Response to Reviewer 1 (D. Mitchell)

I have many comments that should be addressed, but they are only small, so I would recommend minor corrections. Three broad comments that the authors should consider are

1) to be a bit more upfront about the limitations of the CAM5 model, by, for instance including a paragraph on how well the model reproduces the past quantities that are looked at in the paper. Referring to AR5 etc, rather than new analysis could do this.

Thanks. We added the following paragraph to this point:
"CESM1-CAM5 is a single climate model, and like any model is subject to biases in both its present day simulations and in future projections. As such, the ensemble spread in this study does not represent true uncertainty in future projections, rather a single estimate of climate evolution. However, multi-model assessments in the past have indicated that CESM1-CAM5 is one of the better performing models in the CMIP5 archive. \cite{sanderson2015representative} found this model to be the best performing in a selection of mean state metrics, and \cite{flatocoauthors}, Figure 9.37 shows that the model has one of the better simulations of extreme temperature and precipitation metrics in the CMIP5 archive."

2) the nature of using a coupled ocean means that the climate may not be stable within the century. I think this needs to be clearer in the abstract, but also in discussion of Figure 1.

Added this to the abstract to make clear that the emulator was only tested in the 21st century

"These scenarios … **are realized (for the 21st century) in the coupled model** and are freely available to the community."

And added the following to the temperature evolution results:

"Note that although these results suggest that the predicted emulation of stable temperatures in the emulator is validated for the evolution of global temperatures in the coupled system in the 21st century, there may be ocean dynamical processes at longer timescales in the coupled model which are not represented in the emulator's thermodynamic ocean. As such, we have not tested the stability of global temperatures at multi-century timescales with these emissions pathways."

3) In the abstract, and throughout the text, it should be made clearer that this study is only a broad sweep of impact relevant analysis. For instance, each one of the sections on impacts could (and should) be multiple papers of analysis.

Changed abstract as follows:
"Here we describe the design of the simulations and **a brief overview** of their impact-relevant climate response. "

Added this to the end of the introduction:

"We aim in this study to provide a short overview of differences in impact-relevant climate variables, with the hope that further studies will focus in more detail on specific processes, regions or societal impacts."

Comments P1 L6: "impact-relevant long term climate data" – somewhere in the manuscript I think a sentence is needed about what variables are output. Is it everything from AR6? At this stage it is not clear what impact-relevant variables are stored.

The list is far too long to print in the paper. We've added a link to an online table:
http://www.cesm.ucar.edu/projects/community-projects/LENS/data-sets.html

P1 L11: "and only 1 in 40. . ." I think 'only' can be deleted here.

done

P1 L19 - P2 L1: "worlds emissions have been closer. . ." is this true for GHGs and aerosol etc? The interplay of both can be very different in different RCPs.

Expanded as follows:
"Since then, the world's greenhouse gas emissions have been closer to the highest emissions pathway (RCP8.5) than any other, even accounting for a recent slowdown in emissions growth \citep{van2011representative,quere2016global} (aerosol evolution differs relatively much less between RCPs, which are so far broadly in line with observations \cite{klimont2013last})."

P2 L8-10: This sentence is not clear to me, I think the multi-model mean of CMIP5 RCP2.6 gives ~1.5C, which seems in contradiction to your sentence. Of course it depends on pre-industrial definition.

Agreed. Changed as follows:

"Although some individual models exhibited less than 1.5C warming in this scenario (median warming was 1,6C), CESM warming in this scenario is closer to 2 degrees \citep{meehl2013climate}."

P2 L12: "no individual model" should be "no individual fully coupled model".

Done

P2 L18-26: I feel James et al, 2017, WIRES should be cited here, as it gives an overview of all these methods.

Done.

P2 L21: Can you make a comment on the time scales where the pattern scaling is relevant?

Not sure what is meant by this comment.

P2 L27: Acronym is wrong. It should read: "Prognosis and Projected Impacts".

Updated,

I think Mitchell et al, 2017b should also be added, which was the concept of HAPPI.

Added.

P2 L29: Please change 'will use' for 'uses', as these have already been performed.

Done.

Done.

P2 L34: "have the same SSTs. . ." actually there are tier 2 experiments which sample a much wider range of SST patterns (22 different patterns for 10 different years, which is 220 different patterns). Although I agree that is still doesn't sample the full range, as the CAM5 setup does.

Changed as follows:
"Because simulations in HAPPI will have one of a finite set of predefined SST patterns, the estimate of significance of the difference in climate states will not completely sample ocean-driven variability."

P4 L5: I think this should be "Figure 1(a) and 1(b)". Otherwise 1(a) is not referenced. But it makes sense to refer to both panels here anyway.

It was referenced in the previous section, but we've now included it here as well.

P4 L11: "1850-1920", can you provide some justification for choosing this period please.

The large ensemble initial conditions (which we used for these simulations) did not diverge before 1920 (i.e. there's only one ensemble member until then, after which they branch). As such, using 1850-1880 would have been rather noisy - hence we used the longer time period. We've added a sentence to this effect:
"(where pre-industrial is taken as the 1850-1920 mean - averaging over the period before the model initial conditions were branched, and using a 70 year rather than 30 or 50 year mean because there is only one ensemble member for this period). "

P5 L13: I think "until 2100" can be removed, otherwise it sounds like it changes there (but actually just the simulations stop there).

done

P5 L14-15: I do not think the plots look as stable as the authors say, especially not for the 2C experiment. And I wouldn't see how they would be with the long term ocean time scales. Can the authors expand on this section.

We've added the caveat section in response to your major point above, and we've re-worded the paragraph to remove the word "stabilized":

  The \emph{1.5degNE} scenario reaches 1.5C above pre-industrial levels and then maintains this temperature until 2100. The \emph{1.5degOS} scenario reaches a peak temperature in 2050 of 1.7${^\circ}$ above pre-industrial before cooling to 1.5C by 2100, and the \emph{2.0degNE} scenario reaches slightly over 2.1C by 2100.

P5 L16: "large scale climate" sounds unclear. I think "global-scale climate" is better.

done

P5 L20-25: I would note that within uncertainty there is no change over the scenarios.

We already say " The inherent uncertainty in the sea level response at a given emissions level is greater than the difference between the scenarios considered here. "

P7: I think some more text on the reproducibility of the Arctic response is needed, especially in the historical period. There is a large range in CMIP5 projections.

Added: "And while it should be noted that there is large diversity in the rate of loss of Arctic sea ice in CMIP5 models \citep{mahlstein2012september}, the CESM sea-ice loss per degree of global warming to date is less than that which has been observed \citep{Rosenblum_Eisenman_2017}. "

Figure 2: It would be nice to see a bias plot from the model (historical versus CRU, or something similar). This might address the comment above to some extent.

There isn't space to evaluate CESM's historical performance here and I would argue that (1) it's already been comprehensively done and (2) the mean state temperature bias plot tells you relatively little (if anything) about the temperature response (otherwise we would be using it to constrain the response).

P8 L12: I think a stronger reference for this point is Gasparrini et al, 2016. You could either add it on, or replace the old reference with it. Also it would be best to put an 'e.g.' in front of these.

Added as suggested

P8 L28-end: I didn't follow the use of the GEV distribution here. You have a large sample size, 10 ensemble members of 30 years), so you should be able to calculate a return period from that? Why model it? Perhaps it is to use a covariate and account for the transient response? I think this needs more clarification.

The clarification is well explained in the source reference Tebaldi and Wehner (2016). At the grid-point level, the sample size is insufficient to provide a smooth empirical distribution for this level of extreme event, so the extreme value analysis is necessary, even with a 10 member ensemble.

P12 L13-17: It is not clear to me if land use/cover is different in the different scenarios. This will be important here, so should be clarified.

We already detail this in the introduction:
" In each of the low emission scenarios in this paper, only well-mixed greenhouse gas concentration are changed between scenarios, all other forcings (land use, aerosol emissions, and ozone) follow RCP8.5 throughout the 21st century as in \citep{kay2015community})."

Conclusions/discussions: I think this section should be shorter. I like the discussion part but feel other results are repeated in too much detail.

We have removed 2-3 paragraphs which repeat information from the results section.

P13 L17: "simulations to our knowledge" please change to "simulations using a fully coupled model to our knowledge".

Done

P13 L32: "longer than a century" please add "and therefore were not assessed in this study".

This paragraph is now removed

P14 L20-27: I feel this section could be a bit more balanced between this study and HAPPI. I.e. there are advantages and disadvantages to both. Also, note that 2 of the HAPPI models have done sister experiments which include some form of ocean coupling. i.e. the NorESM2 models, and the MetUM-GOLM model. In both cases, they use slab oceans.

Agreed. Re-written as follows:
"A key factor determining whether or not there are significant differences between 1.5C and 2C of warming is the magnitude of the climate system response to a difference of half a degree of warming relative to internal climate variability. This question can be informed by ensembles of coupled climate model simulations including estimates of internal variability arising from the ocean and atmosphere, and yet. These experiments should hopefully provide context (for a single model) for the primary multi-model effort being pursued by the community to address the difference between 1.5C and 2C of warming (HAPPI, \cite{mitchell2017half}) which relies on AMIP simulations with prescribed SSTs."

Response to reviewer 2 (Marcus Sarofim)

First, I would recommend using the more recent Kopp et al. semi-empirical equations in place of the Rahmstorf et al. (2007) C1 version.

Done - using the 10th and 90th percentiles of Kopp's distributions of the 'a' and 'c' parameters to define the uncertainty range.

Second, I would consider comparing future model results against historical records from the model, rather than from observations, in Figure 3 and related text. I can understand not taking the latter recommendation, but in that case, I would include text discussing the how differences between model and observations during the 1976- 2005 historical period might impact the results.

Thanks for the suggestion, but for a number of reasons we would like to keep the figure as a direct comparison to observations. However, the figure produced in the way you suggest looks as follows:
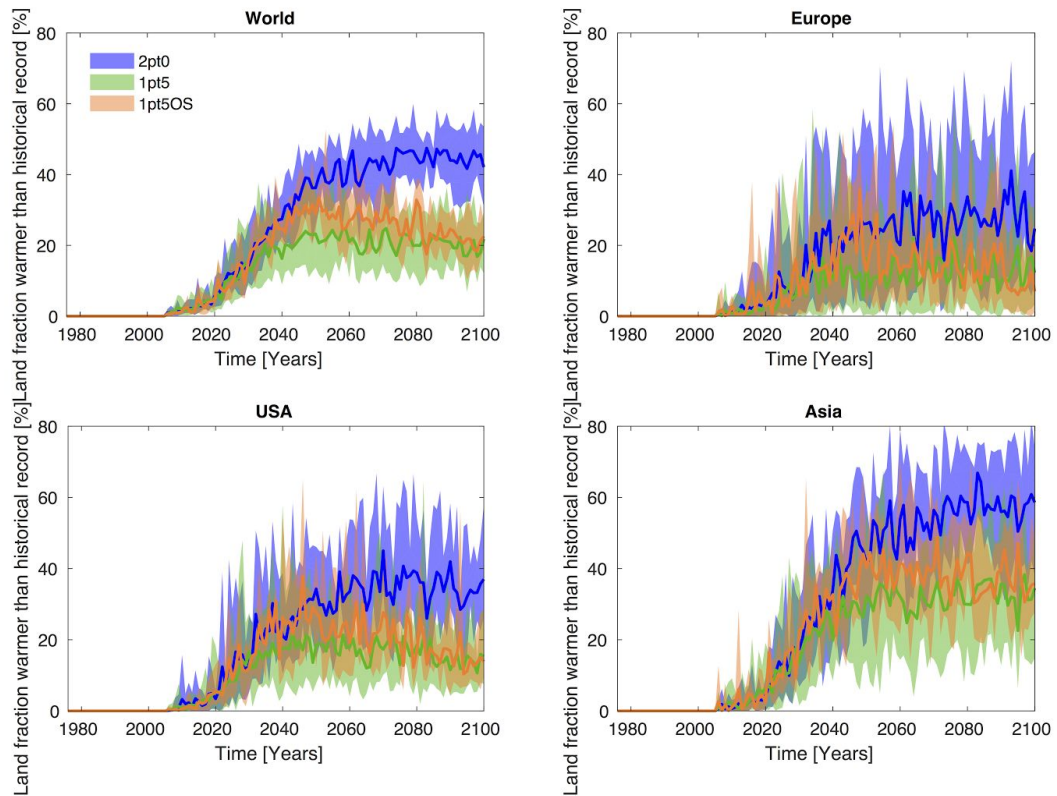
The results are very similar as in the original Figure 3, except for a mean offset that comes from the fact that you look for a record in 10 ensemble members rather than 1 observational record. As such, any given record will very likely be higher because it is based on 10x more samples, making that record harder to break in the future. One could pick a record from one arbitrarily individual simulation, but we feel that would make the figure less relevant as a communication tool. Using all ensemble members, all the time series in Fig 3 would shift down but basically keep their shape and relative position. This would imply about ~30% less land fraction exposed when you look for the record in the 10 ensemble members. As such, and for consistency with Lehner (2016), we would prefer to keep the plot as-is.

We added the following caveat:

"It is notable that some records in Figure \ref{record} are exceeded before 2005 because the historical evolution of the CESM ensemble differs from the real-world historical evolution and there could potentially be some model regional model biases. However, the behaviour of CESM in the period 2006-2016 is in within the range of model record exceedance (both globally and in each of the regions considered), giving confidence that regional biases are not strongly influencing this metric. Note that if the records were taken from the historical simulations of CESM itself for consistency, almost all historical records would be a higher temperature because the effective sample period in a 10 member ensemble is 300 years for the period 1976-2005, which causes a 30 percent reduction in end of 21st century record exceedance (see discussion with reviewer M.Sarofim for further details)."

Other than that, most of my comments below are generally minor sentence edits.

Line by line comments:

Page 1, Line 17: I would also reference Fawcett et al. here as it has a good analysis of the probability of staying below various thresholds for the RCPs (based on simple models, not full GCMs, of course) (DOI: 10.1126/science.aad5761)

Agreed. Done.

Page 2, Line 5: I am unclear how the authors determined that this commitment would lie "on the verge of economic and physical plausibility": as I read Smith et al., they evaluate the cost & capacity of negative emissions technologies, but do not define a plausible upper bound to how

fast society could implement these technologies if properly motivated. I would rephrase this sentence to be more judicious, e.g., "likely requiring substantial commitment to negative net carbon emission technologies in the 2nd half of the century".

Rephrased as suggested

Page 2, Line 19-20 and 23-24: it seems to me that "finding time periods from other scenarios" is equivalent to "another approach is to 'time-shift' by taking periods...": I would delete one of these descriptions.

Agreed, removed the earlier sentence.

Page 4, line 14: delete "in a decade" (it is redundant with "by 2027").

Done.

Page 5, line 2-3: I understand why the authors made the justifiable choice of using RCP8.5 non-GHG forcings for all the scenarios – however, it would be useful to have a brief aside that notes that a 1.5 degree scenario that is internally self-consistent might look slightly different than a 1.5 degree scenario that is a hybrid between RCP8.5 nonGHG forcings and low-GHG-concentrations. In particular, sulfur emissions might be C2 even lower in a 1.5 degree scenario (like RCP2.6 has lower sulfur than RCP8.5, though comparing RCPs should also be done with caution because they come from different IAMs so not all differences are necessarily due to policy effects), which would require even tighter GHG emissions reductions, but more relevantly for the paper, might also impact temperature patterns because aerosols have different land/ocean and hemispheric forcings than well-mixed GHGs. Similarly, a 1.5 degree future that relies heavily on bio-fuels would have very different land-albedo forcings. I also note that the choice of setting RCP2.6 as a limit to non-CO2 GHG reductions has an influence as well, possibly contributing to the necessity for the long-term CO_2 emission floor to be negative (Table C1, column 7) because the CFCs and maybe N_2O have lifetimes long enough that their concentrations would not have stabilized by 2200, requiring ongoing offsetting negative CO_2 emissions (I think this study does not include SF_6 or PFCs).

Added the following paragraph to address these points:

It should be noted that the assumptions of RCP8.5 trajectories for non greenhouse gas forcers is implemented for practical reasons to make the present study tractable. However, a fully self consistent 1.5 degree scenario from an Integrated Assessment Model (IAM) would likely have slight differences. Sulfur emissions are lower in RCP2.6 than in RCP8.5, and maybe lower still in a 1.5 degree scenario (although there large differences in sulfur emissions between individual IAMs with the same policy constraints).

However, any given global temperature target could be achieved with different combinations of aerosol forcing and greenhouse gas forcing, but with regional differences in temperature and precipitation \citep{xu2015importance,pendergrass2015does}, and changes in land use necessary for large scale biofuel production would change surface albedo \citep{caiazzo2014quantifying}. An IAM could also have additional degrees of freedom, with the capacity to reduce N2O and CFC emissions below the RCP2.6 minimum levels.

i would also potentially be curious regarding where CESM falls in terms of climate sensitivity in the larger CMIP universe, which would also determine how aggressive the GHG mitigation would need to be to stay below given targets.

