August 10, 2017

Paolo Tarolli
Editorial Board
Natural Hazards and Earth System Sciences

Dear Dr. Tarolli:

Thank you for handling our manuscript for Natural Hazards and Earth System Sciences, originally entitled “Modeled changes in 100-year flood risk and asset damages within mapped floodplains of the contiguous United States.” Per your request, we have completed a point by point response to the reviewers in this letter, and we have attached a marked-up version of our manuscript documenting the changes we made to our original submission. In addition to this point by point response, we would like to highlight the significant changes we made to the discussion of uncertainties in our paper, as requested. In particular, we added a substantially expanded discussion of all uncertainties in the Methods section of the paper, which now appears in Section 2.4. We moved this discussion of uncertainties up in the paper in response to the concerns raised by the reviewers that the reader needs a better grasp of these uncertainties prior to our discussion of results.

We believe that the changes we have made in response to your comments and those of the reviewers have resulted in a substantially improved manuscript, which we believe will be both acceptable for publication in NHESS, and a significant contribution to this area of natural hazards research.

Our responses to the reviewers’ general and specific comments on the manuscript are listed below. In all cases, reviewer comments are marked with an “RC1” or “RC2” denoting which reviewer they are addressing; and our responses are marked with an “AC”, reflecting author comments. A marked-up version of the manuscript is attached to end of this letter.

We thank you again for your consideration.
Sincerely,

Cameron W. Wobus, PhD
Senior Scientist
Environment & Health Division

Enc.

Reviewer #1 General comments

RC1: This paper considers how flood frequency and the associated flood damages might evolve depending on different greenhouse gas (GHG) emissions pathways. To my knowledge this is the first paper that proposes an automated methodology at the continental scale to estimate the potential cost of GHG emissions through their effect on flood damages. The manuscript addresses the issue of climate change in monetary terms (the cost of modeled flood damages given different emissions pathways) and as such is a timely and important contribution to the literature, and one which I expect will be of interest to a broad audience. Additionally, the authors frame the issue in a positive manner, by showing how global GHG reductions can be used to limit possible increases in flood damages.

The methods are mostly well explained. The authors begin with the mapped 1% annual exceedance probability flood extent (100-year flood) across the continental United States. They then assess how these damages will evolve under two different GHG emissions scenarios. Some aspects could be slightly better clarified (see specific comments below), but the authors are generally upfront about the limitations of the work: they state that the projections "should be considered order-of-magnitude estimates: : :" (p3L.10); they discuss the limitations of GCMs in resolving precipitation (p8), the uncertainties in the hydrological forecasts, the limited data on assets exposed to flooding, the fact that the approach does not account for the effects of changes more/less extreme floods than the 100-year flood, and that it does not take into consideration societal adaptation to flooding. However, these limitations and assumptions are discussed mainly in the conclusions, so the reader is left wondering about some of these matters (e.g. the potential influence of changes in land use) throughout most of the paper. I feel it would help to include a brief statement earlier in the paper, mentioning that the method assumes that there are no changes in land use (no additional constructions in the floodplains, no change in land cover, etc.) and therefore that the overall changes in flood hazard/damage are based mostly on climatic changes.

***AC**: We appreciate the need for additional detail in certain parts of the paper. We included a statement earlier in the paper explicitly noting the assumptions so that the reader does not need to be "left wondering" about some of these matters until the end. In response to reviewer and editor comments, we also added a new section on uncertainties much earlier in the paper to make our assumptions and their uncertainties more explicit. Finally, we critically reviewed our manuscript based on specific comments from the Reviewers, and we made further clarifications to the text as requested and summarized below.*

RC1: The overall approach makes sense given the continental scale of the analysis: the authors consider the distribution of results across all 29 GCMs for each RCP and compute the total number of flood events across the CONUS in each year of the model simulation. While this provides an interesting first estimate of potential future changes in flood damages at the continental scale, the uncertainties may be more problematic at the local scale. Also, as stated by the authors, this general approach is relatively conservative and thus likely underestimates the influence of potential increases in extreme precipitation.

AC*: we agree and acknowledge that the uncertainties from our method are certainly larger at a local scale. We have revised the text to ensure that all of the uncertainties are explicit in the revised manuscript. We also highlighted the limitations of our study in the discussion section of the manuscript.*

RC1: In terms of results, I feel that the paper would benefit from a little more explanation. For instance, it is interesting that some regions (like the Southeast) are more affected by increasing flood damages under RCP8.5 than others, but there is no explanation or suggestion why.

AC*: There are a range of potential reasons why different regions exhibit more significantly increasing flood damages than others. These include differences in the climate change signal, and differences in the distribution of infrastructure within mapped 1% AEP floodplains. We recognize that the manuscript could benefit from more discussion of these nuances, and we have expanded the explanation of topics such as this in the discussion section of our revised manuscript.*

RC1: In sum, the paper is very well written, agreeable to read, and aptly illustrated. The technical language is appropriate, and the references are appropriate and accessible. The title and abstract are both pertinent and clear, with an appropriate and complete summary of the contents of the paper.

AC*: We thank the reviewer for this positive summary of the paper.*

Reviewer #1 Specific comments

RC1: P2 L.1-5. I feel that this paragraph (on climate attribution) does not fit in very well here – the narrative could be strengthened and clarified.

AC*: We expanded and revised this paragraph on revision, to provide a more coherent summary of both recent work in climate attribution and the need for long-term projections of trends in flood frequency and magnitude.*

RC1: P2 L.9. Perhaps the authors could state explicitly why those two RCPs were chosen?

AC*: These two RCPs loosely represent a future with little to no action on GHG mitigation (RCP8.5) and one with relatively concerted efforts to reduce GHG emissions (RCP4.5), and as such provide a good backdrop for evaluating how flood damages could be influenced by a change in emissions. These two RCPs are also being recommended for use in the Fourth National Climate Assessment. We made all of these rationales more explicit in the revised manuscript.*

RC1: P2 L.18. I think there are more recent studies on streamflow trends at the scale of the entire CONUS.

AC*: We agree. While our list of examples cited here was not meant to be exhaustive, we have included more recent references on streamflow trends in the CONUS, including Tamaddun et al. (2016); and Ivancic et al. (2017)*

RC1: P2 L.22. "Because available hydrologic records tend to be short…". I feel this sentence misses the main point of the paragraph. It seems the issue here is not that historical trends are inconclusive or that existing data records are too short (the USGS database has thousands of sites with more than 50 years of streamflow data; and existing analyses are not all inconclusive), but rather that historical trend analyses are unable to tell us much about the future, and therefore there is increasing interest in using climate model outputs to evaluate future flood risk.

AC*: We thank the reviewer for pointing out the confusion from this statement. We revised this paragraph to clarify our meaning.*

RC1: P4 L.21. It's not entirely clear to me how realistic the simulated time series are compared to observed time series- perhaps I missed something; could this be clarified?

AC*: This analysis is included in Mizukami et al. (in review), but as noted in the reviewer's comment below (P4 L.3) we recognize that it is difficult for the reader to evaluate this study since it is not yet published. We developed an additional supplemental information file to more clearly describe the salient results from Mizukami et al. to illustrate the degree of correspondence between the simulated and observed timeseries. We also note that the results from our study are based on a delta approach – that is, we are not using absolute magnitudes of flow to drive any of our modeling results; only changes in frequency of events exceeding a model-derived threshold. We included additional discussion in the body of the manuscript that summarizes all of these points.*

RC1: P3 L.5. (& discussion P8 L.31) "only the 100-year floodplains are consistently mapped and available at a national scale": for future work, it might be interesting to use an automated digital elevation model floodplain extraction method.

