Reviewer Comment 1

The manuscript presents a modeling analysis of the projected period when global temperatures on average will exceed the Paris Agreement thresholds of 1.5 of 2.0°C including and excluding the contribution of Arctic amplification using the CMIP6 surface temperature projection archive. Based on the analysis, the authors conclude that Arctic amplification accelerates crossing the Paris Agreement thresholds 5 (for 1.5°C) and 8 (2.0°C) years with some uncertainty based on the emissions scenario. The authors argue given the important contribution of accelerated Arctic warming to the rate of global warming trends, it is important to improve our coverage and accuracy of Arctic observations for a better forecast of the timing of crossing the Paris Agreement thresholds.

I thought that the analysis was well done, and I found compelling. However, I am somewhat confused about the goal of the study. I agree what the authors conclude that "the importance of accurate surface temperature observations in the region (poleward of 66°N)." But not sure that when the global temperature thresholds of the Paris Agreement is the best example for making this argument. The conclusion that the Arctic has an outsize role in the magnitude of global warming is almost a trivial conclusion since it is obvious given that the Arctic is warming quadrupole the rate of the rest of the globe. Similarly, regions that are warming the least or even cooling are delaying the period when the Paris Agreement thresholds will be reached. Also, this analysis now has me questioning what is societally more relevant as a threshold, the full global average temperature or a more limited global average that excludes the Arctic that accelerates achieving and surpassing the Paris Agreement thresholds. I wonder if a more relevant use of the analysis is to argue how the accelerated Arctic warming leads to more rapid changes in the Arctic and even better how this leads to more rapid changes across the population centers of the Northern Hemisphere.

In summary, I thought that this was a well-executed study and that the results are correct. What I struggle with is the importance of highlighting that Arctic amplification will accelerate crossing the Paris Agreement temperature thresholds that is an obvious and therefore maybe trivial result and conclusion. And I wonder making a different point with the same analysis that is less obvious might be of more societally relevance. For example, because the Arctic is warming so much faster than the rest of the globe, maybe the Paris Agreement thresholds that are global averages understate the risk and hazard of the accepted temperature thresholds because certain regions, best exemplified by the Arctic, which are warming up to four times the rest of the globe are not represented or captured by the global averages. Or alternatively how much warmer are the projections of the Arctic region are than the rest of the globe at the 1.5 of 2.0°C global average thresholds.

Otherwise, I have no other additional comments below and I recommend that the manuscript be accepted pending minor revisions.

Author Response to Reviewer Comment 1

We sincerely thank the reviewer for these positive and useful comments.

"I thought that the analysis was well done, and I found compelling. However, I am somewhat confused about the goal of the study.."

The reviewer expressed some uncertainty over the goal of the study. A similar point was also raised by RC2. As such, we have added a new discussion in the opening paragraph of our revised manuscript addressing this point and highlighting the value we see in quantifying the impact of Arctic amplification on the timing of breaches in the Paris goals. While we agree that the direction of the impact on timing is a straightforward result, since faster warming in the arctic must cause an earlier breach of temperature limits in our framing, we argue that there is value in quantifying the magnitude of this impact. In part, this is because the traditional framing of Arctic amplification in terms of a ratio of warming rates can be difficult to interpret, especially for those from a climate policy perspective, where the more important question is how Arctic amplification contributes to total global warming.

“I wonder if a more relevant use of the analysis is to argue how the accelerated Arctic warming leads to more rapid changes in the Arctic and even better how this leads to more rapid changes across the population centers of the Northern Hemisphere”

The assessment of the local consequences in the Arctic of it’s rapid warming and links to changes in mid-latitude Northern Hemisphere climate, are both important and large research areas. Although not in the scope of this piece, we have added additional reference to these impacts in our discussion.

“In summary, I thought that this was a well-executed study and that the results are correct. What I struggle with is the importance of highlighting that Arctic amplification will accelerate crossing the Paris Agreement temperature thresholds that is an obvious and therefore maybe trivial result and conclusion. And I wonder making a different point with the same analysis..”