Added the following:

CESM also has a higher climate sensitivity (4.0K, \cite{gettelman2012evolution}) than the CMIP5 mean (3.6K, \cite{webb2013origins}), and so emissions need to be reduced faster than average for this model in order to meet any given temperature target.

Page 5, line 3: Fix parentheses – in Kay et al. (2015).

Done

Page 5, line 18-20: I would suggest replacing the Rahmstorf (2007) semi-empirical approach with that from Kopp et al. (2016) (doi: 10.1073/pnas.1517056113): Rahmstorf is a co-author of the latter paper, which claims to reconcile the semi-empirical approach with process-based models, and therefore I would consider this to be an improved update to the Rahmstorf equations. (a correction would still be required for ice sheet melt, so Horton et al. 2014 might still be appropriate there).

Page 8, Line 15-16 (and Figure 3 generally): I note that during the period 1976-2005, models have already exceeded the maximum historical observed temperatures from 1976-2005. This makes me wonder whether the appropriate comparison should be between future model and historical model, rather than future model compared to historical observations. Either that, or there should be a discussion of this potential discrepancy. Reading Lehner et al., I think that paper did do compare to historical models – e.g., Figure 3 has both the observed 1920-2014 and the model 1920-2014, so that one can compare model-future to model-past, e.g., like-to-like. I recognize that there is still the potential for model bias to creep in here (as discussed in Lehner): if the model has more variability than the observed, then it is harder to exceed records, and vice versa, but I think a like-to-like is a cleaner comparison.

As in our response to your major point, our issue here is which historical simulation to use - using all ensemble members to define records would create a meaningless result (because the records would be over a much longer time period). Using just one model would introduce an arbitrary bias. We have added a caveat paragraph to explain the potential for model bias - but we feel that the plot has most value in contrast to actual real world records, with a marked increase between the model's exceedance of real-world records in the late 20th century and the mid 21st century suggesting that the model biases do not dominate this metric.

In addition, for section 3.3, I don't see a cited source for the observed temperatures – is it BEST as in Lehner? Or ERAi? I would suggest an additional paragraph here which could do several things: 1) note the source of observed temperature data,

We already do - we are using the BEST data as in Lehner (2016):

"Observations are from \citealt{rohde2013berkeley}, as in \cite{lehner2016future}. "

2) discuss how well the model reproduces the observations over the 1980-2005 period (and/or if any bias-correction is being used here),

We have added the following caveat:

"It is notable that some records in Figure \ref{record} are exceeded before 2005 because the historical evolution of the CESM ensemble differs from the real-world historical evolution and there could potentially be some model regional model biases. "

But we also note that the IPCC found CESM to be one of the better models in representing historical temperature extremes, as follows:

"\cite{flatocoauthors}, Figure 9.37 shows that the model has one of the better simulations of extreme temperature and precipitation metrics in the CMIP5 archive. "

3) discuss the model-observation comparison over the 2006-2016 period.

Thanks for the suggestion - this period is, we think, an assurance that the biases in CESM are not dominating global or regional aggregate numbers of records exceeded:

"However, the behaviour of CESM in the period 2006-2016 is in within the range of model record exceedance (both globally and in each of the regions considered), giving confidence that regional biases are not strongly influencing this metric."

Page 8, Line 26-27: Related, is this "noteworthy" statement regarding the 2006-2016 period? Please clarify, and see above suggestion.

We have deleted this sentence.

pg 8, line 33-34: 1) some regions experience a greater increase in extreme than in mean: is the opposite true as well? 2) following up on that: it would be very interesting to have a quantitative estimate of this effect: e.g., x% of the land area experiences a warming of extremes more than 50% faster than the mean, while y% experiences a warming 50% slower than the mean. Or, averaged across land areas, extremes warm x% faster than the mean. Or something like that.

Done as suggested:

"(in 2.0degNE, 9\% of the land area experiences a warming of extremes more than 50\% faster than the mean, while less than 1\% experiences a warming 50\% slower than the mean)."

pg 9, line 9: I might note that the greater signal to noise is seen at lower latitudes even though absolute warming at those latitudes is generally smaller (which has the opposite effect of there being less variability at those latitudes).

Agreed, done:

"... the greatest signal to noise is seen at lower latitudes (although the absolute magnitude of warming is smaller)."

pg. 21, line 5: stray period should be deleted.

Fixed

Figure 2: "subplot" should be singular.

Fixed

Figure 4: Is the historical period 1976-2005? Please specify. Also, it is based on observed (like Figure 3) or on modeled historical (like I think that most other figures do)

Fixed:

"Maps showing the expected number of times that the modeled historical 1 in 20 year 3-day warm event in the period 1976-2005 would be exceeded during the period 2071-2100"

Figure 6: legend needs more detail: I assume that black is modeled historical, but it could potentially be observed. Also, what's the time period of smoothing – annual?

Expanded as follows:

"Changes in annual mean precipitation at the (a) Global, (b) Land-only and (c) high Northern latitude land. Values are relative to the 1921-1960 average. Grey lines show members of the historical CESM ensemble, while black line shows the historical mean. Thin colored lines show individual ensemble members for future scenarios, thick bold lines show the ensemble mean."

Figure C2: Please include a legend for the colors as in Figure 1.

Done

Also, I don't think it that this figure extends far enough to demonstrate this, but I'd be curious about whether the 1.5NE and the 1.5OS could be used to investigate path dependence/memory/inertia. For example, one might expect some additional warming of the Arctic Ocean during the years in which the temperature is above 1.5 degrees which might take a number of years to dissipate even after the global surface air temperatures have returned to 1.5 degrees, which might lead to slightly lower sea ice extent in the 1.5OS case than then 1.5NE case for some years after stabilizing back at 1.5 degrees. (One could go further, and imagine hypothetical tipping points that could be exceeded in the 1.5 OS case which would not be resolved by cooling back down to 1.5 degrees, but I would imagine that this would be somewhat unlikely, and even if such a tipping point existed, this modeling system might not be able to catch it). (sea level could be a place where there might be some long-term memory of a brief excursion to 1.7 degrees, as in Zickfeld et al., doi: 10.1073/pnas.1612066114: Figure 1(c) seems to show this – it might be interesting to note the divergence between 1.5OS and 1.5NE at 2100 and what date the two scenarios become equal, if they ever do)

Thanks for the suggestion. Our co-author Alex Jahn is writing a dedicated paper on this topic, so we defer these questions of path dependency to that study.

Table B1: Would it be possible to include an additional column with the values of each parameter that resulted from the calibration process?

Done.

Response to reviewer 3 (KT Tanaka)

1) I start with a broad comment related to the interpretation of the results. The paper ends with the statement stressing the differences in impacts between 1.5◦C to the 2◦C levels: "Irrespective of feasibility, these simulations indicate that a relaxation of ambition from the 1.5◦C to the 2◦C level would result in significantly greater impacts at the global scale, in the tropics and at high latitudes." The abstract also highlights the differences, rather than the similarities: "Exceedance of historical record temperature occurs with 60 percent greater frequency in the 2◦C climate than in a 1.5◦C climate aggregated globally, and with twice the frequency in equatorial and arid regions. Extreme precipitation intensity is statistically significantly higher in a 2.0◦C climate than a 1.5◦C climate in several regions. The model exhibits large differences in the Arctic which is ice-free with a frequency of 1 in 3 years in the 2.0◦C scenario, and only 1 in 40 years in the 1.5◦C scenario."

I take issue with the direction of argument, which is somewhat implicit in this paper. The paper makes me wonder what are the motivations. It is perhaps too broad to raise this here, but given the upcoming IPCC Special Report on Global Warming of 1.5◦C, are we as a community in charge of concluding urgently that there are discernable differences in impacts between 1.5 and 2◦C warming levels? The reason why I am raising this is that my overall impression of the results is drawn more toward the similarities. Visual inspection of the series of results certainly shows that there are significant (but not drastic, except for the sea ice (Fig. 1)) differences for various metrics (e.g. extreme precipitation (Fig. 10)) at the global mean level. But when it comes to regional and grid levels, differences are generally obscured by spatial and temporal variability as indicated by overlapping uncertainty ranges (just like any other global climate projections). In other words, similarities are more dominant than differences in my eyes. If there were multiple models performing the simulations, regional differences could be even less tantalizing. As a suggestion, I would think it is worth pointing out the similarities, not just the differences, at the abstract level. If the authors wish to bring forward only the differences, I would suggest that the basis of judgement be clarified to substantiate the claim.

Thanks for this point, which is well taken. We have weakened the language of the abstract as follows:

"precipitation intensity is statistically significantly higher ... in some specific regions (but not all). " and

"Significance of impact differences with respect to multi-model variability is not assessed."

We have also added caveats to our concluding comments as follows:

"Irrespective of feasibility, these simulations indicate that a relaxation of ambition from the 1.5C to the 2C level would result in significantly greater impacts in some regions, at least compared with internal variability in CESM. Further study should consider these results in a multi-model context, using HAPPI and pattern scaling work together with these coupled single model experiments to produce a comprehensive assessment of avoided impacts in high mitigation scenarios."

2) In my view, comparisons between 1.5degNE and 1.5degOS results are worthy of more discussion especially in the final section of the paper because it informs what the overshoot means in the context of 1.5◦C stabilization. It is unclear how the Paris Agreement would deal with an overshoot from the Agreement text. But, given the closing door for the 1.5◦C target as pointed out in this paper (page 15, line 5), possibilities of overshooting the target before achieving it are ever more relevant. As far as I am aware, implications of overshoot in the context of 1.5◦C target are not specifically analyzed in previous studies (e.g. (Rogelj et al. 2015)). I think a more dedicated discussion on the comparison between 1.5degNE and 1.5degOS results would thus be useful.

We've added the following to the Conclusions:

"Our study considered two mechanisms to achieve 1.5C, one which stabilizes by the mid 21st century, while the other overshoots reaching 1.7C in 2050 and stabilizes at 1.5C by 2100. Although the focus of the impact studies considered here have compared the equilibrium states at 1.5 and 2C, our scenarios allow a consideration of additional impacts which the overshoot would imply. In 2050, an additional 10 percent of global land area would be expected to exceed historical summer temperature records in the 1.5C overshoot, compared with the 1.5C stabilization case - although differences are not significant at the gridcell level. Our results do not suggest significant differences in sea level rise between the 1.5C overshoot case and the stabilization case and ice-free Arctic summers are simulated to be rare in both scenarios. Our analysis not suggest any evidence of long term climatic difference post-2100 of the overshoot relative to the stabilization case."

3) Fig 1 shows that significantly negative CO2 emissions (about -2 GtC/yr in average) for more than 50 years (1.5degNE case) do not lead to a decline in the global-mean temperature. It is a removal of roughly 100 GtC from the atmosphere. I think this appears at odd with the rule of thumb that the stabilization level is determined by the cumulative CO2 emissions (Allen et al. 2009). Is there any explanation or perhaps some references that help clarify this temperature response?

We're working on a paper to talk about this exact issue. But in short, we don't think that the Cumulative emissions rule of thumb is useful in a highly negative scenario. To show this convincingly requires a large ensemble of models with a range of carbon cycle responses - which we're in the process of performing.

4) While the carbon in the land surface (as C sub l) is shown in Fig A1, it does not seem to be the case from the text that the land carbon cycle itself is explicitly modeled. Only the climate-land carbon cycle feedback is provided without being linked to the land carbon mass (Equation (A2)).

Furthermore, in many simple climate models, CO2 fertilization effect is modeled as a logarithmic function of the fractional increase of atmospheric CO2 concentration from preindustrial level (e.g. see equation (2.1.50) in page 28 of (Tanaka et al. 2007)). On the other hand, Equation

(A2) indicates that CO2 fertilization effect is not a function of atmospheric CO2 concentration. These points need to be clarified because applicable ranges of this model may be limited to low scenarios because of the treatment of carbon cycle-related feedbacks.

It is correct that the land carbon cycle pool does not scale the carbon cycle feedback in this version of the model, but it does include a simple linear representation of CO2 fertilization, following Friedingstein 2003 (but as a prognostic model, rather than diagnostic). The ocean carbon model is simple, temperature dependent diffusive (i.e. not using the Friedingstein formulation. We add this caveat.

Note that the land carbon cycle feedback is not a function of the land carbon pool in this version, but is modeled using the parameters of \cite{friedlingstein2003positive}, where land carbon uptake is governed linearly by atmospheric CO2 content and temperature.

5) The paper says in page 3 "Our main design choice was to minimize the number of its degrees of freedom to allow for fast calibration to reproduce the global mean trajectory of any given GCM." But when I look at the number of parameters, especially those for CH4 and N2O, I must say it is not really a model of minimal complexity. As some of the co-authors are aware, I developed a simple climate model (Tanaka et al. 2007; Tanaka et al. 2009), which I consider simple but not minimal at all. Even my model has less tunable parameters for CH4 and N2O (Table 3.2 of (Tanaka et al. 2007)). But this is just a naming issue, not a scientific one.

The point is well taken. The non-CO2 portion of the model is based on a prior study, and we agree is not maximally simple. We have changed the sentence to simply read:

"We have provided a simple multi-gas climate model to perform this emulation,"

Nevertheless, I do not understand some of the parameters in Table B1. For instance, the present-day growth rates for CH4 and N2O (ppb/a) and the present-day concentration of N2O should be model outputs, rather than model parameters because it is stated in page 17 lines 10-11: "The inputs to MiCES are global total emissions of greenhouse gas emissions (CO2, CH4, N2O, CFCs, HCFCs, CO)." This requires a clarification.

The CH4 and N2O models are from Prather (2012), which allows for bias correction in present day growth rates. We've added the following to clarify this:

"The source code for MiCES is included in the supplementary material of this paper. Non-CO$_2$ forcings $F(t)$ are calculated using the atmospheric chemistry model defined and published in \cite{prather2012reactive}, which calculates the lifetimes and radiative forcings of non-CO$_2$ atmospheric components (CH$_4$, N$_2$O, HCFCs, CFCs), the model includes some bias correction for present day concentrations and growth rates. "

Prather, M. J., Holmes, C. D., and Hsu, J.: Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry, Geophysical Research Letters, 39, 2012.

Technical comments:

Appendix A The notation for the conversion factor between ocean carbon content in Pg and ocean carbon concentration is not consistent. It is rho in some places but rho sub o in other places.

Fixed

Page 15: Line 25 The sentence is unfinished.

Fixed

Page 15: Equation (A1) One of the brackets is not closed.

Fixed

Page 16: Line 18 Perhaps "due to" instead of "due"?

References Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M, Meinshausen N (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458 (7242):1163-1166. doi:10.1038/nature08019 Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V, Riahi K (2015) Energy system transformations for limiting end-of-century warming to below 1.5 [deg]C. C4 Nature Clim Change 5 (6):519-527.

doi:10.1038/nclimate2572 Tanaka K, Kriegler E, Bruckner T, Hooss G, Knorr W, Raddatz T (2007) Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2) – description of the forward and inverse modes. Reports on Earth System Science, vol 40. Max Planck Institute for Meteorology, Hamburg Tanaka K, Raddatz T, O'Neill BC, Reick CH (2009) Insufficient forcing uncertainty underestimates the risk of high climate sensitivity. Geophys Res Lett 36 (16):L16709. doi:10.1029/2009gl039642 Interactive comment on Earth Syst. Dynam. Discuss., doi:10.5194/esd-2017-42, 2017. C5

List of substantial changes

- Abstract revised and further caveats added on scope of paper with respect to other literature on 2 degree and 1.5 degree targets.
- Further citations added to introduction
- Statements of socio-economic plausibility have been caveated.
- Expanded discussion of the benefits of the HAPPI protocol
- Added discussion of the suitability and performance of CESM1-CAM5 in terms of the variables considered in the paper.
- Added discussion on the choices of non-CO2 forcers in the emissions trajectories
- Added caveats on the (untested) long term evolution of the scenarios in the fully coupled model.
- Added discussion on the use of real-world temperature records in FIgure 3, rather than model historical generated records
- Removed 3 paragraphs from conclusions, so results are no longer repeated from the previous section.
- Reworded conclusions and added paragraph to note that for some regions, especially at the point level, there are no significant differences between 2 and 1.5 degree climates.
- Reworded conclusions to illustrate relative benefits of other approaches (especially the HAPPI protocol).
- Clarified land carbon feedback in appendix A
- Clarified use of bias correction in N20 and CH4 models
- Added calibrated model parameter column to table B1

Community Climate Simulations to assess avoided impacts in 1.5°C and 2°C futures

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Abstract. The Paris Agreement of December 2015 stated a goal to pursue efforts to keep global temperatures below 1.5°C above pre-industrial levels and well below 2°C. The IPCC was charged with assessing climate impacts at these temperature levels, but fully coupled equilibrium climate simulations do not currently exist to inform such assessments. In this study, we produce a set of scenarios using a simple model designed to achieve long term 1.5°C and 2°C temperatures in a stable

5 climate. These scenarios are then used to produce century scale ensemble simulations using the Community Earth System Model, providing impact-relevant long term climate data for stabilization pathways at 1.5°C and 2°C levels and an overshoot 1.5°C case, which are realized (for the 21st century) in the coupled model and are freely available to the community. Here we describe the design of the simulations and ~~key aspects~~ a brief overview of their impact-relevant climate response. Exceedance of historical record temperature occurs with 60 percent greater frequency in the 2°C climate than in a 1.5°C climate aggregated

10 globally, and with twice the frequency in equatorial and arid regions. Extreme precipitation intensity is statistically significantly higher in a 2.0°C climate than a 1.5°C climate in ~~several regions~~ some specific regions (but not all). The model exhibits large differences in the Arctic which is ice-free with a frequency of 1 in 3 years in the 2.0°C scenario, and ~~only~~ 1 in 40 years in the 1.5°C scenario. Significance of impact differences with respect to multi-model variability is not assessed.