AC*: We agree that it would be interesting and informative to repeat this analysis for a wider range of flood magnitudes. We have done some preliminary analysis of assets exposed to a wider range of flood magnitudes using data from the FEMA Risk MAP program, and we have included some discussion of this as a worthwhile avenue for future research in our revision. However, extending our results using an automated DEM extraction method would be a significant undertaking, and one that is well beyond the scope of this study.*

RC1: P4 L.3. "Full details of the…methodologies are available in Mizukami et al. (In Review)" – it is difficult to comment on a methodology that is under review in WRR…could the authors comment on this?

***AC**: Mizukami et al. (in review) has been revised and resubmitted in response to reviewer comments, and we anticipate that the manuscript should be in press relatively soon. However, as noted above we have included salient details of the Mizukami et al. paper in our supplemental information file to ensure that the reader has enough information available to understand the method.*

RC1: P5 L.29. "We created a random sample of flood depths". This section and the calculation of depth-damage function is interesting, but it is a little unclear how the depths were calculated. I assume the bathymetry of the river and any changes in river capacity are not considered; if so, this would be worth commenting on (and the potential implications for the results).

***AC**: We clarified this part of the description in revision. In addition, we have added a reference to a presentation on the National Flood Risk Characterization tool in the manuscript. This reference contains many of the details sought by the reviewer here.*

RC1: P7 L.17-21. "changes in flood damages broadly mimic changes in flood frequency…". I believe this finding is to be expected, if the method assumes that flood frequency is driven solely by meteorological change, without considering potential temporal changes in the spatial distribution of assets, land use, water management, and/or channel capacity. At this point it would be worth mentioning these assumptions explicitly, rather than waiting until the last paragraph of the manuscript.

***AC**: We thank the reviewer for pointing this out. Our revision is more explicit about assumptions at this point in the manuscript, as well as in the discussion. In particular, we have reiterated that the lack of modeled changes in land use and infrastructure in our method mean that changes in flood frequency are driven entirely by changes in climate forcing.*

RC1: P8 L.1. It seems that the difference in projected flood damages between the Southeast and Northeast is considerable ($2 billion per year by 2100 versus $1 billion per year by 2100), and would be worth explaining.

***AC**: Given that our results are primarily driven by changes in precipitation, this result indicates that precipitation and runoff during the months that cause flooding are projected to increase more consistently in the Southeast than in the Northeast, and/or that there is more infrastructure at risk in the Southeast than in the Northeast. We have expanded the discussion to more explicitly address this finding and our hypotheses for why this is occurring; however, this is in large part an avenue for future research.*

RC1: P8 L.26. "We generated preliminary comparisons of hydrologic projections using two different VIC parameter sets". This is a little vague and is not explained in the paper; perhaps the authors could be more explicit, or include details in the supplementary materials.

***AC**: We expanded this discussion, and we have also included more information on this topic in the new supplemental information file we developed for our resubmittal.*

Reviewer #2 General Comments

RC2: This is an interesting paper, combining several modelling approaches to give order of magnitude estimates of economic losses related to 1% flood events increasing with climate change over the 21st century. I enjoyed reviewing it and broadly speaking I think the paper can be published with minor revisions, principally around tightening up some of the language to convey precise meanings. In short I'd recommend the methods are fine as they are, but the discussions need to take extreme care around how far the results can be extrapolated. This is especially important given that the results could have wider public, policy and media interest, and from that perspective it is perhaps even more important to make sure someone reading the paper without all specialist knowledge/training will not potentially misinterpret some of the findings/discussion. Specifically, I think the fact the study is delivering order of magnitude estimates and should be considered a 'first pass' at answering the question of future flood hydrology/ risk and damage need to be incorporated into the discussion a little more. Even more importantly this needs to be covered in the abstract for the reasons above.

I should add the caveat that I do not consider myself competent to review all technical aspects of downscaling of GCMs and so would defer to the other reviewers and editor on those aspects of the paper.

***AC**: We thank the reviewer for this overall positive review. As with the comments from Reviewer #1, we recognize the need for additional clarity/explanation of some components of the paper, and have addressed these concerns on revision.*

Reviewer #2 Specific Comments

RC2: 10 – The two clauses in the opening sentence don't directly follow from each other. The first part makes link between flood occurrence and extreme weather and says extreme weather events will increase. The second part says therefore flood DAMAGE will increase. Not directly supportable to link increased frequency with increased damage in a general sense. This would need to be amended (at the least) to say "thus [potentially] increasing flood damage.." Or alternatively use a more general concept like increasing risk or exposure.

***AC**: We recognize the potential incongruity as written. We have revised the text as suggested.*

RC2: 13 – (and elsewhere – pg 3, line 3). I'm not sure about the terminology of referring to them as "locations", would "reaches" or "catchments" convey this better?

***AC**: Agreed. We have revised "locations" to "reaches" here and elsewhere for consistency and clarity.*

RC2: 19 – Care in language needed here (and elsewhere). Paper is specifically talking about flood damage, but here talks about flood risk. Not same thing. Would be better to be consistent throughout to avoid confusion.

AC*: We have clarified the use of "damages" vs "risk" throughout the manuscript.*

RC2: 22 – This sentence needs rewording and maybe more caveats adding. At the moment the argument is somewhat tautological when it's boiled down – "we think we are being conservative, therefore our conclusions are conservative". I think this needs be stated in a way which does not seem to infer what the findings of future work would be! A key issue is that the result is an order of magnitude estimate; there are many assumptions made in the methods (either in choices or models) which are assumed to give uncertainty of an order of magnitude less (hence order of magnitude estimate), but for many of these we don't know whether they are over or under. I think what you are trying to say here is that more advanced techniques can constrain this uncertainty for future work. It's almost a separate point to say that you feel you've made methodological choices which would tend towards underestimating total damage. Indeed it may be worth separating out these two ideas/statements.

AC*: We appreciate the reviewer's concern about our use of the word "conservative" here. The reviewer is correct that the point of this sentence is not to imply that we are underestimating or overestimating damages, but to state that further refinements to our methods could improve our understanding of results and their sensitivity to methodological choices. We have clarified the text accordingly.*

RC2: Intro 26 – I don't follow this statement I'm confused how an annual average can have a range, or how annual damage can be an average? – I.E. if annual damage is averaged over 100 years it is a single number? Does this mean just the measured annual damage ranges between x and y, or is it estimated from different sources? Or perhaps decadal/regional averages? Clarify.

AC*: We recognize the confusion in the text as currently written. The intended meaning here was that nationwide inland flooding damages each year typically fall within a range of dollar values. We have clarified our meaning to ensure that there is no confusion.*

RC2: 28– clarify the "damage" here; is this estimated economic costs, actual rebuild costs, including all economic losses not just physical ones? Important as this relates directly to paper findings so important to know.

AC*: The numbers we quote here are reported damages in terms of physical damage to property, as summarized in NOAA (2016). We have clarified the text as requested.*

RC2: 29 – Care with language. This flooding is "historical" in what context? Largest ever? Or do you just mean "large flood events"?!