The reviewer also raises the question of whether additional analyses might further highlight the implications of our results. Two examples are offered but we feel a third option is more amenable to our methods. We have added a new component to our results section in our revised manuscript assessing how the uncertainty in Arctic warming over coming decades impacts the uncertainty in the timing of crossing temperature thresholds. As expected given the faster warming in the Arctic, our calculations show that the region accounts for a larger proportion of the inter-model variability in the timing of crossing temperature thresholds than would be expected based on its size. Using a partial correlation analysis, we estimate that around 15% of the uncertainty in 1.5°C crossing year across the multi-model ensemble under SSP2-4.5 can be attributed to the uncertainty in near-term Arctic warming.

Reviewer Comment 2

This is a short and uncomplicated article, so I'll get straight to the point. Whilst I don't doubt the calculations here are correct (and are perhaps of interest to some readers), I'm struggling to see the logic and benefit of the proposed new framing. We already know the Arctic is warming faster than the global average. It is therefore inescapable that the Paris targets imply much greater warming in the Arctic than the 1.5/2C in the global mean. But, love them or loathe them, the Paris targets refer to (and only to) the global mean temperature. As soon as you start considering averages excluding the Arctic, it ceases to be a global mean and therefore, has no real bearing on the Paris targets. By excluding the Arctic, you are, in essence, redefining the Paris targets. There are limitless ways to reinterpret the Paris targets. Take this to the opposite extreme – suppose we only included the Arctic in the calculation (i.e., imagining that the global mean warmed at the rate of the Arctic, rather than the Arctic warmed at the rate of the global mean) – then the Paris targets would likely have been passed already, decades "earlier" than otherwise. But the Paris targets are not referenced to Arctic warming, nor the global average excluding the Arctic – they only carry meaning in the context of globally averaged warming.

Arctic amplification is an inherent aspect of climate change. Another indisputable feature is that land warms faster than ocean. So, in a similar vein, the Paris targets will be meet "sooner" because of amplified warming over land. You could also argue that any places warming less than the global-mean – much of the ocean and particularly the subpolar North Atlantic – are "delaying" passing the Paris targets. But, I don't think any of these statements make much sense in the context of the Paris targets, which are referenced to global mean temperature.

Although the rationale for the new framing is not well articulated, it appears one motivation is to call for better monitoring and modelling of the Arctic. Whilst I support this goal, it's not at clear to me that the (arguably small) difference in the timing of reaching 1.5/2 attributed to AA provides the best justification for this. Perhaps a clearer way to demonstrate the potential benefits of improved Arctic modelling is to show that uncertainty in AA is related to that in the timing of breaching the Paris goals. You could attempt to put some numbers on this. Rather than compare cases with and without Arctic amplification, you could compare how the upper and lower bounds of modelled AA translate into differences in the projected timing of breaching the Paris targets. That said, I don't expect the numbers to be especially big. Ultimately, I think there are many reasons to want to reduce uncertainties in AA (to improve projections of Arctic impacts, global sea level rise, possible effects on midlatitude weather, and so on), but constraining projections of global mean temperature is not the most obvious.

I think by this stage it's probably clear that the proposed framing doesn't really 'work' for me. However, I (a physical climate scientist) may not be the target audience. I do think there is potential value in different framings as communication tools and possibly, there are people who would find this framing useful. Therefore, I don't strongly object to this manuscript being published , but have 4 recommendations for the authors to consider.

- I would like to see the perceived problem better articulated: Why is this new framing needed? Who is it aimed at? For full disclosure, I have seen some of the authors discussing the submission on social media. It appears there is a backstory to this work: a perceived need to communicate the importance of Arctic warming to policy makers. I think it would be useful to provide some of this context in the manuscript (although I question if this is the best outlet for this "idea", if it is mainly aimed at non-academics).
- The phrasing "X years earlier" could be misleading – it's only "earlier" than an imaginary world that doesn't exist; it's not "earlier" than any meaningful prediction or projection. I think this point needs to be made explicitly.
- Relatedly, be explicit that the Paris targets refer to (and only to) global mean temperature, and although it may of some interest to consider how excluding the Arctic shifts the projected time of reaching the Paris targets, this is taking the Paris targets out of context.
- Consider reframing the piece (or at least adding some calculations) on the effect of model uncertainty in AA to the projected timing of breaching the Paris targets, as a way to better connect to the call for better modelling of the Arctic.