1 Introduction

15 The Paris Agreement of 2015 changed the landscape of climate negotiations by framing the debate on future policy in terms of temperature targets which would require substantial globally coherent emissions reductions in the near future (Sanderson et al., 2016). Mitigation efforts required to achieve a likely probability of staying below the upper limit (2°C) exceed those combined efforts currently pledged by the countries ~~(Rogelj et al., 2016)~~(Rogelj et al., 2016; Fawcett et al., 2015). The Representative Concentration Pathways (RCPs) for the Coupled Model Intercomparison Project (CMIP) which informed the 5th Assessment

Report of the IPCC (AR5, Pachauri et al. 2014) diverged in 2005. Since then, the world's greenhouse gas emissions have been closer to the highest emissions pathway (RCP8.5) than any other, even accounting for a recent slowdown in emissions growth (Van Vuuren et al., 2011; Quéré et al., 2016) (aerosol evolution differs relatively much less between RCPs, which are so far broadly in line with observations Klimont et al. (2013)). Current policy (if enacted) would result in a middle-of-the-

road emissions pathway resulting in a 2.5-4°C warming level (Kitous and Keramidas, 2015). For the lower Paris Agreement temperature goal of 1.5°C, coherent efforts beginning in 2017 would require both emissions rate reductions of at least 5% per year (Sanderson et al., 2016) and ~~a~~ likely requiring substantial commitment to negative ~~emissions levels which would lie on the verge of economic and physical plausibility~~ net carbon emission technologies in the 2nd half of the century (Smith et al., 2016).

Aside from the feasibility or costs of any scenario, it is important to quantify in which ways a climate of 1.5°C above pre-industrial would be different from 2°C, for others to assess whether avoided impacts could justify the costs of the more stringent mitigation. The study of a 1.5°C world, however, is complicated by a number of factors. The lower temperature goal of 1.5°C exhibits less warming than would likely be achieved in the most aggressive mitigation Representative Concentration Pathway (RCP2.6) considered in the 5th Assessment Report of the IPCC (Van Vuuren et al., 2011). Although some individ-

ual models exhibited less than 1.5°C warming in this scenario ~~, there is no comprehensive dataset of Earth System Model (ESM)simulations at this mitigation level~~(median warming was 1,6C), CESM warming in this scenario is closer to 2 degrees (Meehl et al., 2013). Furthermore, no individual fully-coupled model has performed a large ensemble of RCP2.6 which fully samples internal variability at a low forcing level.

Second, the RCP2.6 scenario diverged from historical emissions pathways in 2005, and the lack of significant global mitigation action since that point means that future mitigation action required to achieve 1.5°C are now radically different from what would have been necessary in 2005 (Sanderson et al., 2016; Stocker, 2013). As such, the transient climate evolution of RCP2.6 could noticeably differ from a 2.0°C scenario where mitigation action begins in 2017.

Numerous strategies have been proposed for addressing this discrepancy of scenarios, comprehensively listed in James et al. (2017). Pattern scaling techniques, which assume that patterns of temperature and precipitation change can be scaled by global mean temperatures ~~or by finding time periods from other scenarios where the global mean temperature is equivalent to the target level,~~ can produce quite skillful reproductions of mean climate shifts within 21st century projections (Tebaldi and Arblaster, 2014). However, climate impacts are often functions of the extremes of the distribution, which may not scale in a simple fashion with global mean temperature, especially for precipitation (Pendergrass and Hartmann, 2014). Another approach is to 'time-shift', by taking periods in existing simulations where global mean temperatures equal the warming level of interest. Schleussner et al. (2016) used this approach to compare impacts at 1.5°C and 2°C. However, time-shifting approaches can be complicated when using a period of transient change still exhibiting a strong trend, because the pattern of warming may differ from the equilibrium state (Herger et al., 2015).

An international modelling effort, "Half a degree Additional warming, ~~Projections, Prognosis and~~ Prognosis and Projected Impacts" (HAPPI, ~~Mitchell et al. 2017~~Mitchell et al. 2017, 2016) has been proposed to fill the gap for simulations to inform the planned IPCC special report on 1.5°C. This effort ~~will use~~uses prescribed sea surface temperatures (SSTs) which are consistent

with a scaled CMIP5-mean estimate of predicted equilibrium 1.5°C and 2.0°C climates. This approach has advantages; it is computationally cheap so allows for huge ensembles to be run providing samples of extremes and rapidly deployable for a large number of modeling groups and can provide a multi-model assessment of impacts at the two temperature levels referred to in the Paris Agreement. However, there are potential limitations to the approach. Because ~~all~~ simulations in HAPPI will

5 have ~~the same SST pattern evolution (with a constant pattern offset to represent warming)~~one of a finite set of predefined SST patterns, the estimate of significance of the difference in climate states will not ~~include any~~ completely sample ocean-driven variability. In addition, the use of a single 10 year evolution in SSTs will produce a narrow sample of modes of internal climate variability, but a comprehensive assessment would require a thorough sampling of coupled ocean-atmosphere variability.

Here we present an ensemble of transient coupled climate simulations with the Community Earth System Model (CESM,version

10 1 Hurrell et al. 2013) which achieve the 2°C and 1.5°C goals in line with the Paris targets. These simulations provide a test case for conclusions inferred from other methodologies using the same model (such as pattern scaling, or HAPPI). In this paper, we first document a simple climate model emulator which is able to predict the transient evolution of global mean temperature, and using this emulator we produce concentration scenarios which result in stable 2°C and 1.5°C scenarios in CESM for the 21st century, with a third scenario describing a brief overshoot which returns to 1.5°C by 2100. We then briefly assess the

15 broad climatic features of these two scenarios, including how they differ in both mean state and in the frequency of extremes which might relate most strongly to societal impacts. We aim in this study to provide a ~~broad~~ short overview of differences in impact-relevant climate ~~variables, while~~ variable (a full list of available climate variables is available online (NCAR, 2017)), with the hope that further studies will focus in more detail on specific processes, regions or societal impacts.

2 Methods

2.1 Emulation

The simulations in this study are produced to inform assessment of impacts at 1.5°C or 2°C above pre-industrial levels, and so the end goal is to produce simulations which equilibrate at those temperature targets. Other studies (Sanderson et al., 2016; Meinshausen et al., 2008; Rogelj et al., 2015) have posed the question in terms of devising scenarios which would produce a given temperature target with a certain likelihood (i.e., a certain frequency among a set of GCMs that respond to forcing

25 differently from one another).

But the Paris Agreement requested climate information from IPCC on specific temperature levels: 1.5 and 2°C above pre-industrial levels. In a simple model where variability is limited, this can be achieved by interactively adjusting emissions as a function of past warming (Zickfeld et al., 2009). But in the presence of large internal variability, and in order to produce a GCM simulation which achieves these goals, we need to perform a reverse calibration: to produce an emission scenario which would

30 result in a specific temperature outcome. Because of the computational expense of running a GCM and the natural variability obscuring the forced signal, this inverse problem can alternatively be solved by employing an emulator which can predict the global mean concentration and temperature trajectory for a given emissions scenario, and ~~iteratively adjusting~~ iterating the emissions scenario parameters such that the desired stable temperature level is achieved.

Some simple climate models already exist in the literature, but we chose to design our emulator as a community project, and as such to have it be open-source and publicly available for further community research in line with the climate model and the climate data that we produce. ~~Our main design choice was to minimize the number of its degrees of freedom to allow for fast calibration to reproduce the global mean trajectory of any given GCM. The result is a simple climate model~~We have provided a simple multi-gas climate model to perform this emulation, the Minimal Complexity Earth Simulator (MiCES, 2016) written in MATLAB and capable of emulating the forced global mean temperature and multi-gas concentration evolution of a more complex model with a minimal set of free parameters. The emulator design and calibration process is discussed at length in the supplementary material section A and B, and the code is provided with this manuscript. For the purposes of this study, the model's parameters were calibrated so that MiCES emulates the Community Earth System Model (version 1.1.1, CESM1-CAM5).

CESM1-CAM5 is a single climate model, and like any model is subject to biases in both its present day simulations and in future projections. As such, the ensemble spread in this study does not represent true uncertainty in future projections, rather a single estimate of climate evolution. However, multi-model assessments in the past have indicated that CESM1-CAM5 is one of the better performing models in the CMIP5 archive. Sanderson et al. (2015a) found this model to be the best performing in a selection of mean state metrics, and Flato (2013), Figure 9.37 shows that the model has one of the better simulations of extreme temperature and precipitation metrics in the CMIP5 archive. CESM also has a higher climate sensitivity (4.0K, Gettelman et al. (2012)) than the CMIP5 mean (3.6K, Webb et al. (2013)), and so emissions need to be reduced faster than average for this model in order to meet any given temperature target.

2.2 Scenarios

Once the emulator has been calibrated, we design emissions scenarios which are predicted to produce stable 2°C and 1.5°C climates in CESM1-CAM5 (as in Figure 1(b)). We use the methodology established in Sanderson et al. (2016) to define idealized emissions pathways which produce a smooth emissions trajectory from historical trends into a period of emissions reduction, a net-negative emissions phase (where net-negative emissions are constrained to not exceed levels seen in the SSP database(IIASA, 2016)) and a long-term relaxation to levels compatible with a stable global mean temperature. Scenario parameters are adjusted to produce multi-gas emissions scenarios which achieve 3 outcomes relevant to the 1.5 and 2°C goals:

1.5°C 'never-exceed' (*1.5degNE*) This scenario is designed such that expected multi-year global mean temperature never exceed 1.5°C above pre-industrial levels in CESM-CAM5 (where pre-industrial is taken as the 1850-1920 mean ~~) in CESM1-CAM5~~ averaging over the period before the model initial conditions were branched, and using a 70 year rather than 30 or 50 year mean because there is only one ensemble member for this period). Emissions follow RCP8.5 until 2017, after which carbon emissions rapidly decline reaching 50 percent of 2017 levels ~~in a decade~~ by 2027. Combined fossil fuel and land use carbon emissions reach net-zero (carbon neutral) in 2038. CO2 emissions reach a peak net negative level in 2065, with a net flux of -1.8GtC/yr. After this, negative emissions fluxes are reduced, reaching -0.9GtC/yr

by 2100 (Figure 1(a)). The magnitude of negative emissions continues to decline throughout the 22nd century, reaching -0.3GtC/yr by 2200 (Figure C1(a)).

1.5°C 'overshoot' (*1.5degOS*) This scenario is designed such that expected global mean temperature briefly overshoot before returning to 1.5°C by 2100 in CESM1-CAM5. Emissions follow RCP8.5 until 2017, after which emissions decline slightly less rapidly than in *1.5degNE*, such that emissions are halved from 2017 levels by 2032. In this scenario, combined fossil fuel and land use carbon emissions reach net-zero in 2046. The overshoot requires a larger late century negative emissions commitment, with a peak net negative flux of -4.0GtC/yr in 2080. After this, negative emissions fluxes are rapidly reduced, reaching -1.0GtC/yr by 2100, but then remain slightly negative throughout the 22nd century, reaching -0.5GtC/yr by 2200.

2.0°C (*2.0degNE*) This scenario is designed such that expected multi-year global mean temperature never exceed 2°C above pre-industrial levels. Emissions follow RCP8.5 until 2017, after which emissions decline significantly less rapidly than in *1.5degNE*, such that emissions are halved from 2017 levels by 2042. In this scenario, combined fossil fuel and land use carbon emissions reach net-zero in 2078. The scenario still requires a negative emissions phase but much smaller than the other two scenarios, with a peak net negative flux of -0.8GtC/yr in 2120. After this, negative emissions fluxes are slowly reduced, reaching -0.5GtC/yr by 2200.

Using the calibrated MiCES model, the three emissions scenarios are used to produce concentration pathways which can be used in a CESM1-CAM5 simulation. We use CESM1.1.1 with the Community Atmosphere Model (version 5, CAM5) at finite volume 1 degree resolution and the Parallel Ocean Program version 2 at 1 degree resolution, to be consistent with the previous large ensemble studies using RCP8.5 (Kay et al., 2015) and RCP4.5 (Sanderson et al., 2015b). In each of the low emission scenarios in this paper, only well-mixed greenhouse gas concentration are changed between scenarios, all other forcings (land use, aerosol emissions, and ozone) follow RCP8.5 throughout the 21st century as in ~~(Kay et al., 2015)~~Kay et al. (2015)). A set of 10 simulations are conducted for scenarios *1.5degNE*, and *2.0degNE*, branching from the corresponding historical simulations of Kay et al. (2015) in 2006, running through 2100. A set of 5 simulations are conducted for scenario *1.5degOS*. As such, for each scenario the CESM ensemble samples uncertainty due to internally generated variability conditional on an assumed scenario and model design.

It should be noted that the assumptions of RCP8.5 trajectories for non greenhouse gas forcers is implemented for practical reasons to make the present study tractable. However, a fully self consistent 1.5 degree scenario from an Integrated Assessment Model (IAM) would likely have slight differences. Sulfur emissions are lower in RCP2.6 than in RCP8.5, and maybe lower still in a 1.5 degree scenario (although there large differences in sulfur emissions between individual IAMs with the same policy constraints). However, any given global temperature target could be achieved with different combinations of aerosol forcing and greenhouse gas forcing, but with regional differences in temperature and precipitation (Xu et al., 2015; Pendergrass et al., 2015), and changes in land use necessary for large scale biofuel production would change surface albedo (Caiazzo et al., 2014). An IAM could also have additional degrees of freedom, with the capacity to reduce N2O and CFC emissions below the RCP2.6 minimum levels.
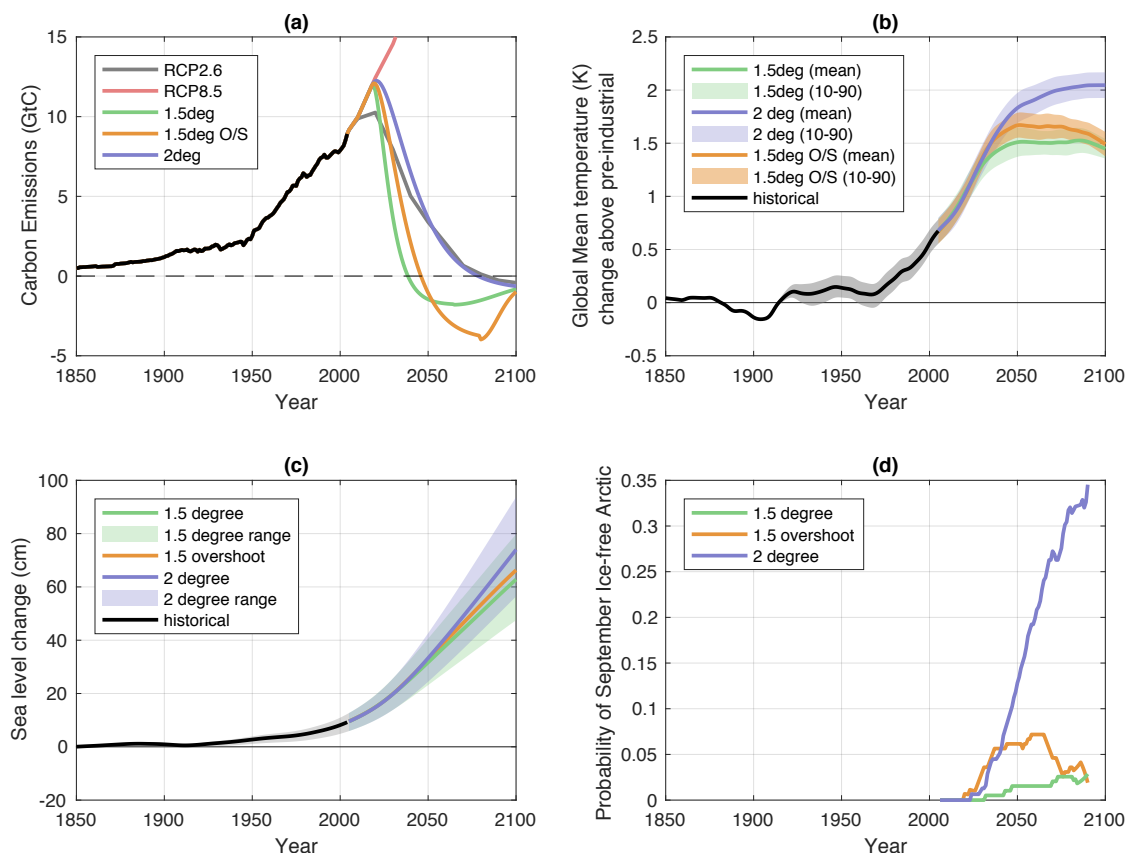
Figure 1. Results from the CESM low emissions scenarios. (a) shows the total carbon emissions trajectory (fossil fuel, cement and land use) used to drive the model simulations. (b) shows the range of annual global mean temperatures changes for the three scenarios, 1.5°C never-exceed (green), 1.5°C overshoot (orange) and 2.0°C (purple). Lines are the most likely values, while the shaded areas are the 10-90 percent expected range in the CESM ensemble. (c) shows the corresponding sea level rise using global mean temperature relationships from ~~Horton et al. (2014)~~ Kopp et al. (2016) and (d) shows the annual likelihood derived from the CESM ensembles that the Arctic will be ice free in September (20 year running mean).