***AC**: We are referring to these events only as "very large flood events." We have clarified the text accordingly.*

RC2: PG2. 1-7 – I think this paragraph could be framed better. I recommend rewording slightly as the three sentences don't seem to exactly follow on, one from the other. In the first it says challenging to understand events to climate change. Then says this is advancing, as well as attributing extremes in general to warming. Then finally says long term trend forecasting is important for stakeholders. At this point you are first making the case for why you would do this work, so I think it would be more powerful to suggest why the approach in the first two sentences is not fit for purpose and so therefore why the trend approach used later on is better/necessary/more useful in an explicit sense. Would be an early marker as to why this is all important and sell it to the reader(s).

***AC**: We thank the reviewer for suggesting ways we could improve this paragraph. We have revised the paragraph to improve the way this part of the introduction frames the remainder of the manuscript.*

RC2: 12 – be explicit here whether you are talking about the mean damage in the 1% event per year, or the cumulative damage of all such events over the time span.

***AC**: We have clarified the text in this part of the manuscript, to make it explicit that our study looks at projected damages from 1% events in each year, based on an ensemble across a suite of GCMs.*

RC2: 15 – I'm uncomfortable with the paper claiming a "deep body of previous work" but not citing any! Is there at least 2-3 review papers that could be cited in terms of "(see A et al, 2006, B & C, 2010: : :.)"

***AC**: We thank the reviewer for pointing this out. As written, we reference some of the "deep body of previous work" in the sentences following this one. However, we have revised to bring some of these references up further in the paragraph to avoid the incongruity pointed out by the reviewer.*

RC2: 22 – reference(s) for inconclusive studies needed.
RC2: 23 – references for significant interest, or be more explicit about the source of this if not based on literature.

***AC**: We have revised this paragraph and the paragraph preceding it to make better reference to the previous literature in the context of our own study.*

RC2: 30 – Use of "flood risk" here, but this time to apply to (I think) the frequency of flood events. If so this is more broadly how I would understand the term, but clashes with usage elsewhere. This needs to be more explicit in this context, or alternatively could define flood risk as a term for purposes of this paper.

***AC**: We thank the reviewer for pointing out our use of this potentially confusing term. We have clarified our intended meaning of "flood risk" throughout the paper*

RC2: PG4. 5 – This needs to be less definitive I think – "are likely to be conservative" rather than "are conservative", unless this is supported with methodological references.

***AC**: We have clarified the text as requested.*

RC2: PG5. 20 – reference to the tool needed – ideally to some form of report/paper/website. And also the name of the tool needed.

***AC**: We have included reference to a publicly available presentation so that the flood risk tool is more fully referenced. This presentation is available here:* http://www.iwr.usace.army.mil/Portals/70/docs/frmp/Flood_Risk_Char/NFRCT_Slides_FRM_wkshp_v1.pdf

RC2: PG7 23 – this is an interesting use of the word "modest" to refer to $1bn! I take the point, but recommend changing.

***AC**: We thank the reviewer for pointing this out. We have revised the language here.*

RC2: PG8 10 – Not sure about "calculate" here, think "estimate" or something similar is more accurate.

***AC**: We have revised to use "estimate" instead of "calculate".*

RC2: PG9 5 – I'm not convinced by the way this is framed. I agree that larger floods can be more damaging, but not necessarily that they always ARE. Likewise, small, more frequent floods can also cause damage, but not always. This will be very catchment and site specific and depend on the floodplain topography and siting of assets. In some cases, it may be that the 1% event floods all assets in a location, and therefore a bigger flood makes no additional difference. I'm therefore a bit uncomfortable with the certainty that all the estimates are underestimates of damage, particularly given levels of uncertainty in the methods anyway. I'd recommend this section is reworded to be less explicit in predicting the results of refining the methods! Perhaps just highlighting the absence of the frequent small floods and the potential effects of larger events in some (most? many?) catchments and saying it will invariably effect the damage estimates, rather than specifically state your estimates are definitely underestimates of damage in all cases.

***AC**: We appreciate this comment from the reviewer, and also recognize this to be a clear avenue for future research. We have reworded this section to more clearly reflect what we can and cannot infer from our results.*

RC2: Figure 3 – I'm not sure about the p-value reported in the caption. The purpose of a p-value is only to show that it is less than the alpha value set for significance, which is normally 5% or 1% in natural sci. The value of <0.00000001 reported is unnecessary as it doesn't give any more info than something like p<0.001 (0.1%) and may incorrectly imply an incredibly high level of significance is being looked for (as alpha is not explicated stated elsewhere)

AC*: We appreciate this comment and we have revised the figure caption accordingly*.

RC2: Figure 8 – I am perhaps admitting my ignorance of US geography here! But I was not able to easily visualise what the different labelled regions coincided with, particularly given it is being published in a European based journal (albeit an international one) it may be worth adding a map of where you divide up the regions, perhaps this could be incorporated into one of the existing map figures as a background layer to save adding another figure?

Addendum: After typing my report I read the other review comment and noted they have recommended a little more discussion of some of the regional based results. In light of that I really think a map reference of some kind to guide the reader through, as suggested in my figure 8 comment above, would be very helpful.

AC*: These region labels are included in Figure 4, but we recognize that they could be missed if they are not described more explicitly in figures such as Figure 8. We have added reference to Figure 4 here and elsewhere in the manuscript, so that it is more clear to the reader where each of the regions is located.*

~~Modeled changes in~~Climate Change Impacts on 100 year Flood Risk and Asset Damages within Mapped Floodplains of the Contiguous United States

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Abstract. A growing body of ~~recent~~ work suggests that the extreme weather events that drive inland flooding are likely to increase in frequency and magnitude in a warming climate, thus potentially increasing flood~~ing~~ damages in the future. We use hydrologic projections based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) to estimate changes in the frequency of modeled 1% annual exceedance probability (1% AEP, or “100-year”) flood events at 57,116 ~~locations~~ stream reaches across the contiguous United States (CONUS). We link these flood projections to a database of assets within mapped flood hazard zones to model changes in inland flooding damages throughout the CONUS over the remainder of the 21st century. Our model generates early 21st century flood damages that reasonably approximate the range of historical observations, and trajectories of future damages that vary substantially depending on the greenhouse gas (GHG) emissions pathway. The difference in modeled flood damages between higher and lower emissions pathways approaches $4 billion per year by 2100 (in undiscounted 2014 dollars), suggesting that aggressive GHG emissions reductions could generate significant monetary benefits over the long-term in terms of reduced flood ~~risk~~damages. Although the downscaled hydrologic data we used have been applied to flood impacts studies elsewhere, this research expands on earlier work to quantify changes in flood risk by linking future flood exposure to assets and damages at a national scale. Our approach relies on a series of simplifications that could ultimately affect damage estimates (e.g., use of statistical downscaling, reliance on a nationwide hydrologic model, and linking damage estimates only to 1% AEP floods). Although future work is needed to test the sensitivity of our results to these methodological choices, our results indicate that monetary damages from inland flooding could be significantly reduced through substantial GHG mitigation.~~This work uses relatively conservative assumptions and methods that ultimately affect damage estimates; future work is needed to test sensitivity related to these methodological choices (e.g., more sophisticated downscaling methods, use of multiple hydrologic models, and consideration of a wider range of flood magnitudes).~~