Author response to Reviewer Comment 2

We thank the reviewer for these detailed and thoughtful comments which have been helpful in improving our manuscript.

The reviewer makes 4 specific recommendations which we now reply to in turn, after which we then respond to several other comments made in the made body of the review.

(1) 'I would like to see the perceived problem better articulated..'

We have reworked our opening paragraph in the revised manuscript to highlight the value we see in quantifying the impact of Arctic amplification on the timing of breaches in the Paris goals. This text will also explain that we aim to produce a useful statistic for those interested in Arctic change from a broad range of backgrounds, including those in the climate policy community, for whom the traditional framing of Arctic amplification in terms of a ratio of warming rates can be difficult to interpret. We argue that framing Arctic amplification in terms of its contribution to global warming, and the timing of Paris breaches, provides a more intuitive and therefore impactful quantification of the phenomenon.

(2) 'The phrasing "X years earlier" could be misleading..'

We agree that the "years earlier" phrasing had the potential to be misleading. As such, we have edited this throughout the paper for our revised version, and in Figure 1, so that we will now refer to the real world (with Arctic amplification) as our base case and then refer to the number of years 'later' when crossing occurs under the hypothetical case without Arctic amplification.

For example, our abstract previously read: "Here we reframe this amplified Arctic warming in terms of global climate ambition to show that it causes a breach of the Paris Agreement's 1.5 °C and 2 °C limits 5 and 8 years earlier, respectively."

It will now read: "Here we reframe this amplified Arctic warming in terms of global climate ambition to show that without Arctic amplification, the world would breach the Paris Agreement's 1.5°C and 2°C limits 5 and 8 years later, respectively."

(3) 'Relatedly, be explicit that the Paris targets refer to (and only to) global mean temperature..'

This is an important point. We now add an explicit note to this effect at the end of our introduction:

"We also note that our analysis does not imply any change from current estimates in the expected timing of breaching Paris limits, which refer explicitly and only to global mean temperature (UNFCCC. Conference of the Parties (COP), 2015)."

(4) 'Consider reframing the piece (or at least adding some calculations) on the effect of model uncertainty in AA to the projected timing of breaching the Paris targets, as a way to better connect to the call for better modelling of the Arctic.'

This is a useful suggestion, and we have performed the suggested extra analysis and added it to our results section as the new penultimate paragraph. As expected given the faster warming in the Arctic, our calculations show that the region accounts for a larger proportion of the inter-model variability in the timing of crossing temperature thresholds than would be expected based on its size. Using a partial correlation analysis to control for the fact that Arctic warming is strongly correlated to warming outside of the Arctic (across the multi-model ensemble), we estimate that around 15% of the uncertainty in 1.5°C crossing year across the multi-model ensemble under SSP2-4.5 can be attributed to the inter-model variation in near-term Arctic warming.

Responses to other comments:

'As soon as you start considering averages excluding the Arctic, it ceases to be a global mean and therefore, has no real bearing on the Paris targets. By excluding the Arctic, you are, in essence, redefining the Paris targets.'

Our analysis does exclude the Arctic, but only so as to model what the global warming would be in a world where the Arctic warms at the global mean rate. As such, our interpretation is that we are always comparing global mean warming in our analysis, it's just that the method to estimate the 'global mean warming' in our hypothetical (and unphysical) world without Arctic amplification uses an average excluding the Arctic.

'Although the rationale for the new framing is not well articulated, it appears one motivation is to call for better monitoring and modelling of the Arctic. Whilst I support this goal, it's not at clear to me that the (arguably small) difference in the timing of reaching 1.5/2 attributed to AA provides the best justification for this.'