3.1   Global-scale mean changes

~~Figure 1(b) shows~~ Figures 1(a) and (b) show the CESM ensemble mean global mean temperature trajectory for the three scenarios, which broadly shows that the emulation process was able to correctly predict the expected ensemble mean temperature evolution for CESM (compare with Figure C1 in the Supplemental Material). The *1.5degNE* scenario ~~stabilizes in 2050 at~~

reaches 1.5°C above pre-industrial levels and then maintains this temperature until 2100. The *1.5degOS* scenario reaches a peak temperature in 2050 of 1.7° above pre-industrial before cooling to 1.5°C by 2100, and the *2.0degNE* scenario ~~stabilizes at~~ reaches slightly over 2.1°C ~~, reaching 2.1°C by 2090.~~ by 2100. Note that although these results suggest that the predicted emulation of stable temperatures in the emulator is validated for the evolution of global temperatures in the coupled system in the 21st century, there may be ocean dynamical processes at longer timescales in the coupled model which are not represented in the emulator's thermodynamic ocean. As such, we have not tested the stability of global temperatures at multi-century timescales with these emissions pathways.

We can consider what these global temperature trajectories mean for ~~large~~ global scale climate change. Figure 1(c) shows the expected range of possible sea level rise over the 21st century for the three scenarios. The CESM1-CAM5 model can only simulate one component of future sea level rise, that of thermal expansion. Notably it does not include ice sheet melt, so in order to show the range of possible sea level trajectories we use ~~the semi-empirical formulation of Rahmstorf (2007), combined with uncertainty ranges from Horton et al. (2014)~~ formulation of Kopp et al. (2016), using the 10th and 90th percentiles of the posterior parameter distributions for the semi-empirical model fitted to Mann et al. (2009) data to define range. The inherent uncertainty in the sea level response at a given emissions level is greater than the difference between the scenarios considered here. Using these estimates, the *1.5degNE* scenario would result in ~~35–65cm~~ 50–80cm of sea level rise by the end of the century, while the *2.0degNE* scenario would result in ~~45–75cm~~ 60–90cm of rise. On a longer timescale, these two scenarios will further diverge. Schaeffer et al. (2012) found that by 2300, the most likely estimate from a 1.5°C stable temperature would be a stable 150cm of sea level rise, but a 2°C stable temperature would result in 270cm and still increasing in 2300.

In our simulations, we find one of the most dramatic divergences between the 1.5 and 2°C simulations comes at high latitudes. This is illustrated in Figure 1(d), which shows the annual likelihood of ice-free Arctic September conditions in the three scenarios. Ice-free is defined as a condition where September average Arctic sea ice area is less than 1 million square kilometers. Our analysis counts the number of ice-free September years in a 20 year moving window in each 10 member ensemble to assess the probability of ice-free conditions as a function of time. We find that in *1.5degNE*, ice-free conditions remain rare, a 1 in 40 year occurrence by the end of the century. In *1.5degOS*, the likelihood of ice-free conditions peaks in 2060, where there is a 1 in 15 chance of ice-free conditions - but this likelihood then declines such that the likelihood is similar to *1.5degNE* by 2100. However, the *2.0degNE* shows significantly greater chances of ice-free conditions; by 2100, 1 in 3 years are simulated as ice-free with likelihoods still increasing at the end of the century. It is notable that the difference between the 2.0°C and 1.5°C scenarios largely arises due to the reduced summer survival of multi-year ice in *2.0degNE*, with only 8 percent of annual mean sea-ice in 2100 in *2.0degNE* that is older than one year, compared with 15–20 percent in the *1.5degNE* and *1.5degOS* (and 35 percent in 2005 - see Figure C2 in the Supplemental Material). Compared to recent statistical analysis of CMIP5 RCP8.5 and RCP4.5 simulations by Screen and Williamson (2017), our results show a higher likelihood of ice-free conditions for *1.5degOS*. The occurrence of ice-free conditions in a 1.5°C world was deemed "exceptionally unlikely" in Screen and Williamson (2017), but occurs in three out of ten *1.5degOS* ensemble members at least once before the end of the 21st century. All of these occur after the first crossing of the 1.5°C threshold defined by Screen and Williamson (2017), illustrating the importance of dedicated ~~stabilisation~~ stabilization simulations for these targets in order to assess the probability

7

of extreme-value climate events such as an ice-free Arctic in the presence of large internal variability. And while it should be noted that ~~there is~~ large diversity in the rate of loss of Arctic sea ice ~~is lost more rapidly with warming in CESM than in some~~ ~~in~~ CMIP5 models (Mahlstein and Knutti, 2012), ~~it is lost less rapidly~~ the CESM sea-ice loss per degree of global warming ~~than~~ ~~in observations~~ to date is less than that which has been observed (Rosenblum and Eisenman, 2017).

5 **3.2 Regional Differences**
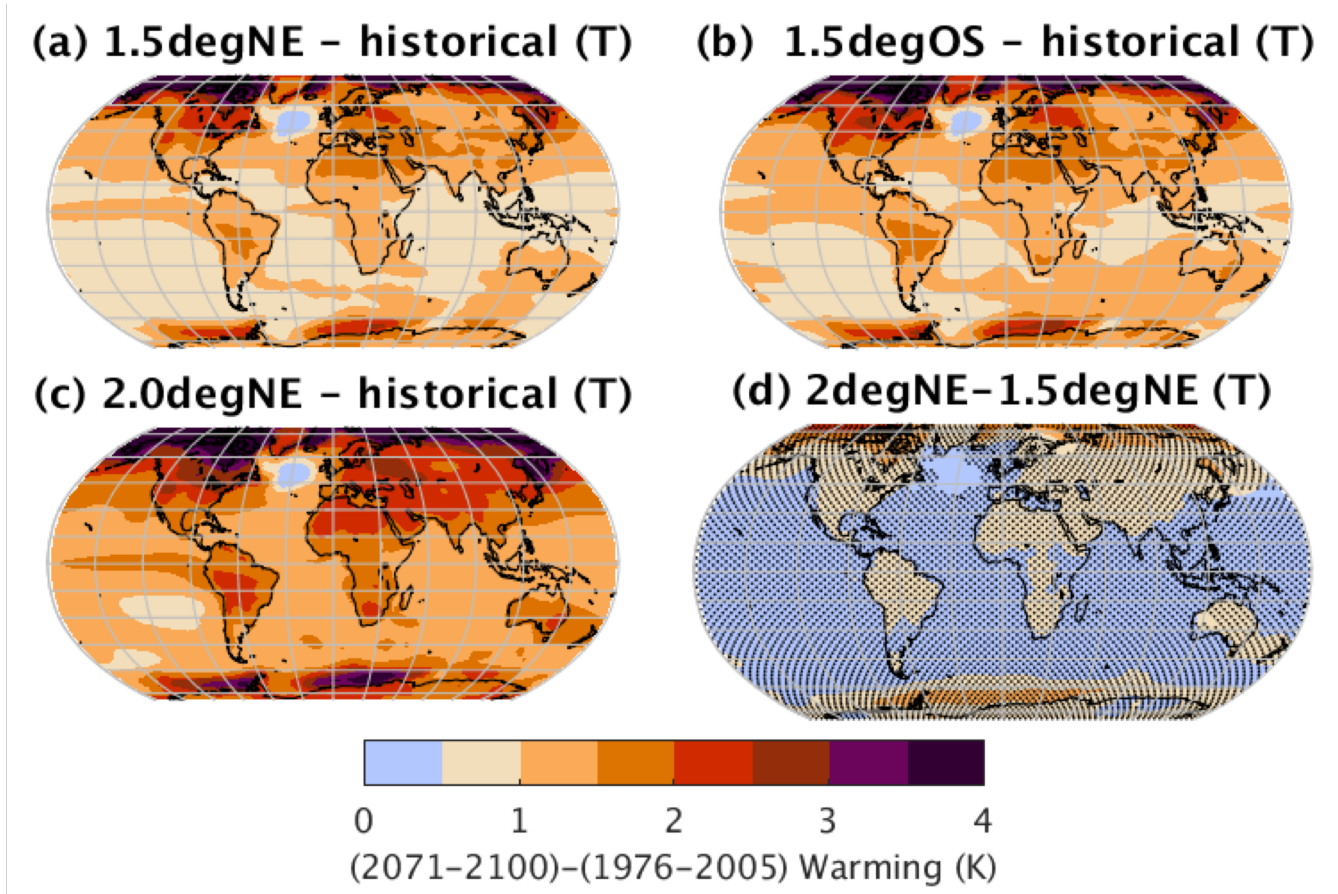
Figure 2. Maps showing ensemble mean 2071-2100 temperature changes relative to 1976-2005 historical conditions in *1.5degNE* (a), *1.5degOS* (b), *2.0degNE* (c) scenarios. ~~Subplots~~ Subplot (d) ~~show~~ shows the difference between mean 2080-2100 conditions in *1.5degNE* and *2.0degNE*, where significant regions are stippled. Significance is defined as a pixel in which the difference between the mean of the *2.0degNE* and *1.5degNE* ensembles exceeds the standard deviation of 2080-2100 values in the *2.0degNE* ensemble.

The regional differences in mean climate between the two scenarios is illustrated in Figure 2. Spatial patterns of warming remain similar in all simulations, with land regions, especially in high latitudes and desert regions, warming more than average. It is notable that for a given global mean temperature target, land temperature warming will be greater: the ensemble mean

2071-2100 land surface temperature is 1.8°C warmer than 1851-1880 in *1.5degNE*, and 2.4°C warmer in *2.0degNE*. At high latitudes, Greenland, for example has an ensemble mean warming of 2.3°C in *1.5degNE* and 3.1°C in *2.0degNE*.

In almost all regions of the globe, the difference in 30 year mean warming for 2071-2100 between *2.0degNE* and *1.5degNE* is statistically significant compared with intra-ensemble random variability (shown in Figure 2(d)). The differences in mean
5   temperature change between *1.5degNE* and *1.5degOS* are subtle, the latter showing more extensive ocean warming and slightly more warming over North America and Central Asia - but most regions do not show detectable differences between the two scenarios at the end of the 21st century (not shown).

3.3   Temperature Extremes

Human impacts such as mortality vary disproportionately with the upper tail of the distribution of temperature (Guo et al., 2014)(e.g.
10   Guo et al. (2014); Gasparrini et al. (2016)), hence it is of relevance to consider the frequency with which historical temperature extremes will be exceeded in the future. We consider this in a couple of ways, firstly by adapting the methodology of Lehner et al. (2016), which assesses the frequency with which records are exceeded in the future. Figure 3(a) shows the fraction of global land area which is simulated to exceed the observed 1976-2005 record summer temperature in any given year, for each of the three scenarios. By 2040, there is little separation between the scenarios - globally, about 50-60 percent of the global
15   land area exceeds historical temperatures in any given year. However, towards the end of the century, there is a significant difference. 45-55 percent of land area is simulated to exceed the historical record in *1.5degNE*, compared with 70-80 percent in *2.0degNE*. Observations are from Rohde et al. 2013, as in Lehner et al. (2016).

It is notable that some records in Figure 3 are exceeded before 2005 because the historical evolution of the CESM ensemble differs from the real-world historical evolution and there could potentially be some model regional model biases. However, the
20   behaviour of CESM in the period 2006-2016 is in within the range of model record exceedance (both globally and in each of the regions considered), giving confidence that regional biases are not strongly influencing this metric. Note that if the records were taken from the historical simulations of CESM itself for consistency, almost all historical records would be a higher temperature because the effective sample period in a 10 member ensemble is 300 years for the period 1976-2005, which causes a 30 percent reduction in end of 21st century record exceedance (see discussion with reviewer M.Sarofim for further details).
25   Assessed at a regional level, there is greater ensemble spread in the fraction of land area which exceeds the historical record summer temperature (as would be expected from the scale/variability relationships discussed in Deser et al. 2012). However, in the US and in Europe, roughly double the fraction of land experiences historical record breaking summers in *2.0degNE* relative to *1.5degNE* by 2071-2100. Over Asia, the ratio of warming to natural variability is greater for all scenarios, so even the *1.5degNE* scenario is simulated to exceed historical records in 50-90 percent of the region each year (compared with 80-100
30   percent in *2.0degNE*). It is noteworthy that globally, as well as for the individual regions, the model range encompasses the values derived from observations.

We can consider the spatial distribution of extreme temperature events by following the methodology of Tebaldi and Wehner (2016), which fits a Generalized Extreme Value (GEV) distribution to the upper tail of 3-day temperature averages for both the historical period (1976-2005 in this case) and the future (2071-2100) under different scenarios. The GEV is used to assess,
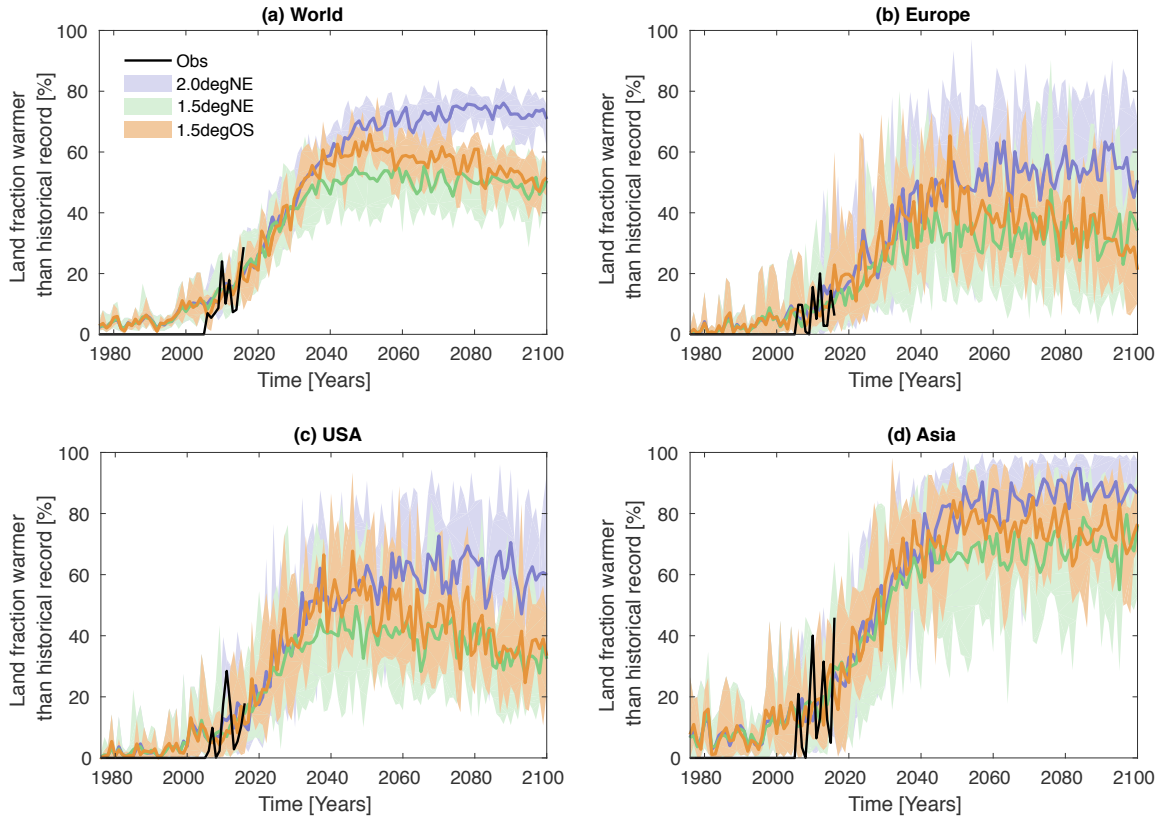
Figure 3. Fraction of land in which the observed historical summer temperature record defined during the period 1976-2005 is broken in any given year. Summer is defined for each grid cell as the climatologically warmest 3-month period. (a) is the fraction of global land area, while (b-d) refer to the fraction of a specific region. The solid central line is the ensemble mean for each scenario, and the shaded areas represent the full ensemble range.

historically, the 3 day average temperature which would be considered a 1 in 20 year event. Figure 5 shows the increase in the expected temperature for a 1 in 20 year 3-day warm event in each of the scenarios. When compared with Figure 2, it becomes clear that some regions experience a greater increase in extreme temperatures than the mean temperature increase ˍ (in *2.0degNE*, 9% of the land area experiences a warming of extremes more than 50% faster than the mean, while less than 1%

5 experiences a warming 50% slower than the mean).