1 Introduction

Inland floods are among the most costly natural disasters in the United States (e.g., Pielke and Downton, 2000), with ~~average~~ annual damages ranging from hundreds of millions to many tens of billions of dollars over the past century (Downton et al., 2005; NOAA, 2016). In 2016, inland flooding events in Louisiana and North Carolina alone caused over $10 billion of physical damages to homes, businesses, and other assets (Fortune, 2016; LED, 2016). This follows on other recent years with ~~historical~~ extreme flooding in Michigan (2014) and Colorado (2013), and the mid-Atlantic floods caused by Superstorm Sandy in 2012 (NOAA, 2016). With each occurrence of these damaging flood events, there is renewed interest in determining whether climate change may be partially responsible for changes in the magnitude or frequency of these events (e.g., IPCC, 2012; Trenberth et al., 2015). ~~While the capacity to attribute an individual flood event to climate change remains challenging, the~~ Although the science linking changes in climate extremes to human-caused warming is advancing (e.g., Trenberth et al., 2015; National Academies of Sciences, Engineering, and Medicine, 2016), there are still many challenges to attributing observed historical trends in flooding to human-caused climate change (e.g., Kundzewicz et al., 2014; Berghuijs et al., 2016). As a complement to these attribution studies, forward-modeling approaches using linked climate-hydrologic models could help to characterize future changes in flood risk and vulnerability (e.g., Das et al., 2013; Hirabayashi et al., 2013; Arnell and Gosling, 2016). ~~In any case, projection of long-term trends in the frequency and magnitude of inland flooding remains important for municipalities, utilities, and national decision-makers as they assess their future infrastructure needs and climate vulnerabilities.~~

This study ~~analyzes~~ evaluates 21st century flood risk and flood-related damages across the contiguous United States (CONUS) using downscaled hydrologic projections from 29 global climate models (GCMs) and 2 representative concentration pathways (RCPs) for ~~greenhouse gas (~~GHG~~)~~ forcing~~ extracted from the CMIP5 archive~~. W~~W~~e cross-referenced spatially explicit hydrologic projections with a database ~~that catalogs~~of built assets within each of the mapped “100-year” floodplains in the CONUS. ~~and models flood exposure and damages within each of the mapped 1% annual exceedance probability (AEP; “100-year”) floodplains in the CONUS.~~ Using this combined dataset, we generate regional estimates of how ~~modeled~~ cumulative damages from what are currently 1% AEP events might change through the 21st century, due to changes in the frequency of these events through time. We then compare ~~and~~ how ~~these~~ flood damages might differ under a higher GHG emissions scenario (RCP 8.5) vs a lower emissions scenario (RCP 4.5). We focused on these two RCPs both for consistency with the forthcoming Fourth National Climate Assessment (USGCRP, 2015) and to help quantify changes in flood risk in response to reduced GHG emissions globally.

~~Our analysis builds on a deep body of previous work that has mined both historical hydrologic records and future climate projections to evaluate where detectable changes in extreme precipitation or flooding might have already occurred, as well as where we might expect these changes to occur in the future. For example, a number of studies have found statistically significant trends in streamflow for some regions of the United States (e.g., Lins and Slack, 1999; Mallakpour and Villarini, 2015; McCabe and Wolock, 2002). However, even where trends exist in these records, these trends are not always spatially~~

~~coherent (e.g., Archfield et al., 2016), and the extent to which these trends can be attributed to anthropogenic forcing is not always clear (e.g., Hirsch and Ryberg, 2012).~~

Because available hydrologic records tend to be short relative to the return interval of extreme flood events, ~~analyses~~ simply detecting ~~of historical flood~~ trends in historical flooding can be challenging (e.g., Hirsch and Ryberg, 2012; Mallakpour and Villarini, 2015; Archfield et al., 2016)~~are commonly inconclusive~~. Furthermore, even where hydrologic changes can be detected, concurrent changes in land use and population make it difficult to attribute changing flood damages to climate change (e.g., Pielke and Downton, 2000; Kundzewicz et al., 2014). Thus, there may be some advantages to using forward modeling approaches where the effects of climate change can be modeled in isolation. ~~has been significant interest in using climate model outputs to evaluate future flood risk.~~ Unfortunately, this is expensive computationally: at present the most widely used strategy for assessing changes in future flood risk requires downscaling GCM outputs to hydrologically relevant spatial scales; estimating precipitation, infiltration, and runoff within a hydrologic modeling framework; and routing the resulting flows through a model river network (e.g., ~~Das et al., 2013; Hirabayashi et al., 2013;~~ Reclamation, 2014). Although less computationally demanding, studies attempting to link projected changes in extreme precipitation directly to changes in flooding (i.e., without a spatially explicit hydrologic model) tend to have high uncertainties (e.g., Kundzewicz et al., 2014; Wobus et al., 2014).

~~More r~~Recently, computational power has increased to the point that ~~methods to~~studies using downscaled and routed GCM-derived precipitation have become more ~~readily~~ common ~~available~~ (e.g., Gosling et al., 2010; Hirabayashi et al., 2008; Reclamation, 2014). These outputs have been used to project future flood risk at scales ranging from local (e.g., Das et al., 2013) to global (e.g., Hirabayashi et al., 2013; Arnell and Gosling, 2016~~; Hirabayashi et al., 2013~~). However, to our knowledge there has not yet been a CONUS-scale assessment of how ~~these~~ changing inland flood ~~risks~~ hydrology could translate into changing monetary damages.

2 Methods

We used simulated daily hydrographs at 57,116 ~~locations~~ stream reaches across the CONUS between 2000 and 2100 to calculate a CMIP5 modeled baseline (“~~‘~~current climate”~~’~~) 1% AEP event, and changes in the frequency of flows exceeding this magnitude through the 21st century. We quantified asset exposure and expected flood damage within mapped floodplains using a combination of Federal Emergency Management Agency (FEMA) flood maps, US Census block data, and land cover data. Because only the “100-year” floodplains are consistently mapped and available at a national scale, our model of flood damages is driven only by changes in the frequency of what are currently 1% AEP events through the 21st century. We also do not project changes in population growth, floodplain development or flood protection through time, ~~as~~ since 1) such projections would require assumptions that would be difficult to apply at a national scale across multi-decadal timeframes (e.g., Elmer et al., 2012); and 2) the impacts of those assumptions might obscure the climate change signal we seek to characterize. ~~are more difficult to justify at a national scale than for more regional or localized studies (e.g., Elmer et al., 2012).~~

Our model projections should therefore be considered order-of-magnitude estimates of how differences in emissions scenarios might propagate into changes in flood damages throughout the United States~~, based on available data from CMIP5~~.

2.1 Hydrologic Modeling Inputs

We used spatially and temporally disaggregated precipitation and temperature at 1/8th degree resolution from 29 GCMs and 2 emissions scenarios (RCP4.5 and RCP8.5), generated using the bias correction and spatial disaggregation (BCSD) method (e.g., Wood et al., 2004). The BCSD method uses a quantile mapping approach to match the distribution of GCM-derived monthly outputs to the observed monthly data at a 1-degree resolution in a historical period (1950–2000). It then uses the spatial pattern of daily observations from an analog month as a proxy for sub-grid scale daily (temporal) variability, and scales or shifts these daily observations to ensure that the analog monthly average values match the rescaled GCM output. During the bias correction process (which applies to monthly precipitation and temperature values at the GCM scale), projected precipitation values exceeding the upper end of the climatological range are extrapolated following an extreme value Type I distribution. Additional details of the BCSD weather generation are given in Harding et al. (2012) and Wood and Mizukami (2014).

