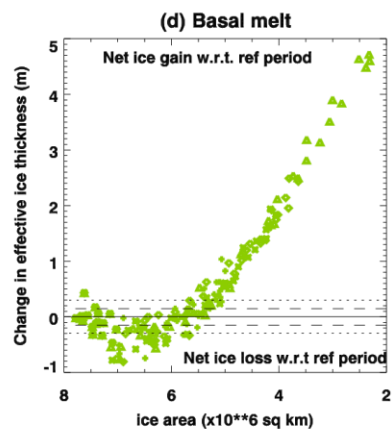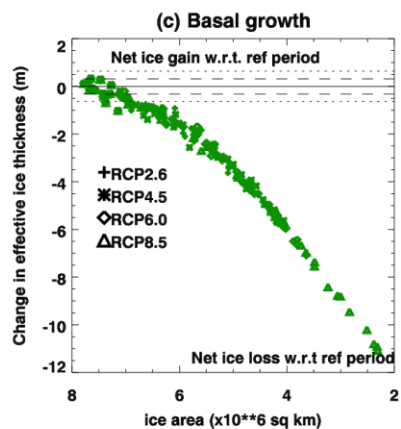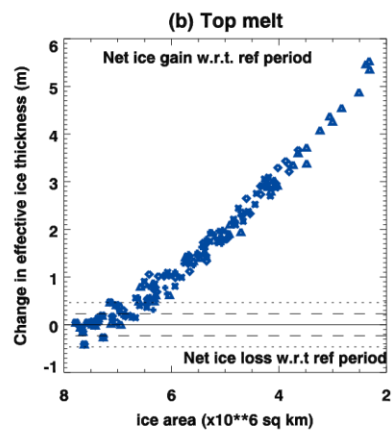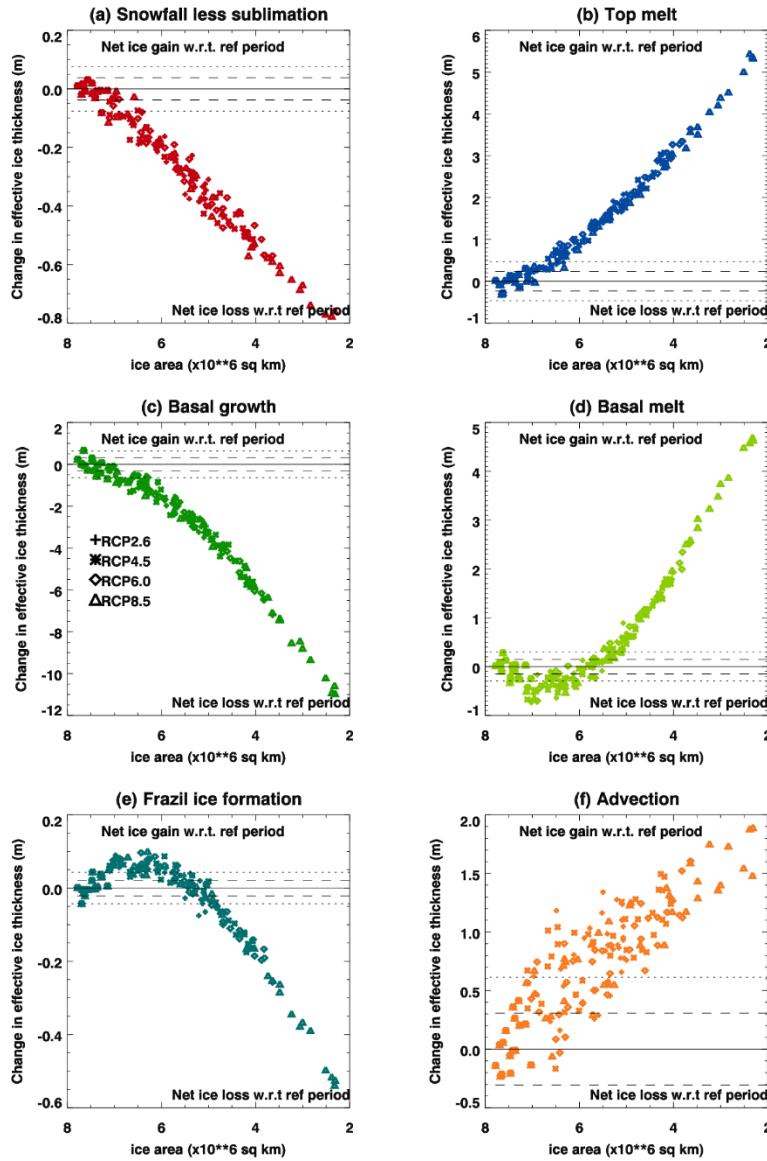
Figure 9: Decadal mean HadGEM2-ES sea ice volume budget components for ~~HadGEM2 ES~~ all the forcing scenarios plotted as differences relative to the reference period 1960-~~989~~, and as a function of the decadal mean ice area. Positive values correspond to net ice gain relative to the reference period. The ~~dash~~horizontal dashed and ~~dot~~dotted lines show +/- 1 and 2 standard deviations as calculated from 250 years of the HadGEM2-ES pre-industrial integration. Note that the plots have different vertical scales.
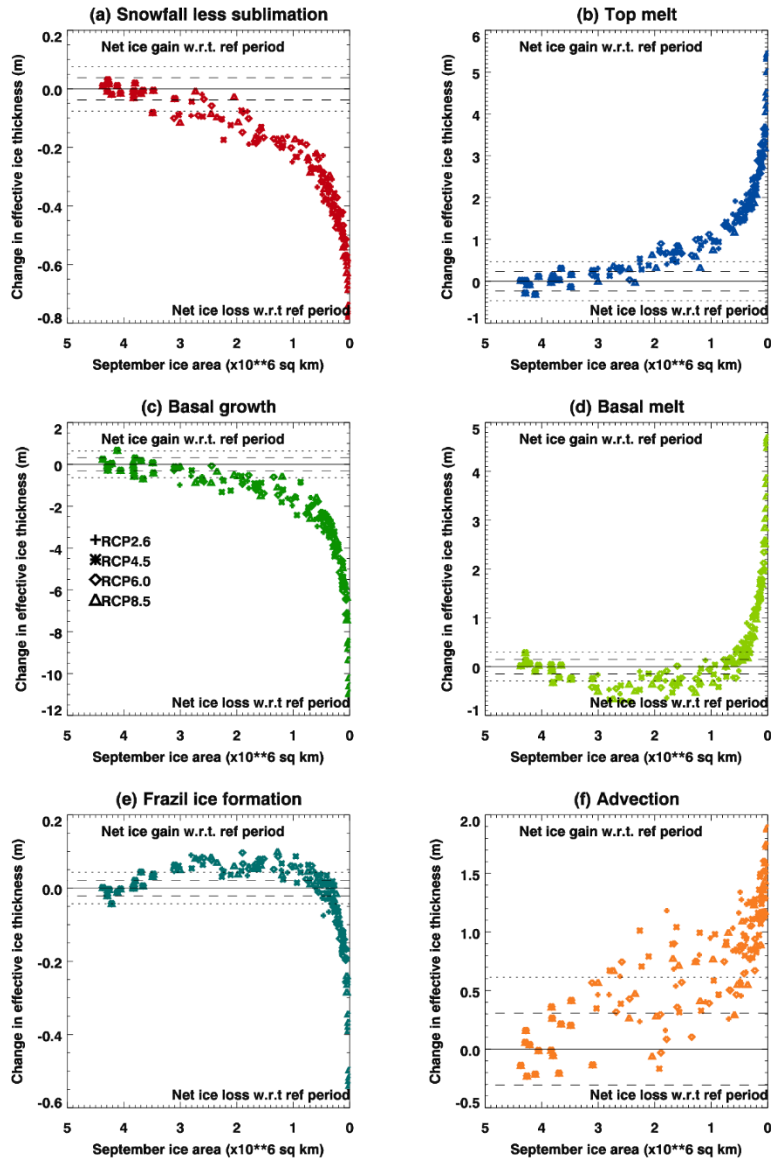
(a) Snowfall less sublimation