For example, comparing Figure 2(c) and 5(a) - certain regions such as the northern USA/Southern Canada, northern Europe, Eastern China and western Brazil/Bolivia which experience increases in extreme 3-day temperatures of about 4K - about twice the mean temperature increase. Comparing *1.5degNE* and *2.0degNE*, most regions globally show a difference of less than 1°C between the scenarios - with the exception of Canada and Northern Europe which show differences of 1-2°C.
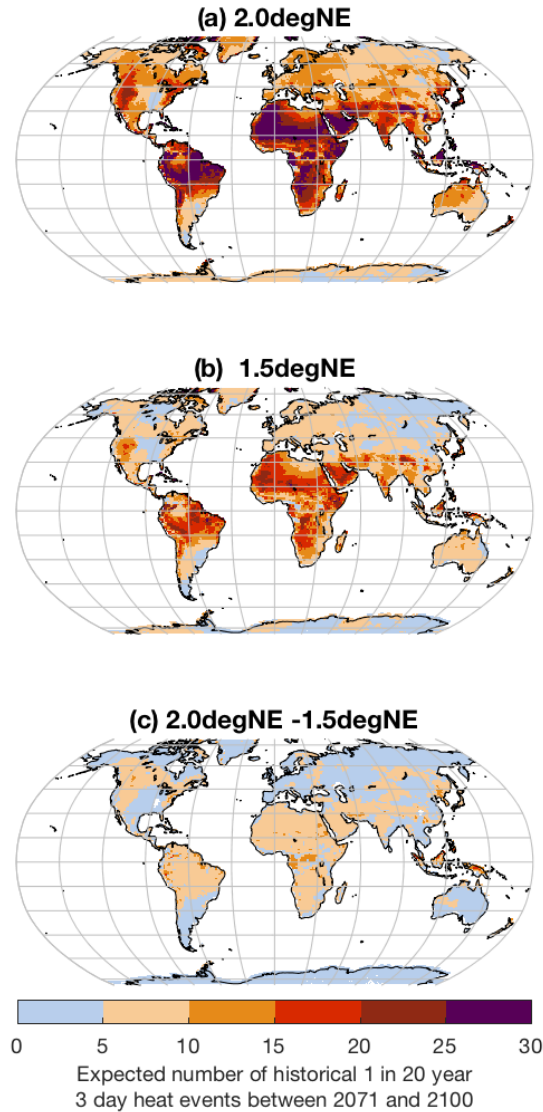
(a) 2.0degNE

(b) 1.5degNE

(c) 2.0degNE -1.5degNE

0	5	10	15	20	25	30

Expected number of historical 1 in 20 year
3 day heat events between 2071 and 2100

Figure 4. Maps showing the expected number of times that the ~~current~~ modeled historical 1 in 20 year 3-day warm event in the period 1976-2005 would be exceeded during the period 2071-2100 for (a) *1.5degNE*, (b) *2.0degNE* and (c) the difference between the number of events in each scenario. By definition, no change from historical climate would correspond to a value of 1.5 events per 30 years.

We can also consider the expected frequency of exceedence of historical 1 in 20 year 3-day warm event levels. Figure 4 shows the frequency with which these current temperature extremes would be exceeded in *2.0degNE* and *1.5degNE*. This metric shows the greatest increase in regions with a large ratio of mean change to ensemble variability. Because internal variability is greatest at high latitudes in this model (Kay et al., 2015) and indeed in most CMIP5 models (Mahlstein et al.,

11
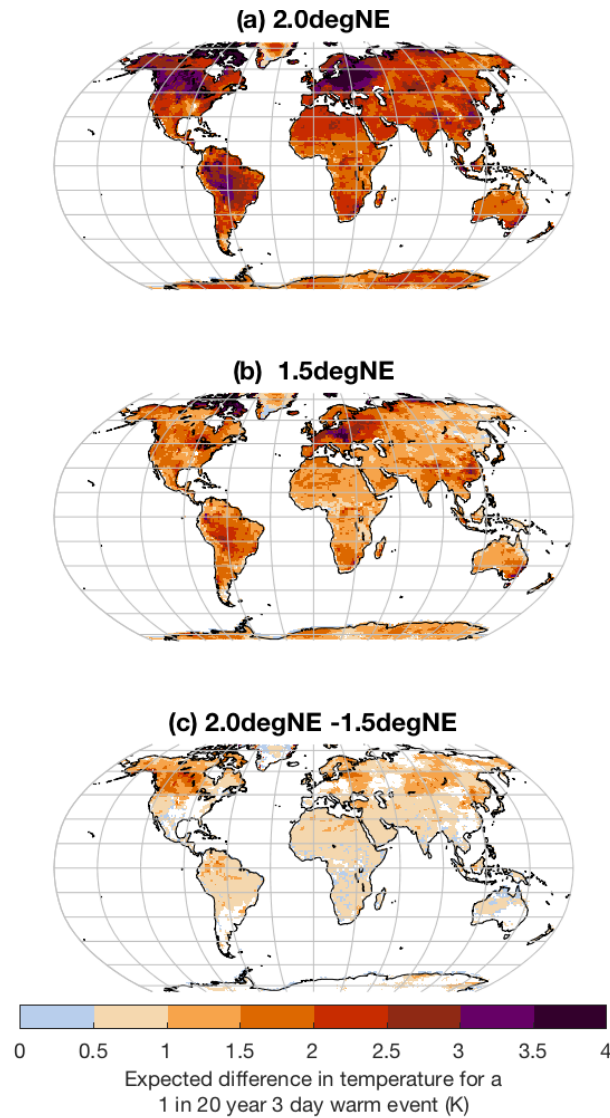
Figure 5. Maps showing the expected difference from 1976-2005 in temperature for a 1 in 20 year 3 day warm event for (a) *1.5degNE*, (b) *2.0degNE* and (c) the difference in temperature between each scenario.

2011), the greatest signal to noise is seen at lower latitudes (although the absolute magnitudec of warming is smaller). Central Africa, the Saudi Arabian peninsula, Brazil, Peru and to a lesser extent Western India and the Western USA all show significant increases in the frequency of expected exceedance of the current 1 in 20 year maximum 3-day temperature event. In *1.5degNE*, these regions are simulated to experience 10-20 such events between 2071 and 2100, while in *2.0degNE* exceedance would be

5   an annual event for most of the regions in question.

4 Precipitation changes

4.1 Mean

At the global level, there are statistically significant differences in precipitation between 1.5°C and 2°C climates. Global-mean precipitation increases by 3.3 % in *1.5degNE* but 4.5 % in *2.0degNE* from 1976-2005 to 2070-2100 (Figure 6(a); the difference between the two scenarios exceeds twice the standard deviation of the *2.0degNE*). Over land (Figure 6(b)), mean precipitation increases are slightly less than global mean increases in both cases: 2.8% for *1.5degNE* and 4.3% *2.0degNE* over 1976-2005 levels. At higher latitudes, mean increases are greater at 5.4 and 6.8%. The difference in the mean aggregated land-based precipitation in *1.5degNE* and *2.0degNE* is not significant by the end of the century (neither over all land, nor land north of 20°N).

Precipitation differences between the climate states are less significant at the grid point level (Figure 7). All simulations show increased precipitation in the tropics, decreased precipitation in the subtropics and increased precipitation at high latitudes. Very few land regions show a net decrease in precipitation, but there are some exceptions: the southwest US, Amazonia and Indonesia all suggest reductions in precipitation in *2.0degNE*. In most cases, local differences in precipitation between *1.5degNE* and *2.0degNE* are not statistically significant over land; only over the Arctic and Southern oceans are there significant differences (Figure 7(g)).

4.2 Water availability and aridity

Water availability is controlled by joint changes in precipitation minus combined evaporation and transpiration from the surface (hereafter P-E). Figure 7 also shows how P-E changes in the different scenarios. Notably, although very few land regions show a decrease in precipitation, most land regions in all scenarios show a net decrease in P-E by 2071-2100. However, very few regions show a significant difference between changes in *1.5degNE* and *2.0degNE* (exceptions being central Amazonia and the Mediterranean).

We can also consider *aridity*, the ratio of precipitation to potential evapotranspiration (PET, the evaporative demand of the atmosphere; Fu and Feng 2014; Lin et al. 2015). Regions where the ratio of P/PET is less than 0.65 are classified as 'dry land' as in Lin et al. (2015). In these simulations, the increase in dry land in a 2°C world is double that of a 1.5°C world: figure 8(a) shows that the global area of dry land increases by 1.25 million km^2 between 1976-2005 and 2071-2100 under *2.0degNE* while under *1.5degNE*, global aridity peaks in 2040, such that there is an increase of only 0.66 million km^2 by 2071-2100.

Although the difference in change in total arid area is significant, aggregating changes in aridity by region (Figure 8(b)) suggests that only some regions exhibit statistically significant differences in changes between 2 and 1.5°C climates. Notably both Europe and Southern Africa show large differences in the expected change in aridity by 2071-2100 in *2.0degNE* and *1.5degNE*. Comparing with Figure 7(h), in this is driven largely by Mediterranean regions in Europe and by eastern coast of South Africa and Namibia in Africa.

4.3 Extreme Precipitation

The changing intensity of extreme precipitation is an impact-relevant quantity for ecosystems (Knapp et al., 2008), disease transmission (Curriero et al., 2001) and infrastructure planning (Hossain et al., 2010). We consider the changing patterns of extreme precipitation both at the point level and regionally. Figure 9 shows that only some specific regions would expect large increases in extreme precipitation (quantified here as the annual 1 day maximum rainfall) - eastern Amazonia, Congo, Peru, central India and northern Canada are simulated to experience a 25-50 percent increase. Differences between the *2.0degNE* and *1.5degNE* are subtle by this metric, with very few regions showing significant differences at the grid point level.

However, when precipitation is aggregated over larger regions, significant differences in extreme behavior between scenarios can become apparent (Fischer and Knutti, 2015). This is illustrated in Figure 10, showing the aggregated relative frequency of events which exceed the historical 99th percentile of daily precipitation. Globally aggregated, there is a large and significant difference between the scenarios: a 7-8 percent increase in events above the historical 99th percentile of daily precipitation in *1.5degNE*, and a 13-15 percent increase in *2.0degNE*. When events are aggregated to the regional level, there are still significant differences in some regions between the frequency of events in *2.0degNE* and *1.5degNE*. High northern latitude regions show consistent separation (Alaska, N.Canada, Greenland, N.Asia), as does the Eastern USA, Eastern Africa, Eastern Asia.

In short, at the grid cell level, there is no significant difference in the likelihood of extreme precipitation events in a 2°C and 1.5°C climate. However, there are significant differences at the regionally and globally aggregated scales.

5   Conclusions and Discussion

In this study, we investigate whether there are significant differences between 1.5°C and 2.0°C of warming in the physical climate system that might have societal impacts. We present a climate model emulator that solves for a concentration pathway leading to a particular temperature target for a particular climate model. Using this emulator, we design three ensembles of coupled climate simulations with a single climate model, CESM, which produce stable equilibrium global mean temperature at 1.5°C and 2°C above pre-industrial levels, the first set of ~~such~~ coupled simulations to our knowledge.

We use these simulations to compare impacts at the two stabilization targets. The question of how substantial this difference in mean climate might be depends on both scale and variable. Mean temperatures are significantly different throughout the globe in a 1.5 and 2°C warmer climate, and various aspects of extreme temperature exposure are distinguishable, especially when aggregated over large areas. ~~We find that 70-80 percent of the global land surface is expected to experience summer temperatures in excess of the pre-2006 record level, every year in the 2°C scenario. Mitigation to~~ There are significant differences in exposure to events exceeding historical heatwaves in a 1.5 ~~°C reduces this land fraction to 45-55 percent. Exposure to historical 1 in 20 year 3-day heat waves is doubled for most tropical regions in the~~ and 2°C ~~world relative to 1.5°C. In central Africa and equatorial South America, this implies that in a 2°C~~ warmer world, historical-period 1 in 20 year 3-day heat waves would be annual events (and approximately biennial for the 1.5°C world). The warmest events also increase disproportionately to the mean in some regions, for example in the USA where mean warming is 1-2°C in a 2°C scenario, but 1 in 20 year 3-day events warm between 2-4°C scenario.

We find also that the difference between 1.5°C and 2°C spans a threshold for the persistence of summer sea-ice in the Arctic, such that ice-free Septembers in the Arctic remain rare in a 1.5°C world, but occur ~~on average every 3 years~~ regularly in a 2°C world. ~~Differences in sea-level rise at these levels is estimated to be be on the order of 0.4-0.6m by 2100 in the 1.5°C case, and 0.5-0.75m in in the 2°C case, but this 20 percent difference could translate into a higher relative cost impact due to flooding (Brown et al., 2011). However, much of the sea level response occurs on a timescale longer than a century; by 2300 a 2°C equilibrium climate might be expected to result in almost 3 meters of sea level rise compared with 1.5 meters for a 1.5°C stable climate (Schaeffer et al., 2012).~~

~~For mean precipitation, both 1.5°C and 2°C climates show some consistent changes relative to historical levels. Precipitation increases at high latitudes, mountainous regions and western continental boundaries; very few land regions experience a net decrease in precipitation. Increases in evaporation occur globally, such that the net water availability decreases in most regions. Extreme precipitation increases in tropical regions (including western Amazon, Eastern Africa, central India). For both~~

For both mean and extreme precipitation changes, gridpoint-level differences between a 1.5°C and 2°C climate are not significant over most land areas. But when aggregated regionally, some impact-relevant differences become apparent. Most regions experience an increase in the frequency of events above the historical 99th percentile of precipitation, and this increase is significantly greater in the 2°C simulations than in the 1.5°C simulations - an effect particularly pronounced in high latitude regions. ~~Similarly, although regional changes in aridity are not generally significant, aggregated globally, the increase in dry land is 90 percent greater in the 2°C climate than in the 1.5°C case.~~

Taken together, it can be argued that if these simulations are representative of the true climate system, there could be substantial differences in impact-relevant aspects of climate, at least regionally, between a climate system stabilized at the 1.5°C and 2°C levels. Further targeted study would be necessary to demonstrate how these differences in climate translate to human and ecosystem impacts. Furthermore, the statements of statistical significance in this study account only for the model's internally variability, and does not account for structural uncertainty. Repeating these experiments with a range of coupled climate models would therefore be of value. The climate model emulator presented here can in principle be applied to other climate models to enable these experiments.

A key factor determining whether or not there are significant differences between 1.5°C and 2°C of warming is the magnitude of the climate system response to a difference of half a degree of warming relative to internal climate variability. ~~The best available tool for investigating this question is~~ This question can be informed by ensembles of coupled climate model simulations ~~, because they include the best available~~ including estimates of internal ~~climate variability . Simulations with prescribed SSTs exclude internal variability~~ variability arising from the ocean ~~, or from interactions between the atmosphere and ocean~~ and atmosphere, and yet~~, the primary tool~~. These experiments should hopefully provide context (for a single model) for the primary multi-model effort being pursued by the community to address the difference between 1.5°C and 2°C of warming (HAPPI, Mitchell et al. (2017)) ~~relies on these prescribed-SST simulations . We anticipate that the ensemble of simulations presented here will be a useful benchmark to evaluate the representation of internal climate variability in the HAPPI simulations.~~ which relies on AMIP simulations with prescribed SSTs.