Catchment hydrology was simulated using the variable infiltration capacity (VIC) hydrologic model (Liang et al., 1994) forced by the BCSD precipitation and temperature fields. The VIC model simulates the range of hydrologic processes relevant to generating runoff, including interception on the forest canopy, evapotranspiration, water storage and melt from snowpack, infiltration, and direct runoff. The runoff component of each model grid cell was remapped to the Hydrologic Response Units (HRUs) defined in the United States Geological Survey (USGS) Geospatial Fabric (GF; Viger and Block, 2014), and then routed through the GF river network using the MizuRoute routing tool, which incorporates both hillslope and river channel processes (Mizukami et al., 2016a). The GF dataset contains ~57,000 river segments and ~108,000 HRUs (including the right and left bank of most river segments), representing catchments approximately equivalent in area to 12-digit Hydrologic Unit Code basins. The methods used for the downscaling and land surface hydrology were identical to those used in previous studies (e.g., Das et al., 2013; Reclamation, 2014). However, for this effort we used a multi-scale parameter regionalization approach (Samaniego et al., 2010) to improve the spatial coherence of VIC model parameters across basin boundaries (Mizukami et al., In Review). Nash-Sutcliffe Efficiency coefficients indicate that the model adequately captures the magnitude and variability of observed flows across most of the CONUS, while the updated VIC parameters remove some of the artifacts that were observed from the Reclamation (2014) dataset (see Supplemental Information File #1). Full details of the downscaling, VIC model parameters, and routing methodologies are ~~available~~ described in ~~Mizukami et al. (In Review) and~~ Reclamation (2014) and Mizukami et al. (In Review), and are summarized in Supplemental Information File #1.

~~Future changes in extreme precipitation are uncertain, but the methods used here are conservative with respect to predicting increases in precipitation. A growing body of work indicates that future extreme events are likely to increase more than the mean increase in precipitation (e.g., Kendon et al., 2014; Prein et al., 2016); however, BCSD only scales the extreme events~~

~~with the mean changes. Although downscaling is required to simulate catchment hydrology at a physically meaningful scale, and the BCSD method has been used in the past to account for precipitation changes in hydrologic modeling applications (e.g., Das et al., 2013; Shrestha et al., 2014; Ning et al., 2015), downscaling methods are themselves imperfect. While BCSD has been shown to have fewer artifacts in historical climate compared to other commonly used methods (e.g., Gutmann et al., 2014), we show here that BCSD does introduce an artifact into the precipitation time series between historical and future projections. In particular, we found that the bias correction process generates a step change in the distribution of extreme precipitation events in the year 2000 (the break between the hindcast and the forecast periods in this BCSD application). As summarized below, we accommodated this in our analysis by using an early 21st century ensemble average to represent baseline hydrologic conditions instead of the more traditional late 20th century. This choice is also conservative, as a longer time period starting in the late 20th century would increase the modeled changes, even if there were a way to do so without folding in the artifact introduced by the BCSD method.~~

2.2 Modeling Flood Probability

For each of the 58 GCM/RCP combinations in the hydrologic model output, we extracted the time series of annual maximum flow between 1950 and 2099 at each of the ~ 57,000 GF stream locations in the CONUS. Average annual maximum flows in the modeled reaches range from < 5 m^3/s to > 1,000 m^3/s (Figure 1). Prior to generating statistics of peak flows from these events, we plotted the normalized annual maximum time series across all segments and all models (Figure 2). This plot revealed a step in the annual maximum flow time series in the year 2000, which corresponds to the end of the hindcast period used in the BCSD method. This step is even more pronounced in the BCSD precipitation inputs (Figure 3), and most likely reflects the change in how the BCSD method constrains the distribution of events in the historical period compared to in the future period.

In order to prevent this artifact from influencing our analysis of future flooding events, we used an early 21st century ensemble average (2001-2020) to represent baseline hydrologic conditions, rather than the more traditional late 20th century baseline. We calculated the magnitude of the "baseline" modeled 1% AEP flood event at each stream segment by fitting a generalized extreme value (GEV) distribution to the full ensemble of annual maximum flow estimates for each RCP over the 2001–2020 period (29 models x 20 years = 580 values), and extracting the 99th percentile value from this model fit. Although the emissions pathways for RCP4.5 and RCP8.5 begin to diverge in 2006, there were no systematic differences between GEV fits for the two RCPs, justifying our treatment of this early 21st century period as a baseline across the full ensemble.

Individual GCMs exhibit a degree of dependence due to shared code, shared scientific literature, shared observations, etc., and as such are not statistically independent (Abramowitz, 2010; Knutti et al., 2010b; Bishop and Abramowitz, 2013). However, the consensus of the community remains that it is best to average across many ensemble members (Tebaldi and Knutti, 2007; Knutti et al., 2010a) as we have done here. In addition, there were no systematic differences in results in the annual maximum time series from the 29 individual GCMs, justifying our treatment of the full ensemble of 580 ~~of~~ annual maxima when assessing peak flow magnitudes. From this full ensemble, we evaluated uncertainty in the 1% annual probability event by bootstrapping (see Supplemental Information File #2~~1~~). Based on these analyses, we expect the sample uncertainty on our 1% AEP flood event to be in the range of 5–20%. As shown later, the variability in the multimodel GCM ensemble is much larger than this uncertainty in the GEV fits, so we did not propagate this source of uncertainty through all of our calculations.

To estimate future flood frequency and damages through the 21st century, we compared the full transient of future annual streamflow maxima for each GCM/RCP combination to the baseline 1% AEP event. In all of the summaries that follow, we define a “flood” at a given stream segment as an annual maximum flow value that exceeds the baseline 1% AEP event at that segment. The comparison between future flows and the 1% AEP threshold yields a time series of floods at each segment, as well as an estimate of the total number of flood events nationwide in each year. At each segment, we also calculated an ensemble average probability of exceeding the 1% AEP event in each year, by tabulating the fraction of models experiencing a flood and smoothing these probabilities over a 20-year moving window. These time- and ensemble-averaged flood probabilities by segment were then linked to the assets exposed within each floodplain to calculate projected annual damages, as summarized below.

2.3 Asset Exposure and Damages

We estimated asset damages resulting from current 1% AEP flood events using data from an experimental tool under development for the U.S. Army Corps of Engineers Institute for Water Resources (~~USACE~~IWR, 2014). For this tool, we compiled all of the 1% AEP floodplains as mapped by FEMA and included in the National Flood Hazard Layer (NFHL). We then used a series of steps to calculate the depth of flooding and resulting damages from 1% AEP events, and merged this information with the flood probabilities described in Section 2.2. A brief summary of the flood damage calculations follows. Supplemental Information File #2 provides more complete details of the flood damage calculations.

2.3.1 Cataloguing Damages by Flood Zone

To catalog damages by flood zone, we intersected 1% AEP flood boundaries with Census blocks to create a set of flood zone polygons subdivided by Census block boundaries. Within each of these flood zone/Census block units, we calculated the distribution of ~~created a random sample of~~ flood depths for the 1% AEP event using the National Elevation Dataset (NED; USGS, 2016). We then merged this information with land cover data from the National Land Cover Dataset (Homer et al., 2015) to determine the distribution of flood depths within “developed” ~~and “undeveloped”~~ portions of each Census block, and~~. For portions designated as “developed,” we used the distribution of depths to~~ estimated exposure of built assets using FEMA’s HAZUS-MH General Building Stock inventory (FEMA, 2009). The General Building Stock inventory provides estimates of the number and aggregate dollar value of multiple types of residential, commercial, and industrial buildings for each Census block.

For the developed portion of each Census block/floodzone intersection, we created damage estimates using depth-damage functions from USACE and FEMA (FEMA, 2009; USACE, 2000, 2003). A separate depth-damage function was used for each of 28 different categories of buildings (e.g., residential one-story homes without a basement). Each depth-damage function describes the percent loss as a function of depth. The depth-damage functions were applied to the aggregate value for each building category within each NFHL-Census block intersection, using the depth exposure results described above.