This is a fair point, and one which we have taken into account in reworking our final paragraph. Our revised discussion (the final paragraph) is shorter, and more strongly caveats the importance of our findings for motivating Arctic science.

'Perhaps a clearer way to demonstrate the potential benefits of improved Arctic modelling is to show that uncertainty in AA is related to that in the timing of breaching the Paris goals. You could attempt to put some numbers on this. Rather than compare cases with and without Arctic amplification, you could compare how the upper and lower bounds of modelled AA translate into differences in the projected timing of breaching the Paris targets.'

The suggested uncertainty analysis is included in our revised manuscript. In addition to the analysis discussed above, to answer the question posed here we use a multiple linear regression model for crossing year of the 1.5°C threshold under SSP2-4.5 predicted by the (1) near-term Arctic warming rate and (2) near-term warming rate outside the Arctic. Such a model suggests that controlling for warming outside the Arctic, the difference in Arctic warming rate between the 10th and 90th percentile models causes a 3 year difference in crossing year for the 1.5°C threshold.

Community Comment 1

I engaged with the authors of this preprint over Twitter (https://twitter.com/RobbieMallett/status/1656290828094959616) and promised to follow-up with an actual comment, so here we are!

First I want to just state that overall I'm a big fan of approaches like this - a quick, and somewhat provactive, idea of how to reframe an important question with a clear figure and nice introduction/description to back it up all in an open peer review. Sometimes we don't need 10 figures and a lengthy manuscript that only a few motivated people will actually read. So in general my comments below are not an attempt to prevent publication, just to tlak through the ideas presented and hopefuly help improve them.

I initially read the paper and had doubts about the methodology (expressed to the authors on Twitter!), but after a bit of head scratching it does now make sense to me that this really is simply turning off/on the increased temps of the Arctic and assessing what that does to projections of GMST in terms of 1.5C and 2C breaches which I think can acurately be described as the impact of AA in its bluntest formulation!

As you say in the paper, the counter-factual isn't really a world without the feedback mechanisms that drive AA, it's just a weird world where for some reason the Arctic warms at exactly the same rate as the rest of the globe. That's all fine in my head now but I share the feelings of the other reviewers that this result isn't really all that remarkable and I'm finding it a little tough to understand how best to interpret the 'delayed years' concept in light of the very unnatural counterfactual. I think as the reviewers have alluded to, the Paris targets are really focussed around policy responses to prevent certain GMST targets being reached, so the framing around Paris in this paper almost makes it sound like AA is something we could potentially turn off or on, which obviosuly we can't. I think the papers closest to this are the ones that try and isolate the role of say sea ice changes in driving AA/GMST changes, but I dont think i've seen those expressed in terms of delayed years for temp breaches, but the motiovation behind this study is a bit different perhaps.

I'm also doubtful of the idea that the analysis shown here presents a compelling case to study the Arctic more beyond what we already knew about the fact it's warming much more than other parts of the world (a concept us polar scientists regularly use in proposals already!). I think, as another reviewer pointed out too, that better highlighting how the uncertainity in AA contributes to the timing of breaches would be much better for this. You touch on this but it's not that clear, so perhaps a clearer demonstration would be assessing how the AA factor changes over time, and the degree to which fixing the current AA factor in future runs would change the expected timing of breaches. Then the question becomes - how does a low or high end AA scenario impact Paris breaches? If that spread is meaningful then i think you could say 'look, we need to study the Arctic more to know what type of AA we are in for and how this might impact Paris breach timings!'. I hope that makes sense..?

A final little comment, most papers I've seen studying AA use temperatures in the tropics (-30 to 30) as the baseline. I see why you didn't do that but I think it might be worth a comment?

Thanks again!

Alek Petty

Author Response to Community Comment 1

Thank you for taking the time to post these insightful and constructive comments, which have been very useful in improving our work. We respond to indivdual apsects of the comment in turn below:

'As you say in the paper, the counter-factual isn't really a world without the feedback mechanisms that drive AA, it's just a weird world where for some reason the Arctic warms at exactly the same rate as the rest of the globe. That's all fine in my head now but I share the feelings of the other reviewers that this result isn't really

all that remarkable and I'm finding it a little tough to understand how best to interpret the 'delayed years' concept in light of the very unnatural counterfactual.'