Our study considered two mechanisms to achieve 1.5°C, one which stabilizes by the mid 21st century, while the other overshoots reaching 1.7°C in 2050 and stabilizes at 1.5°C by 2100. Although the focus of the impact studies considered here have compared the equilibrium states at 1.5 and 2°C, our scenarios allow a consideration of additional impacts which the overshoot would imply. In 2050, an additional 10 percent of global land area would be expected to exceed historical summer temperature records in the 1.5°C overshoot, compared with the 1.5°C stabilization case - although differences are not significant at the gridcell level. Our results do not suggest significant differences in sea level rise between the 1.5°C overshoot case and the stabilization case and ice-free Arctic summers are simulated to be rare in both scenarios. Our analysis not suggest any evidence of long term climatic difference post-2100 of the overshoot relative to the stabilization case.

The question of whether a 1.5°C world is 'worth' the mitigation costs beyond the already aggressive goal of 2°C is a complex one, ideally requiring a comprehensive assessment of both the costs and the impacts associated with the two temperature targets. This study focuses on the differences of the physical climate system in order to inform one aspect of this question: are the differences between these temperature targets significant in terms of aspects of climatology which might have societal impacts? To assess the impacts themselves is left for future study, for which we hope these experiments will prove useful.

Our 1.5°C scenarios require net zero emissions by 2040 if the expectation value for global mean temperatures is never allowed to exceed 1.5°C, and by 2045 if a brief overshoot is allowed. These emissions scenarios are conditioned on CESM representing the true climate system, but these dates are broadly consistent with a more general treatment is considered in Sanderson et al. (2016). However, our model contains no representation of society or economy, and cannot be used to assess the more general question of whether this rate of decarbonization is an achievable goal in reality. Rogelj et al. (2013) considered the probabilistic cost estimates of mitigating to different equilibrium targets, finding that a 1.5°C solution was technically possible in some integrated assessment models with assumptions of low future energy demand. However, a number of studies suggest that the window for a plausible 1.5°C future is rapidly closing, if it has not closed already. Huntingford and Mercado (2016) points out that with many current GCMs, present day concentrations would already result in equilibrium global mean temperatures which would be warmer than 1.5°C. As such, mitigation costs are highly sensitive to political inaction, such that by 2020 in Rogelj et al. (2013), there is no level of carbon taxation which could achieve a 50 percent chance 1.5°C climate.

Mitigation to 1.5°C may or may not be politically feasible. However, it is perhaps more useful to think of a 1.5°C climate as the lowest feasible level of warming which could be achieved this century in ideal conditions: assuming low energy demand, a cooperative global political commitment to decarbonization, fast growth in low carbon technology and development of wide-scale negative emissions infrastructure by mid-century. Simulations such as those presented in this study and those to be conducted in the HAPPI framework provide a quantitative context for the consequences of these idealized conditions failing to be realized. Irrespective of feasibility, these simulations indicate that a relaxation of ambition from the 1.5°C to the 2°C level would result in significantly greater impacts at the global scale, in the tropics and at high latitudes in some regions, at least compared with internal variability in CESM. Further study should consider these results in a multi-model context, using HAPPI and pattern scaling work together with these coupled single model experiments to produce a comprehensive assessment of avoided impacts in high mitigation scenarios.

6 Code Availability

The simple model used to create and optimize the scenarios used in this study is open-source and freely available at the MiCES github repository (`https://github.com/benmsanderson/mices`).

7 Data Availability

The output data from the simulations produced for this study are freely available at (`http://www.cesm.ucar.edu/experiments/1.5-2.0-targets.html`.

Appendix A: Minimal Complexity Earth Simulator (MiCES)

This study uses a simple model emulator developed by the authors in MATLAB to predict the global mean response of CESM to an emissions scenario, a simple energy balance representation of the Earth's temperature and carbon cycle response. The ~~model~~

~~An illustration of the logic flow in the MiCES simple model~~

~~The~~ core of the model is a set of five differential equations. The first describes the evolution of the atmospheric temperature:

$$\frac{\partial T_a}{\partial t}(t) = \frac{1}{\kappa_l}(6.3 \cdot log(C_a(t)/C_a(0)) + F(t) - \lambda \cdot T_a(t)) - D_o \cdot (T_a - T_o) \tag{A1}$$

where t is time, T_a and T_o are the atmospheric and ocean temperatures, $F(t)$ is the sum of all non-CO_2 forcing, κ_l is the thermal heat capacity of the land surface, C_a is the atmospheric carbon content in Pg, λ the climate sensitivity parameter in (K^{-1}) and D_o is the thermal diffusion-like coupling parameter between the atmosphere and the shallow ocean.

The second equation describes the evolution of the atmospheric carbon content:

$$\frac{\partial C_a}{\partial t}(t) = \frac{E(t) - (\gamma_l + \gamma_o) \cdot \frac{\partial T_a}{\partial t}(t) \cdot (1 + \delta T_a)}{1 + \alpha(\beta_l)} - \beta_o(\alpha C_a - \rho_o C_o), \tag{A2}$$

where $E(t)$ is the carbon emissions at time t in Pg, γ_l and γ_o are the land and ocean temperature driven carbon feedbacks (in Pg/K), δ is a carbon feedback amplification factor (allowing the carbon release from the land or ocean to respond non-linearly to temperature, in K^{-1}), α is a conversion factor from Pg to atmospheric carbon concentration, β_l is the CO_2 fertilization parameter and β_o is the carbon diffusion coefficient between the atmosphere and ocean, ~~$(\alpha C_a - \rho C_o)$~~ $(\alpha C_a - \rho_o C_o)$ is the difference in carbon concentration between the atmosphere and ocean, where ρ_o is the conversion factor between ocean carbon content in Pg and ocean carbon concentration. Note that the land carbon cycle feedback is not a function of the land carbon pool in this version, but is modeled using the parameters of Friedlingstein et al. (2003), where land carbon uptake is governed linearly by atmospheric CO2 content and temperature.

The third equation describes the evolution of the shallow ocean carbon content:

$$\frac{\partial C_o}{\partial t}(t) = \beta_o(\alpha C_a - \rho_o C_o) + \gamma_o(1 + \delta T_a)\frac{\partial T_a}{\partial t}(t) - \beta_{od} \cdot (\rho_o \cdot C_o - \rho_{od} \cdot C_{od}), \tag{A3}$$

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where $\beta_o(\alpha C_a - \rho C_o)$ $\beta_o(\alpha C_a - \rho_o C_o)$ is the diffusion-based carbon flux from the atmosphere, $\gamma_o(1 + \delta T_a)\frac{\partial T_a}{\partial t}(t)$ is the loss of carbon from the ocean to the atmosphere due to temperature-driven feedbacks, β_{od} is the carbon diffusion coefficient between ocean and deep ocean and $(\rho_o \cdot C_o - \rho_{od} \cdot C_{od})$ is the carbon concentration difference between the shallow and deep oceans (C_{od} is the conversion factor between deep ocean carbon content in Pg and deep ocean carbon concentration).

5   The fourth equation describes the evolution of carbon in the deep ocean, C_{od}, which changes due to a diffusive flux of carbon from the shallow ocean:

$$\frac{\partial C_{od}}{\partial t}(t) = \beta_{od}(rho \cdot C_o - rho2 \cdot C_{od}), \tag{A4}$$

Finally, the fifth equation describes the temperature evolution of the shallow ocean, where κ_o is the thermal heat capacity of the shallow ocean and D_o is the diffusion coefficient. Heat diffusion across the shallow ocean bottom boundary was not found

10   to be a necessary complexity for emulation.

$$\frac{\partial T_o}{\partial t}(t) = D_o \cdot \kappa_o \cdot (T_a - T_o), \tag{A5}$$

The source code for MiCES is included in the supplementary material of this paper. Non-CO_2 forcings $F(t)$ are calculated using the atmospheric chemistry model defined and published in Prather et al. (2012), which calculates the lifetimes and radiative forcings of non-CO_2 atmospheric components (CH_4, N_2O, HCFCs, CFCs), the model includes some bias correction

15   for present day concentrations and growth rates. Aerosols are calculated by assuming that net aerosol radiative forcing is proportional to global, annual SO_x emissions. The coupled equations are solved using the ODE solver (ode45) in MATLAB.

Appendix B: Tuning for model emulation

The model defined in Section A has a number of free parameters, both in the climate and carbon cycle equations defined in the text and in the chemistry treatment of Prather et al. (2012). Our aim in this study is to reproduce the behavior of the CMIP5

20   configuration of CESM1-CAM5. (Hurrell et al., 2013). This requires reproducing the carbon-cycle and atmospheric chemistry behavior of the closed-source MAGICC model used to produce the concentration pathways for the RCPs (Meinshausen et al., 2008), as well as emulating the global mean temperature response of CESM1-CAM5.

The free parameters in the model, as well as their prior boundary values, are listed in Table B1.

In order to tune the model to CESM1-CAM5, we perform historical and future climate simulations which can be compared

25   to CESM1-CAM5. Climate simulations are conducted from 1850 to 2100 for the 3 scenarios. The models are validated against CMIP5 simulations from CESM-CAM5. The inputs to MiCES are global total emissions of greenhouse gas emissions (CO_2, CH_4, N_2O, CFCs, HCFCs, CO). There is no explicit aerosol scheme in MiCES, instead global mean SO_2 emissions are used as a scaling factor for net anthropogenic aerosol forcing.

The CMIP5 greenhouse gas pathways are derived from MAGICC (Meinshausen et al., 2008), hence our calibration target

30   is actually a hybrid of CESM and MAGICC, where temperatures are matched to CESM and greenhouse gas concentrations to MAGICC's CMIP5 default configuration.

Submodel	Description	Name	Lower	Upper	Calibrated
climate	Climate Sensitivity ($Wm^{-2}K^{-1}$)	λ	0.6	3.8	0.9
climate	Land Surface Heat Capacity $Ka^{-1}(Wm^{-2})^{-1}$	κ_l	1	30	9.3
climate	Ocean Heat capacity a^{-1}	D_o	1	300	21
climate	Atmosphere-ocean diffusion coefficient $Ka^{-1}(Wm^{-2})^{-1}$	κ_o	0.001	1	0.21
climate	Pre-industrial CO_2 concentration (ppm)	ppm_1850	270	290	287
climate	biosphere CO_2 fertilization parameter (Pg/ppm)	β_l	0	3	1.9
climate	biosphere temperature response (Pg/K)	γ_l	-.5	0.5	-.13
climate	Shallow ocean initial carbon stock (Pg)	$C_o(0)$	100	~~10000~~ 600	600
climate	Ocean carbon diffusion parameter (Pg/ppm)	β_o	0	5	1.6
climate	Ocean carbon solubility response (Pg/K)	γ_o	0	0.5	0.2
climate	Deep-shallow ocean carbon diffusion coefficient (Pg/ppm)	β_{od}	0.	4	0.5
climate	Deep ocean initial carbon stock (Pg)	$C_{od}(0)$	20000	100000	100000
climate	Aerosol 1990 forcing (Wm^{-2})	f_{1990}	-3	0	-1.2
CH4	Present-day OH feedback, unitless	sOH	-0.37	-0.27	-0.28
CH4	Present-day loss frequency due to tropospheric Cl, 1/a	kCl	0.0025	0.0075	0.005
CH4	Present-day loss frequency due to all stratospheric processes, 1/a	kStrat	0.0073	0.02	0.01
CH4	Present-day loss frequency due to surface deposition, 1/a	kSurf	4e-3	8e-2	3e-2
CH4	Present-day loss frequency due to surface deposition, 1/a	cPI	650	750	667
CH4	Pre-industrial concentration, ppb	cPD	1600	1815	1670
CH4	Present-day growth rate, ppb/a	dcdt	4	6	4.5
CH4	Ratio of PI/PD natural emissions, unitless	anPI	0.8	1.2	0.98
CH4	Ratio of PI/PD loss frequency due to tropospheric OH, unitless	aPI	0.75	3	1.38
CH4	Ratio of y2100/PD loss frequency due to tropospheric OH, unitless	a2100	0.5	2	1.09
CH4	Present-day methyl-chloroform decay frequency, 1/a	kMCF	0.176	0.3	0.23
CH4	Present-day MCF loss frequency due to ocean uptake, 1/a	kMCFocean	-7.1e-3	7.1e-3	1e-3
CH4	k(Species+OH)/k(MCF+OH) at 272 K	r272	0.1	0.66	0.12
N2O	Present-day concentration	cPD	300	326	310
N2O	Present-day growth rate, ppb/a	dcdt	0.6	0.9	0.70
N2O	Pre-industrial concentration, ppb	cPI	100	300	294
N2O	Present-day loss frequency due to all stratospheric processes, 1/a	kStrat	7.e-3	9e-3	8e-3
N2O	Ratio of PI/PD loss frequency due to stratosphere, unitless	aPIstrat	0.75	1	0.80
N2O	Present-day stratosphere feedback, unitless (dln(kStrat)/dln(C))	sStrat	0.06	0.2	0.16
N2O	Conversion between tropospheric abundance and total burden, Tg/ppb	b	4.78	4.9	4.83
N2O	MCF fill factor, global/troposphere mean mixing ratios, unitless	fill	0.96	1.0	0.98
N2O	Ratio of y2100/PD loss frequency due to stratosphere, unitless	a2100strat	0.9	1.1	1.07
N2O	Ratio of y2100/PD loss frequency due to tropospheric OH, unitless	a2100	0.9	1.1	0.99
N2O	Ratio of PI/PD loss frequency due to tropospheric OH, unitless	aPI	0.5	3.0	2.23

Table B1. Parameter Ranges for the MiCES model used in this study, and calibrated parameters for CESM emulation.

The methane and nitrous oxide components are each calibrated in isolation because their evolution is not sensitive to the temperature or carbon state of the model. In each case, an error function is computed as the sum-squared difference in concentration over the integration period for the 3 scenarios:

$$E^{N_2O}(p) = \sum_{s=1}^{3} \sum_{t=1850}^{2100} (c_{mices}^{N_2O}(t,s,p) - c_{magicc}^{N_2O}(t,s))^2 \tag{B1}$$

$$E^{CH_4}(p) = \sum_{s=1}^{3} \sum_{t=1850}^{2100} (c_{mices}^{CH_4}(t,s,p) - c_{magicc}^{CH_4}(t,s))^2 \tag{B2}$$

where $E^{N_2O}(p)$ and $E^{CH_4}(p)$ are the error terms for parameter state p, c is the annual mean concentration of methane or nitrous oxide at time t in MiCES and MAGICC, s represents the 3 scenarios (RCP2.6, RCP4.5 and RCP8.5). The parameter state p is initialized from the default values in Prather et al. (2012) and optimized to minimize the value of $E^{CH_4}(p)$ using MATLAB's 'fmincon' function. Other non-CO_2 components (CFCs, HCFCs, CO) are simple decay functions kept at the default values from Prather et al. (2012).

Once the non-CO_2 components are calibrated, the climate component is tuned by considering the temperature from CESM1-CAM5 and the CO_2 trajectories from MAGICC from the CMIP5 RCP2.6, RCP4.5 and RCP8.5 simulations. We start by performing a 10^6 member perturbed ensemble of the model for 3 different scenarios - RCP2.6, RCP4.5 and RCP8.5. Each parameter in the 'climate' sub-component in Table B1 is perturbed using a flat prior sampling with lower and upper bounds as listed. A cost function $E^{climate}(p)$ for the climate components is calculated as a product of combination of the CO_2 and temperature cost functions:

$$E^{CO_2}(p) = \sum_{s=1}^{3} \sum_{t=1850}^{2100} (c_{mices}^{CO_2}(t,s,p) - c_{magicc}^{CO_2}(t,s))^2 \tag{B3}$$

$$E^{T^g}(p) = \sum_{s=1}^{3} \sum_{t=1850}^{2100} (T_{mices}^{T^g}(t,s,p) - c_{CESM-CAM5}^{T^g}(t,s))^2 \tag{B4}$$

$$E^{climate}(p) = E^{CO_2}(p)E^{T^g}(p), \tag{B5}$$

where c^{CO_2} is the concentration of CO_2, and T_g is the global mean temperature. The parameter configuration with the lowest cost function in the 10^6 member ensemble is used as an initial condition for an fmincon optimization, which adjusts the parameters to minimize $E^{climate}(p)$. Figure B1 shows the calibrated behavior of MiCES for reproducing the concentrations and temperature response of the CESM1-CAM5/MAGICC hybrid used to create the CMIP5 simulations.

Appendix C: Emissions scenario design

The emissions scenarios developed for this study are not produced in an integrated assessment model. Rather, we use the strategy of Sanderson et al. (2016), which produced idealized emissions scenarios which follow RCP8.5 until a mitigation

phase begins at time t_m, after which emissions follow a smooth trajectory (the derivative of emissions is continuous at time t_m), peaking and then decaying asymptotically to an 'emissions floor' (E_m^0). A parameter t_m^{50} determines how quickly mitigation occurs, and sets the length of time after t^m that emissions are 50 percent of the way to the asymptotic emissions floor.