2.3.2 Aggregating Damages to National Scale

Once the damage estimates were generated for each Census block/floodplain intersection, we aggregated this information up to the same HRUs that were used in the hydrologic analysis. We then linked each stream segment at which flood statistics were calculated back to the total asset damages resulting from a 1% AEP event at that location. Figure 4 shows the total damages expected from 1% AEP events at each of the HRUs across the CONUS.

For each GCM, we combined the timeseries of floods at each stream segment with the assets exposed in that HRU to compute a timeseries of monetary damages. When averaged across all nodes in the CONUS, this approach yielded a relatively smooth curve of CONUS-wide monetary damages through the 21st century. However, this approach treats the hydrologic timeseries from each GCM as a deterministic, rather than a probabilistic, projection of future conditions. In order to use the full ensemble of GCMs in a more probabilistic framework, we used a Monte Carlo approach. We simulated 1,000 100-year time series of flood damages in the CONUS using the ensemble average probability of exceeding the 1% AEP event at each segment in each year. This yielded a distribution of flood damages in each year, from which we extracted a minimum, maximum, and ensemble average for each of the RCPs.

2.4 Uncertainties

Each of the methodological steps outlined above introduces uncertainties into our analysis. While it may not be possible to quantify all of these uncertainties, we summarize each of them here along with our best judgement on the magnitude and directionality of their impacts.

First, GCMs have historically not resolved precipitation well (e.g., Flato et al., 2013), such that downscaling is required to simulate catchment hydrology at a physically meaningful scale. Although the BCSD method has been used in the past to account for precipitation changes in hydrologic modeling applications (e.g., Das et al., 2013; Shrestha et al., 2014; Ning et al., 2015), downscaling methods are themselves imperfect. While BCSD has been shown to have fewer artifacts in historical climate compared to other commonly used methods (e.g., Gutmann et al., 2014), our analysis shows that the BCSD method does introduce an artifact into the precipitation time series between historical and future projections, which is not well understood (see Figures 2-3). Our use of an early 21st century "baseline" to circumvent this artifact is likely to be conservative, since it reduces the magnitude of climate changes since the mid-20th century. Furthermore, since precipitation extremes are likely to increase more quickly than averages in the future (e.g., Kendon et al., 2014; Prein et al., 2016), our reliance on BCSD downscaling to drive future hydrologic changes is likely to underestimate changes in hydrologic extremes through time.

Second, the choice of hydrologic model will introduce uncertainty into our analysis (e.g., Mendoza et al., 2015; 2016; Mizukami et al., 2016b). Comparison of hydrologic results from different VIC parameter sets indicates that the choice of hydrologic model parameters within the VIC modeling framework does not substantially change the model's ability to simulate natural flows (see Supplemental Information File #1), though it may alter model performance at specific locations or times. ~~This suggests that changes in parameterization within a given model may not substantially alter results.~~ However, because our method includes spatially explicit estimates in flooding and damages, the direction and magnitude of impact from selection of a different hydrologic model would depend on how differently an alternative hydrologic model simulates relevant hydrologic processes in different regions, and is therefore difficult to estimate *a priori*.

Third, because the 1% AEP (100 year return interval) floodplains are the only flood risk zones consistently mapped at a national scale, our model tabulates damages only within these mapped floodplains. Consideration of a wider range of flood magnitudes would increase modeled damages under both baseline and future scenarios, since floods smaller and larger than 1% AEP events will also generate monetary damages. The relative change in future vs baseline flood damages across a full range of flood magnitudes would depend on the spatial distribution of built assets in each modeled reach, and how the relative change in smaller (e.g., 25-year) vs larger (e.g., 500-year) events interact with this distribution of built assets.

Finally, we did not propagate projected changes in population, floodplain development, or flood protection through our analysis. We made this choice so that we could isolate the effects of hydrologic changes, which are themselves uncertain, from the effects of socioeconomic changes, which ~~that~~ may be impossible to predict. For example, while increased development in flood-prone areas could increase exposure of built assets to increased flooding, flood protection investments that decrease exposure may be equally likely. Because the uncertainties in socioeconomic projections and future changes to floodplain management could potentially overwhelm the uncertainties in our hydrologic model outputs, our results rely on the simplifying assumption that the built environment remains static through the 21st century. Over the past century, development ~~has typically~~appears to have contributed to increased flood damage costs (e.g., Pielke ~~et al. 2002~~and Downton, 2000), so to the extent that human behavior remains it is likely that our assumption underestimates future costs.

Despite these uncertainties, CONUS-wide annual inland flooding damages estimated using our approach are very similar to inland flooding damages observed over the 20th and early 21st century, as summarized below. Based on this observation and the caveats summarized above, we expect that our nationwide projections represent at least order-of-magnitude estimates of historical and future flood damages.

3 Results

~~Although each GCM/RCP combination yields its own time series of flooding, we have no a priori reason to focus on or exclude any individual models. Thus we center our discussion on the distribution of results across all 29 GCMs for each RCP.~~

3.1 Flood Frequency Projections

Since the hydrographs generated by the downscaled hydrology outputs are unique to each GCM/RCP combination, each model also produces its own time series of flooding at each stream segment. As one way of summarizing these data, we calculated the total number of flood events across the CONUS in each year of each model simulation. We then summarized the distribution of the total number of flood events across all 29 GCMs for each RCP (Figure 5). As expected based on our method, the annual number of 1% AEP floods across the CONUS across all models averages approximately 500 events between 2000 and 2020 (~1% of the ~ 57,000 segments in the CONUS). This average number of floods increases ~~slightly~~ to approximately 750 events by 2100 under RCP4.5, and up to approximately 1,250 events under RCP8.5.

Using the time series of flooding for each segment and combining these values across all models, we calculated an average flood frequency by segment for 20-year intervals in the baseline (2001–2020), mid-century (2040–2059), and late century (2080–2099). This allowed us to calculate an ensemble-averaged change in flood frequency for each segment, to evaluate where there may be spatially coherent patterns of increased flood risk. As shown in Figure 6, the largest fractional changes in flood frequency across the CONUS occur in the southern Appalachians and Ohio River valley, the northern and central Rocky Mountains, and the Northwest. In each of these regions, the ensemble average across models suggests that historical 1% AEP events could become 2–5 times~~x~~ more frequent by the end of the century.

In some regions of the United States (e.g., the southern Appalachians and northern Rocky Mountains), the spatial patterns of increased flood frequency can be explained by the increased occurrence of extreme precipitation events projected by ~~BCSD~~ the GCM-derived precipitation outputs. In other regions such as the Sierras and the Cascades, increases in the frequency of flood events are not as easily explained by changes in precipitation alone. In these locations, the increase in frequency of extreme floods more likely reflects changes in the nature of winter precipitation (rain vs snow) compared to baseline conditions (e.g., Das et al., 2013).