While we agree that the sign of the effect we present is unsurprising, we think that it would be useful for the community both within polar science and more broadly to have a peer-reviewed estimate of it's magnitude. Part of the motivation for conducting this analysis was that the traditional framing of Arctic amplification in terms of a ratio of warming rates can have little cut-through with those used to thinking about the climate problem in terms of global mean temperature change and targets. Our framing aims to provide a more readily interpretable quantification of the phenomenon. We spell out this motivation more clearly in our updated introduction.

'I think as the reviewers have alluded to, the Paris targets are really focussed around policy responses to prevent certain GMST targets being reached, so the framing around Paris in this paper almost makes it sound like AA is something we could potentially turn off or on, which obviosuly we can't. I think the papers closest to this are the ones that try and isolate the role of say sea ice changes in driving AA/GMST changes, but I dont think i've seen those expressed in terms of delayed years for temp breaches, but the motiovation behind this study is a bit different perhaps.'

Our motivation in linking AA to the Paris targets was simply to find a quantification for the size of AA with which readers will be most familiar. We agree though, that it is important to be absolutley clear that our results do not have any impact on when we expect to cross thresholds, since as you say, we can't control AA. We have added a sentence highlighting this at the end of our introduction (see response to RC2).

'I'm also doubtful of the idea that the analysis shown here presents a compelling case to study the Arctic more beyond what we already knew about the fact it's warming much more than other parts of the world (a concept us polar scientists regularly use in proposals already!).'

This is a fair point and we have made several changes to our discussion to better put in context the implications of our findings for motivative Arctic science. Our revised discussion (the final paragraph) is shorter, and more strongly caveats the importance of our findings for motivating Arctic science.

'perhaps a clearer demonstration would be assessing how the AA factor changes over time, and the degree to which fixing the current AA factor in future runs would change the expected timing of breaches. Then the question becomes - how does a low or high end AA scenario impact Paris breaches? If that spread is meaningful then i think you could say 'look, we need to study the Arctic more to know what type of AA we are in for and how this might impact Paris breach timings!' '

The suggestion to focus more on how uncertainty in Arctic warming influences uncertainty in crossing of temperature thresholds was also made by RC2, and we agree makes a good addition. As such, we have conducted analysis on this point which we have added to our revised results section, as the penultimate paragraph. As expected given the faster warming in the Arctic, our calculations show that the region accounts for a larger proportion of the inter-model variability in the timing of crossing temperature thresholds than would be expected based on its size. We estimate that around 15% of the uncertainty in 1.5°C crossing year across the multi-model ensemble under SSP2-4.5 can be attributed to the uncertainty in near-term Arctic warming. We also assess the specific question posed, of how different near-term rates of Arctic warming influence the crossing year using multiple linear regression model for crossing year of the 1.5°C threshold. This model suggests that controlling for warming outside the Arctic, the difference in Arctic warming rate between the 10th and 90th percentile models causes a 3 year difference in 1.5°C crossing year. This is larger than difference in crossing years between our low and high emissions scenarios. The reason to construct this analysis in terms of Arctic warming rate, rather than the Arctic amplification (AA), is that decreased warming outside the arctic increases the warming ratio and thus the value of AA. As a result, the AA variable itself doesn't allow for separating the influence of local Arctic warming versus (correlated) warming outside the Arctic on crossing year in the multi-model ensemble.

'A final little comment, most papers I've seen studying AA use temperatures in the tropics (-30 to 30) as the baseline. I see why you didn't do that but I think it might be worth a comment?'

Thanks for this point. We have added a note (line 25) that: “Our definition of Arctic amplification differs from some analyses (e.g. Pithan and Mauritsen, 2014) which use the tropics as the baseline region, rather than the world outside the Arctic.

References:

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