In this study, we add a second 'rampdown' phase to allow a period of intensive negative emissions followed by a long term relaxation of effort to achieve a stable temperature level. The rampdown phase follows a simple exponential decay, beginning at time t_r, with a long term asymptotic emissions level of E_r^0 and a relaxation time t_r^{50}, such that CO_2 emissions at time t can be described as follows:

$$E(t) = \begin{cases} E_{RCP8.5}, & \text{if } t \leq t_m \\ A_m[(t - t_m^e)e^{-t/\tau_m}] - E_m^0, & \text{if } t_m < t \leq t_r \\ A_r[e^{-(t)/\tau_r}] - E_r^0, & \text{if } t > t_r \end{cases}$$

with 5 parameters to solve: A_m and A_r, t_m^e, τ_m and τ_r. These parameters can be solved using boundary conditions already established. We first solve for the parameters for the mitigation stage by fixing the emissions and rate of change of emissions at time t_m, as well as the timescale of mitigation:

$$E(t_m) = E_{RCP8.5}(t_m) \tag{C1}$$
$$\frac{dE}{dt}(t_m) = \frac{dE_{RCP8.5}}{dt}(t_m) \tag{C2}$$
$$E(t_m + t_m^{50}) = (E_{RCP8.5}(t_m) + E_0)/2. \tag{C3}$$

We can then solve for the rampdown parameters in a similar fashion by fixing the emissions at time t_r to allow a smooth transition into the rampdown phase.

The parameters (E_m^0, t_m^{50}, t_r, E_r^0 and t_r^{50}) for the three scenarios were adjusted manually to achieve the desired temperature behaviour: a stable 2°C climate, a stable 1.5°C climate and an overshoot of 1.5°C, with a stable 1.5°C climate post-2100. The parameters which were found to achieve these characteristics in the calibrated MiCES model are listed in table C1.

As in Sanderson et al. (2016), non-CO_2 greenhouse gas emissions depart from RCP8.5 at time y_m, and then decay asymptotically in a simple exponential to the RCP2.6 pathway using a timescale defined by t^m. Each follows RCP8.5 until t^m, and then decays to the respective RCP2.6 pathway with the decay constant τ_m, such that for a gas j:

$$E^j(t) = \begin{cases} E_{RCP8.5}^j, & \text{if } t \leq t_m \\ E_{RCP8.5}^j e^{-(t-t_m)/\tau_m} + E_{RCP2.6}^j(1 - e^{-(t-t_m)/\tau_m}), & \text{otherwise} \end{cases}$$

Where j can correspond to CH_4, N_2O, CO, VOCs, NOx, CFC-11, CFC-12, HFC-134a, HCFC-22 and SOx. There is no separate rampdown phase for non-CO2 emissions. Non greenhouse gas concentrations (aerosols, ozone etc.) follow RCP8.5 throughout the simulation.

Scenario	Year to begin mitigation phase	Time to 50% of long term (years, mitigation phase)	Mitigation phase emissions floor (PgC/yr)	Year to begin rampdown phase	Time to 50% of long term (years, rampdown phase)	Long term emissions level (PgC/yr, rampdown phase)
Parameter	t_m	t_m^{50}	E_m^0	t_r	t_r^{50}	E_r^0
1.5 never-exceed	2018	10	-1.8	2065	35	-0.3
2.0 never-exceed	2018	25	-0.85	2120	60	-0.4
1.5 overshoot	2018	18	-4	2080	15	-0.5

Table C1. Parameters for the three scenarios described in this study, using the functional form established in Sanderson et al. (2016), t^m is the year that emissions depart from the RCP8.5 scenario and begin the mitigation phase, t_m^{50} describes the rate of decarbonization in the mitigation phase, defined as the number of years after the mitigation phase start time that the emissions are equidistant between 2018 emissions and the emissions floor level, E_m^0 is the asymptotic level to which carbon emissions decay in the mitigation phase, t_r is the year in which the mitigation phase ends and the rampdown phase begins, t_r^{50} is the number of years after the rampdown start time that the emissions are equidistant between emissions in year E_r^0 and the long term emissions floor level and e_f^r is the asymptotic level to which carbon emissions decay in the rampdown phase.

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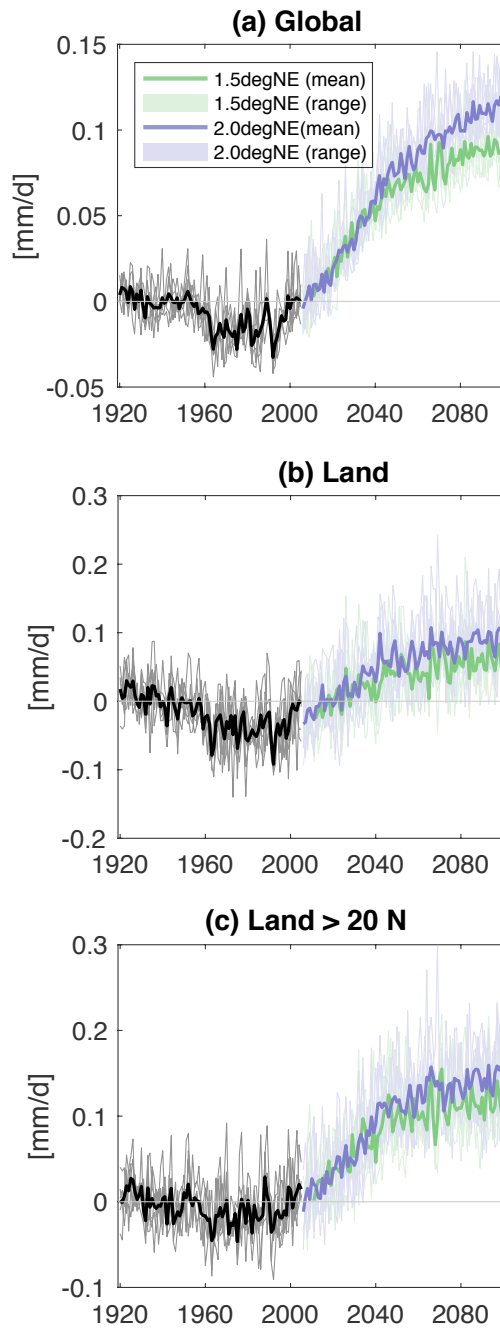
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Figure 6. Changes in annual mean precipitation at the (a) Global, (b) Land-only and (c) high Northern latitude land. Values are relative to the 1921-1960 average. Grey lines show members of the historical CESM ensemble, while black line shows the historical mean. Thin colored lines show individual ensemble members for future scenarios, thick bold lines show the ensemble mean.
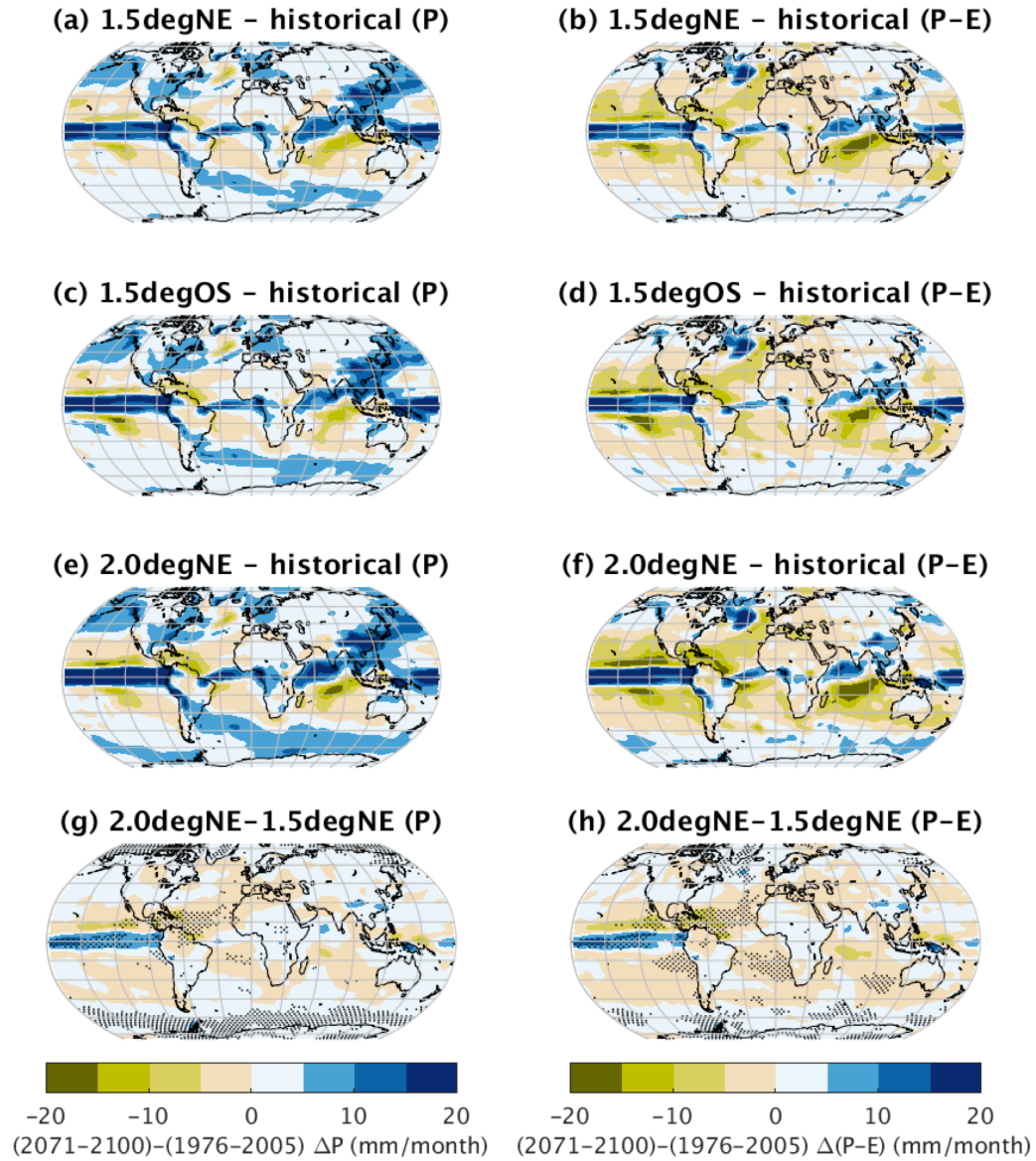
Figure 7. Maps showing ensemble mean 2071-2100 Precipitation and Precipitation-Evaporation changes from 1976-2005 historical conditions in *1.5degNE* (a,b), *1.5degOS* (c,d), *2.0degNE* (e,f) scenarios. Subplots (g,h) show the difference between mean 2080-2100 conditions in *1.5degNE* and *2.0degNE*, where significant regions are stippled. Significance is defined as a pixel in which the difference between the mean of the *2.0degNE* and *1.5degNE* ensembles exceeds the standard deviation of 2080-2100 values in the *2.0degNE* ensemble.
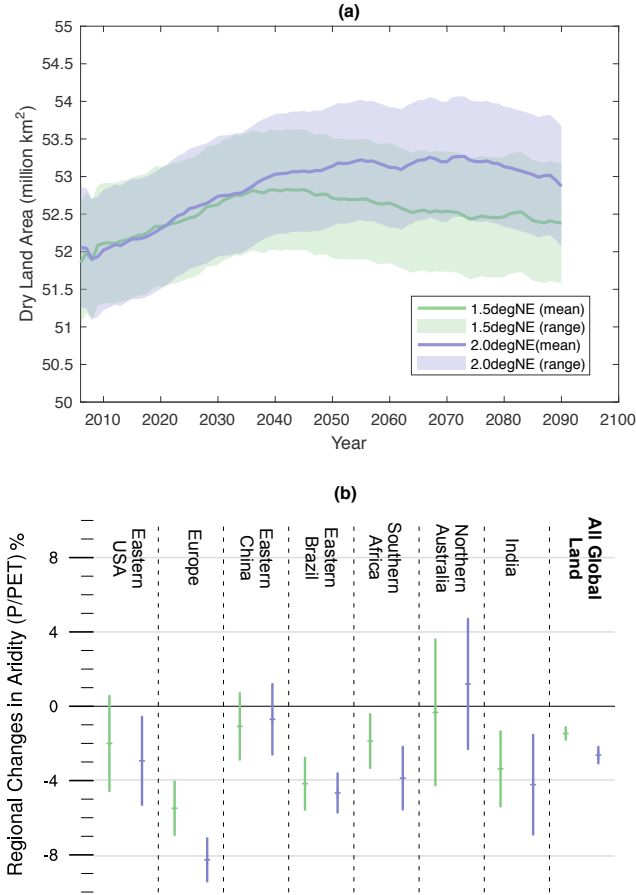
Figure 8. (a) Solid lines show the ensemble mean of aggregated land which qualifies as 'dry' land, where aridity (P/PET)<0.65. Lines are smoothed to show the 20 year running average value. Shaded areas are calculated as ±1 annual standard deviation from the mean in the respective ensemble. (b) shows the change in aridity for a number of specific regions in 2071-2100 relative to 1976-2005. Central dash indicates the ensemble mean value, while the vertical lines indicate the full spread in the *1.5degNE* and *2.0degNE* ensembles.

(a) 1.5degNE - historical (P)

(b) 2.0degNE - historical (P)

(c) 2.0degNE-1.5degNE (P)

-50   -25   0   25   50

(2071-2100)-(1976-2005)