3.2 Flood Damage Projections

By combining the changes in frequency of flooding at each segment with the asset exposure and damage associated with each floodplain, we generated a full time series of projected changes in flood damages across the CONUS through the 21st century. Figure 7 shows the results from 1,000 individual simulations of nationwide flood damages using the probability of flooding at each segment, as described in Section 2.3.2. Since we assume no changes in built assets or flood protection within mapped floodplains, ~~As shown in Figure 7,~~ changes in flood damages broadly mimic changes in flood frequency at a national scale (Figure 7; compare to Figure 5~~5~~), with minor differences between these trends reflecting the way that regional trends in flood frequency interact with asset exposure within 1% AEP floodplains (see Figure 4). ~~In particular, e~~Expected annual flood damages under the RCP4.5 scenario increase ~~modestly~~ from approximately $3 billion between 2000 and 2020 to approximately $4 billion by the end of the century. Under the RCP8.5 scenario, expected annual flood damages increase from approximately $3 billion in the early 21st century to over $7 billion by 2100.

Figure 7 also highlights how different GHG emissions pathways generate different trajectories of flood damages through the remainder of the 21st century. While the RCP4.5 and RCP8.5 pathways are generally similar through mid-century, the damage trajectories under the two emissions scenarios begin to diverge in the latter half of the 21st century. By 2075, the average annual difference between flood damages under the RCP4.5 and RCP8.5 emissions pathways is approximately $2 billion, and by 2100 this difference grows to almost $4 billion.

The increasing flood damages under RCP8.5 relative to RCP4.5 are not evenly distributed throughout the United States. Figure 8 shows the time series of average annual damages in each region of the CONUS. As shown in Figure 8, the most significant differences between projected flood damages under the two emissions scenarios are in the Southeast, where the difference between the two trajectories approaches $~~2~~ 1.5 billion per year by the end of the century; and in the Northeast and Midwest, where the difference between the two scenarios is ~~almost $1~~close to $750 million ~~billion~~ per year by 2100. Although there are ~~subtle~~ also differences in damages between the two emissions scenarios in other regions ~~(e.g., the Southwest and the Midwest)~~, these differences are generally small relative to those ~~two~~ three regions of the country. The increasing flood damages projected for the Southeast, Northeast and Midwest are consistent with increases in modeled changes in annual maximum precipitation throughout the eastern United States, as described in the third National Climate Assessment (e.g., Walsh et al., 2014), combined with the high value of built assets within floodplains in these regions relative to the rest of the nation (see Figure 4).

4 Discussion and Conclusions

Based on our model, we find that if future GHG emissions remain unchecked, monetary damages from flooding throughout the CONUS are likely to increase through the 21st century. Global GHG reductions, represented by RCP4.5, could limit these increasing flood damages, potentially saving ~~up to $4 billion~~billions of dollars per year (in undiscounted 2014 dollars) by the end of the century. To our knowledge, this study is the first to link spatially explicit hydrologic projections from a full ensemble of climate model projections to mapped assets in order to ~~calculate~~ estimate future flood damages at a national scale.

Although this study represents a significant methodological advance in projecting future inland flooding damages nationwide, there are a number of ~~caveats that must be noted~~avenues for future work. As summarized in Section 2.4, these avenues include further exploration of different downscaling methods; consideration of different hydrological models; and simulation of a wider range of flood magnitudes and the intersection of these flood zones with built assets.

~~Perhaps most importantly, GCMs do not resolve precipitation well (e.g., Flato et al., 2013). The BCSD downscaling method used here was designed in part to improve the representation of historical precipitation, but our analysis shows that this method also introduces artifacts into the time series of extreme precipitation between the historical and future projections that are not well understood (e.g., Figure 3). The gradual increase in future precipitation extremes observed between 2000 and 2100 reflects increasing precipitation projected by the raw GCMs, which ultimately drives increases in the frequency of damaging floods in our modeling. However, an improved representation of precipitation extremes would improve confidence in our results.~~

Preliminary analysis of precipitation outputs from the newer localized constructed analogue (LOCA: Pierce et al., 2014) ~~statistical~~ downscaling method suggests that artifacts introduced by the BCSD method are likely to exist in other products as well. Ideally, future hydrologic projections could be driven by a dynamically downscaled climate model to avoid the artifacts introduced from~~se~~ statistical ~~artifacts~~downscaling.~~;~~ H~~h~~owever, full dynamical downscaling through the 21st century at the scale of the CONUS may remain computationally prohibitive for a number of years to come (see for example Liu et al., 2016).

In the interim, future work could replicate the method described here using quasi-dynamical downscaling methods (e.g., Gutmann et al., 2016).

~~In some cases, the uncertainty introduced by hydrologic model choice could also be significant (e.g., Mendoza et al., 2015; 2016; Mizukami et al., 2016b). We generated preliminary comparisons of hydrologic projections using two different VIC parameter sets as a part of this work, which suggest that the VIC parameters may not significantly influence extreme flow estimates at the reach scale. However, future work could expand this analysis to more rigorously evaluate projections from different parameter sets and/or hydrologic models.~~

~~In addition to potential issues with the downscaled hydrology, our method is limited by available data on assets exposed to inland flooding. Because the 1% AEP (100 year return interval) floodplains are the only flood risk zones consistently mapped at a national scale, our model tabulates damages only within these mapped floodplains. Our simulations generate damage estimates in the early part of the 21st century that are remarkably similar to historical inland flooding damages nationwide (Figure 8), suggesting that our damage estimates are reasonable. However, it is important to stress that we are unable to project damages outside of these mapped floodplains, including flash floods that could be driven by localized extreme precipitation events (e.g., Prein et al., 2016).~~

~~Our method also relies on the simplifying assumption that damages from *any* flow exceeding the 1% AEP event can be estimated based on the asset inventory and depth-damage functions tabulated within mapped floodplains. In reality, larger floods will cause more damages than smaller floods, so the magnitude of the flow above the 100-year baseline event will play a role in determining total damages. However, ~~W~~w~~ith the exception of limited mapping of 500-year floodplains, there is no national data available to evaluate how damages might increase with increasing flood magnitude above or below the 1% AEP event. However, there are some locations in the United States where floodplains are mapped at a range of magnitudes both above and below the 1% AEP event (FEMA, 2014). Case studies from these locations could allow us to explicitly model the damages encompassed by these smaller and larger events, and evaluate local changes in flood damages driven by a wider range of flood events.

~~Similarly, more frequent floods (e.g., the 10- or 50-year event) will still result in monetary costs not evaluated here. Thus our estimates of damages within 100-year floodplains will be minimum estimates for both the baseline and the future time periods. To the extent that floods become both larger and more frequent through time, the degree to which we underestimate flood damages should also increase in the future.~~

Finally, we stress that even if global GHG emissions are substantially reduced, ~~because~~ there is no *a priori* way to predict how humans will adapt to future flood risk under any emissions scenario~~, our model does not account for current or future adaptations to protect against changing flood frequencies~~. ~~For similar reasons, we also do not account for population growth or increasing development within flood risk zones. Existing flood control structures are in many cases able to mitigate downstream impacts of extreme flows, such that future changes in the frequency of those flows may not translate directly into increased damages in flood-protected locations.~~ As summarized in Section 2.4, f~~F~~uture demographic and infrastructure changes could ~~also~~ either increase or decrease damages from flooding in the future: increased flood protection measures could decrease damages, while increases in development in ~~the floodplain~~flood-prone areas could increase them. While ~~it seems clear~~ our modeling indicates that nationwide exposure to flooding will increase through the 21st century~~ in many parts of the United States~~, the overall damages incurred will depend ~~in large part~~both on how we alter our emissions, and how we ~~humans~~ adapt to ~~this increasing~~changing risks of future flood~~-~~ing~~risk~~.