(b) Top melt

(c) Basal growth

+RCP2.6
✳RCP4.5
◇RCP6.0
△RCP8.5

(d) Basal melt

(e) Frazil ice formation

(f) Advection

Figure 10: As figure 9, but plotted against decadal mean September ice area rather than the decadal mean over all months.

5 Title of the manuscript

Angie A. Aman[1], B. Bradley Bman[1], Carl Cman[2]

[1]Department example, University example, city, postal code, country
[2]Laboratory example, city, postal code, country

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Abstract. Please use only the styles of this template (MS title, Authors, Affiliations, Correspondence, Normal for your text, and Headings 1–3). Figure 1 uses the style Caption and Fig. 1 is placed at the end of the manuscript. The same is applied to tables (Aman et al., 2014; Aman and Bman, 2015) adipiscing elit. Mauris dictum, nibh ut condimentum pharetra, quam ligula varius est, sed vehicula massa erat ut metus. In eget metus lorem. Fusce vitae ante dictum, elementum sem non, lacinia dui. Integer tellus tortor, convallis et aliquam non, dictum vel mauris. Quisque maximus mollis dui, a mollis mauris vehicula in. Duis dui ligula, suscipit ac lectus vitae, fringilla euismod diam.

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References

Aman, A. A. and Bman, B. B.: The test article, J. Sci. Res., 12, 135–147, doi:10.1234/56789, 2015.

15 Aman, A. A., Cman, C., and Bman, B. B.: More test articles, J. Adv. Res., 35, 13–28, doi:10.2345/67890, 2014.

Figure 2: The logo of Copernicus Publications.