Change in expected max daily Extreme Precipitation intensity (%)
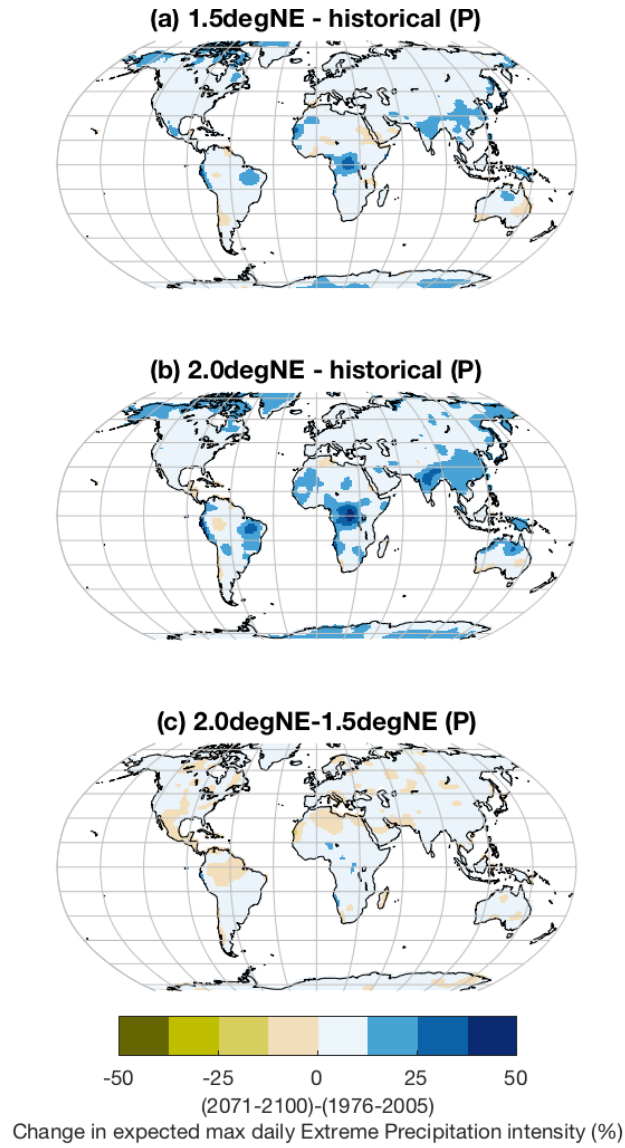
Figure 9. Maps showing the simulated percentage change in ensemble average annual maximum one-day precipitation for historical periods (1976-2005) and future (2071-2100) for (a) *1.5degNE*, (b) *2.0degNE* and (c) the difference between the scenarios. Maps are smoothed with a 2-D Gaussian smoothing kernel with standard deviation of 2 gridcells.
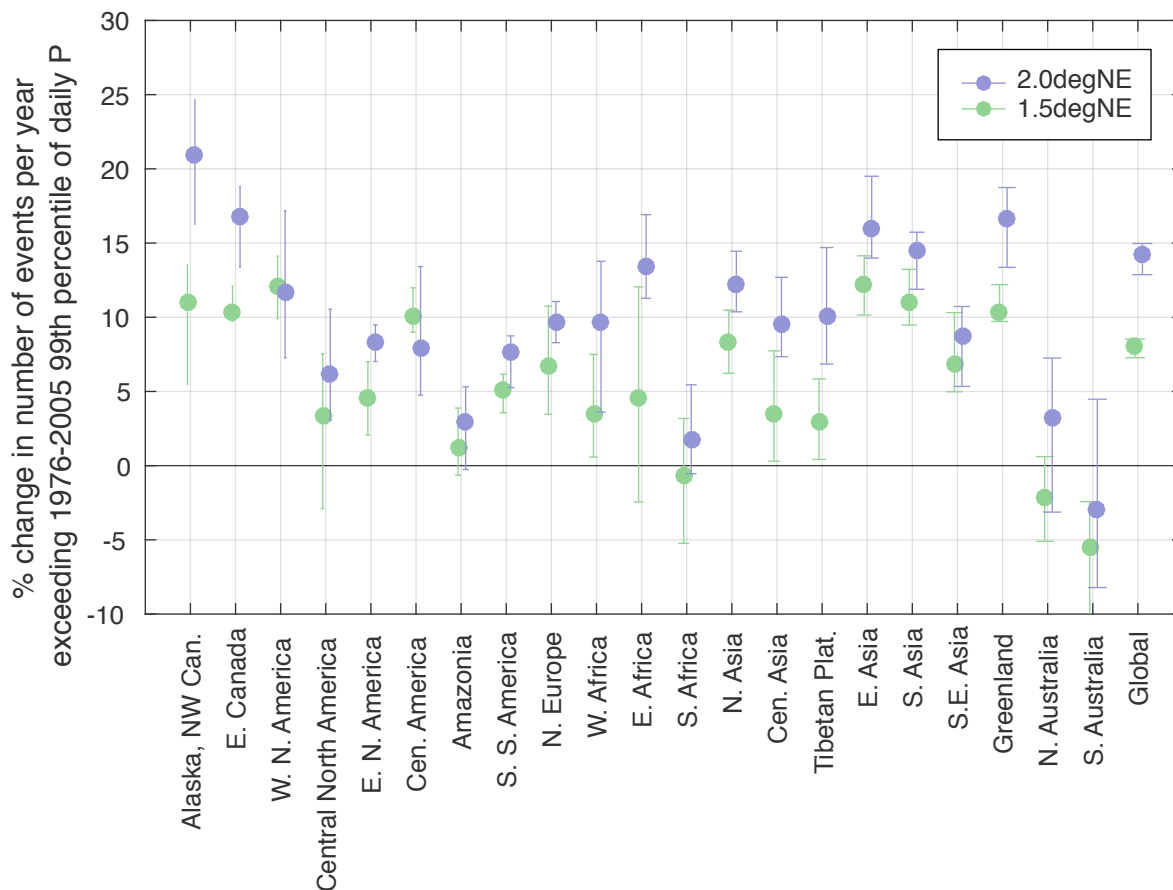
Figure 10. Aggregated percentage change in the aggregated frequency of exceedance of the historical 99th percentile of precipitation over regions as defined in Giorgi and Mearns (2002). Historical 99th percentile is calculated at a grid-cell level from the distribution daily precipitation from years 1976-2005, for ensemble members 1-10 (making 300 years of data). Events exceeding their point-level 99th percentile are summed over the relevant region for each ensemble member, such that the ensemble mean value of the number of exceedances represents the baseline. Future values are calculated from years 2071-2100 of *2.0degNE* and *1.5degNE*, again summing events which exceed the 1976-2005 99th percentile. The ensemble mean and range of percentage change in number of events in 2071-2100 relative to 1976-2005 is plotted.
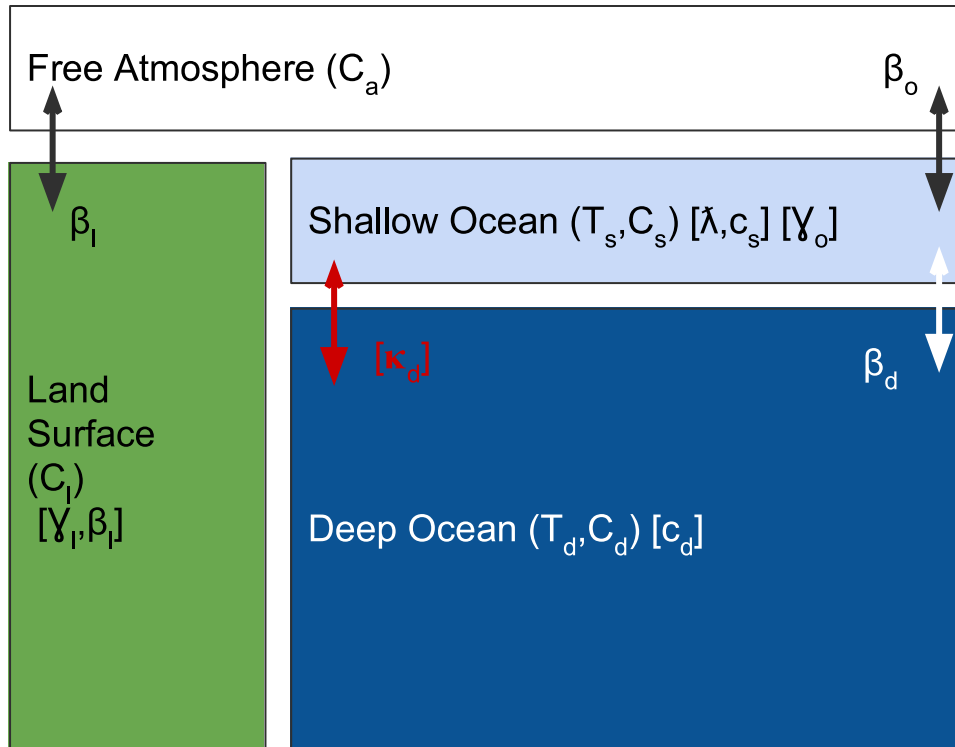
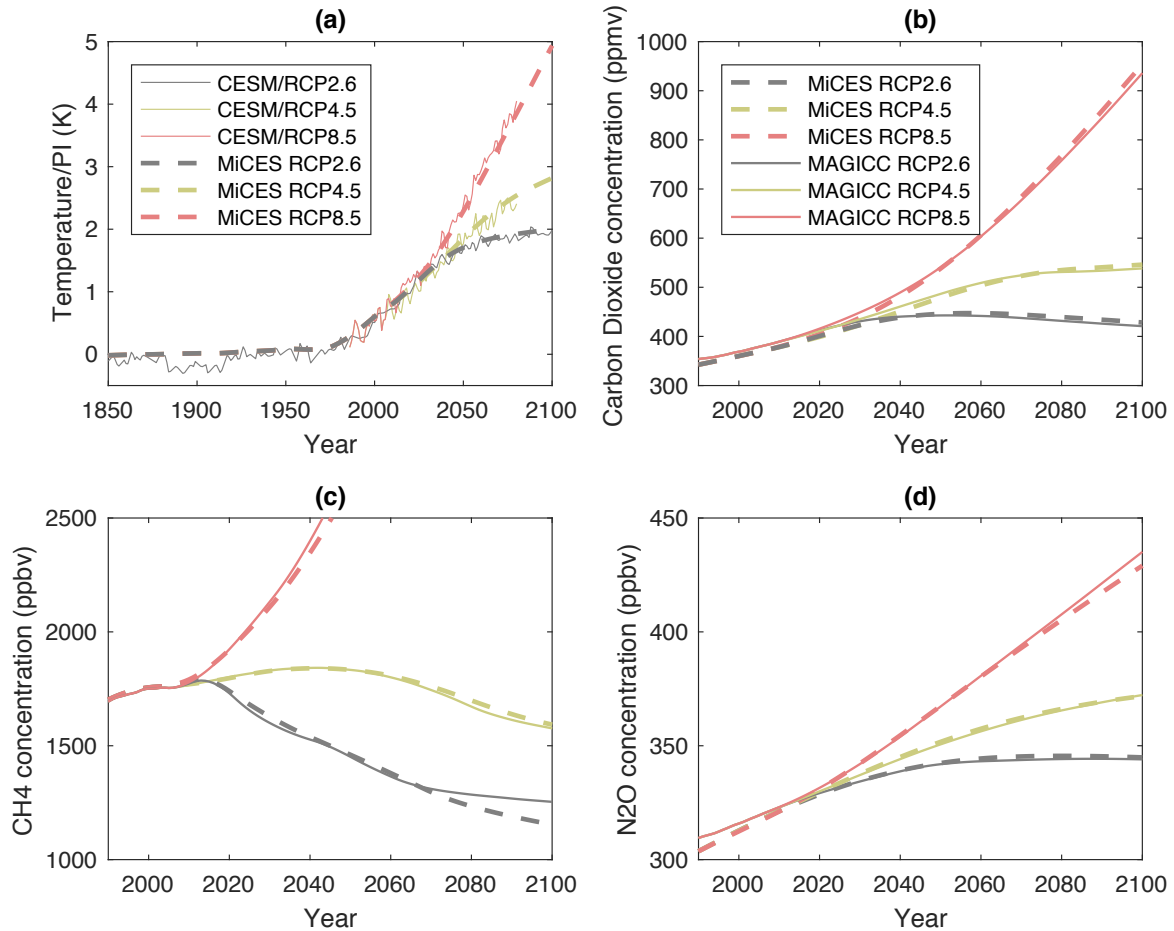**Figure A1.** An illustration of the logic flow in the MiCES simple model

Figure B1. Calibrated behaviour of the MiCES model in the context of the temperature targets (subplot a, target is CESM1-CAM5) and the concentration targets (subplots b-d, where target is MAGICC). In each case, the target is represented by a solid line, and the optimized MiCES simulation is represented by a dashed line. The colors represent the three scenarios used in calibration.
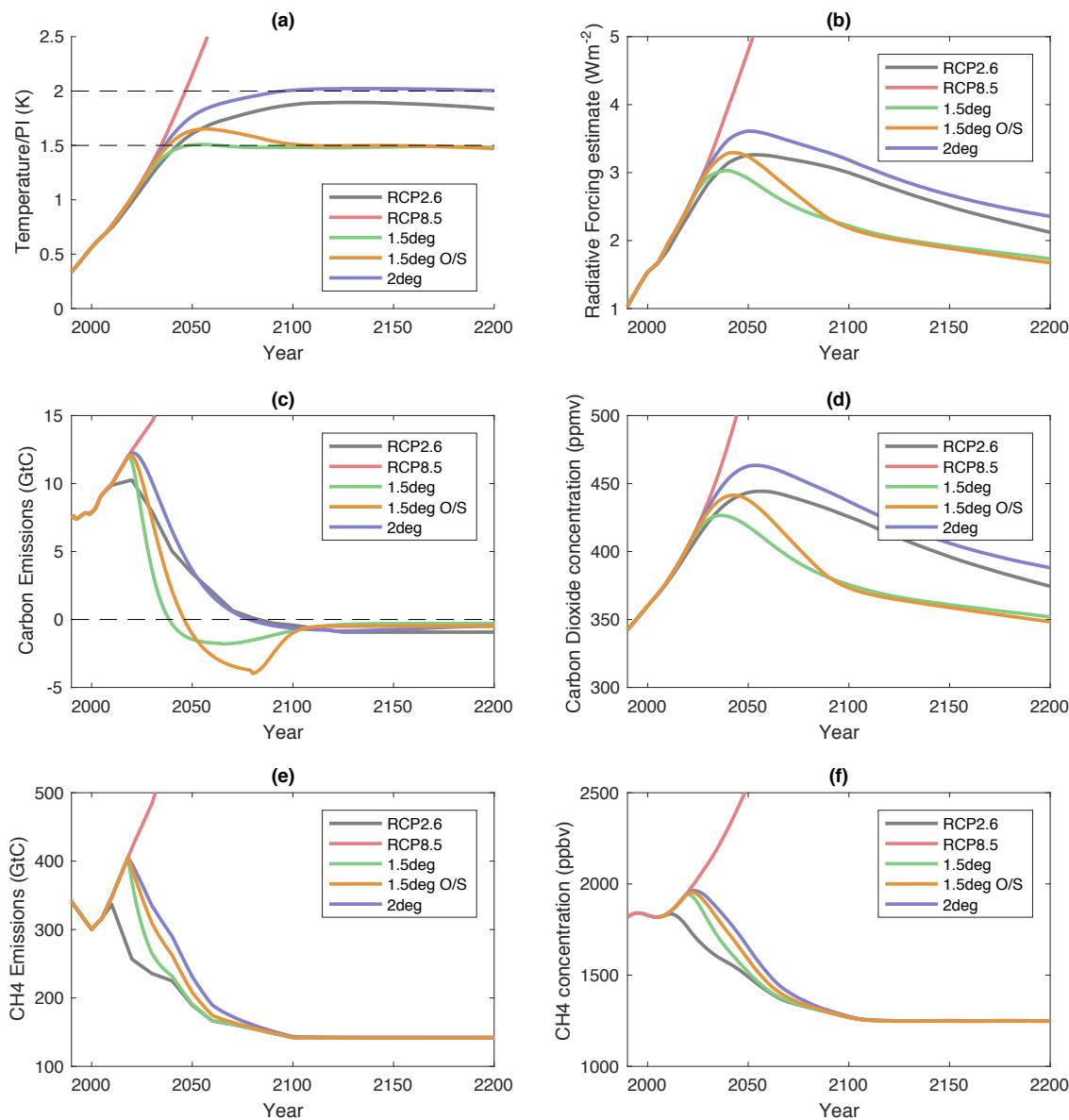
Figure C1. New scenarios used for this study. Figure (a) shows the predicted global mean temperature evolution, (b) shows the radiative forcing evolutions, (c) shows net anthropogenic carbon emissions (fossil fuel and land use combined), (d) shows CO_2 concentrations, (e) shows methane emissions and (f) shows the methane concentrations. Blue, green and orange lines are $2°C$, $1.5°C$ and $1.5°C$ overshoot respectively.
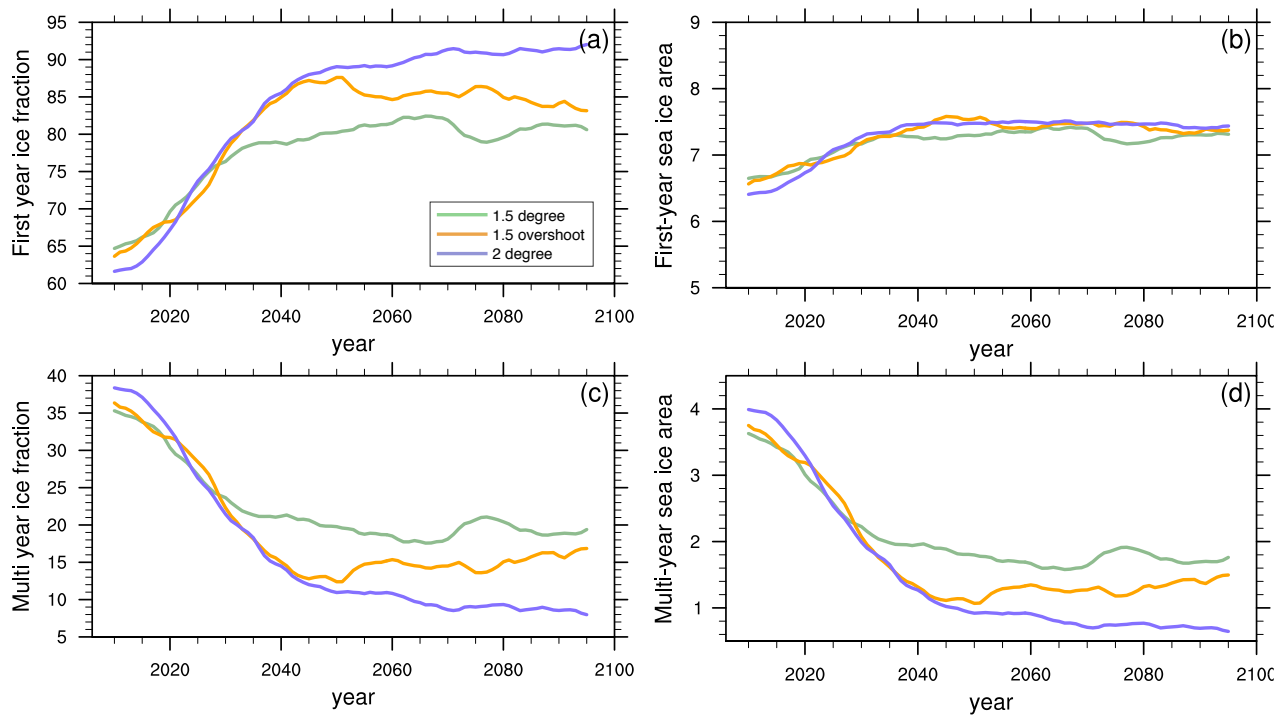
Figure C2. Evolution of the annual 10-year running ensemble-mean of first year and multi-year Arctic sea ice in the low emission simulations. (a) shows the fraction of Arctic sea ice which is less than a year old, (b) shows the sea ice area which is less than a year old, (c) shows the fraction of sea ice which is greater than a year old and (d) shows the total sea ice area which is greater than a year old.