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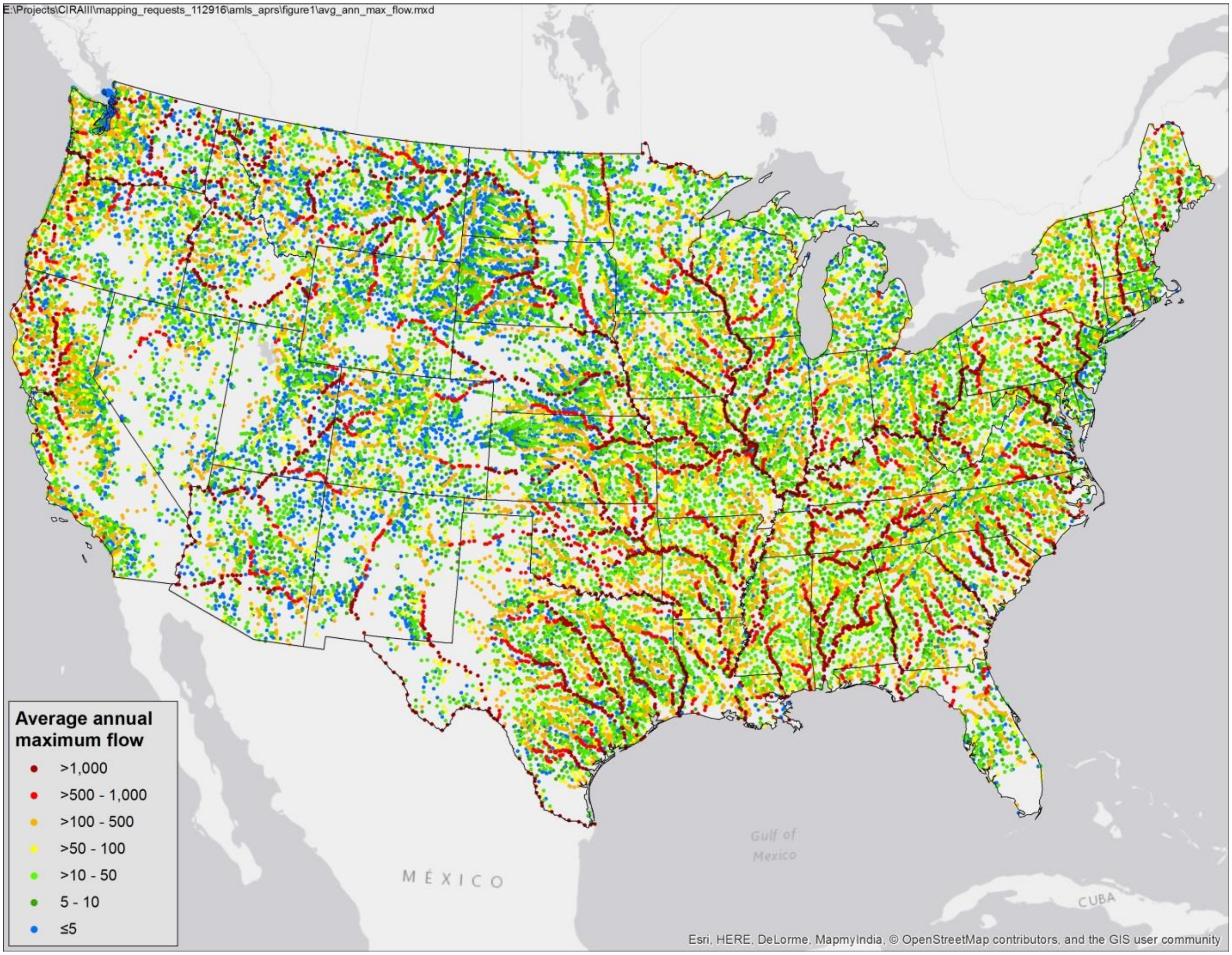

Figure 1: Locations of the 57,116 stream segment with hydrologic projections used in our analysis. Color corresponds to the baseline average annual maximum flow for each segment, in m^{3}s^{-1}.

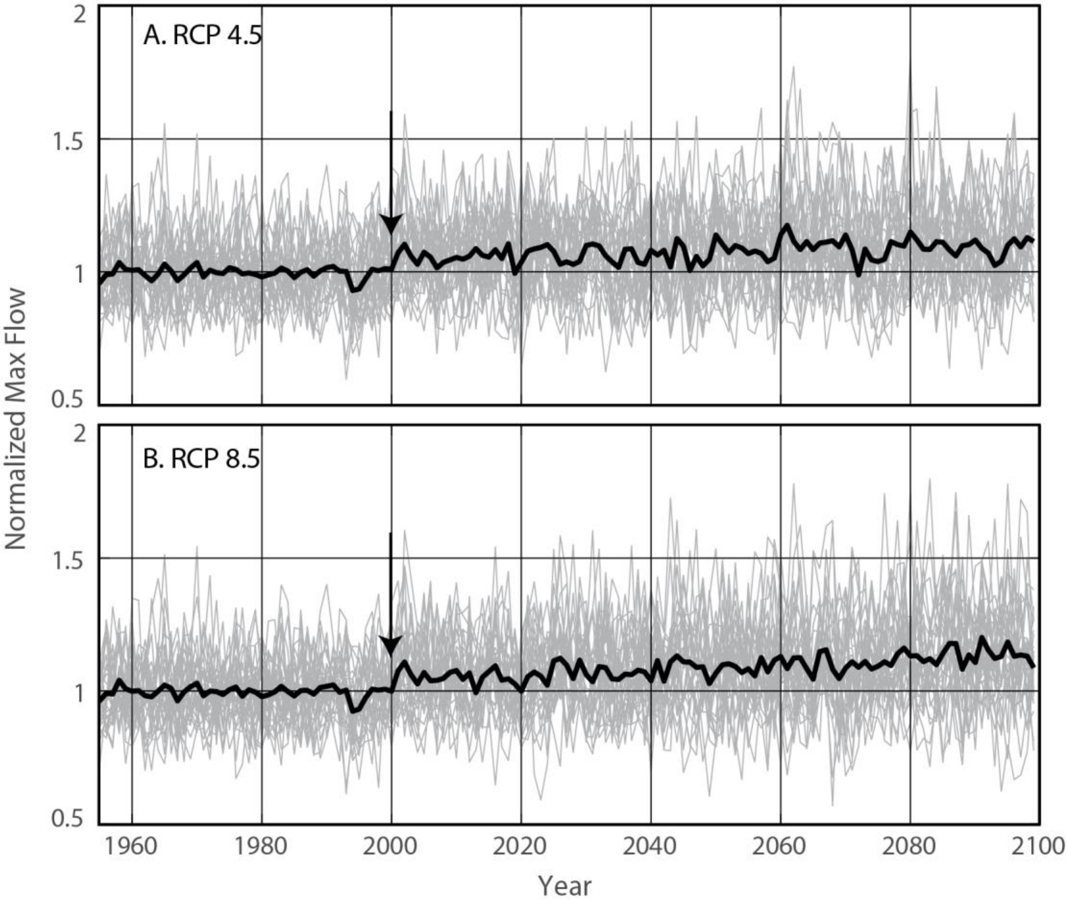

Figure 2: Trends in annual maximum flow across all stream segments in the CONUS. Thin grey lines represent annual maximum flow normalized to 2001–2020 mean, and averaged across all segments for each individual model. Thick black line represents ensemble average. Step increase in the year 2000 for both RCPs (black arrow) is an artifact of the BCSD method. Accordingly, the "baseline" 1% AEP event was calculated from an early 21st century ensemble (see text).

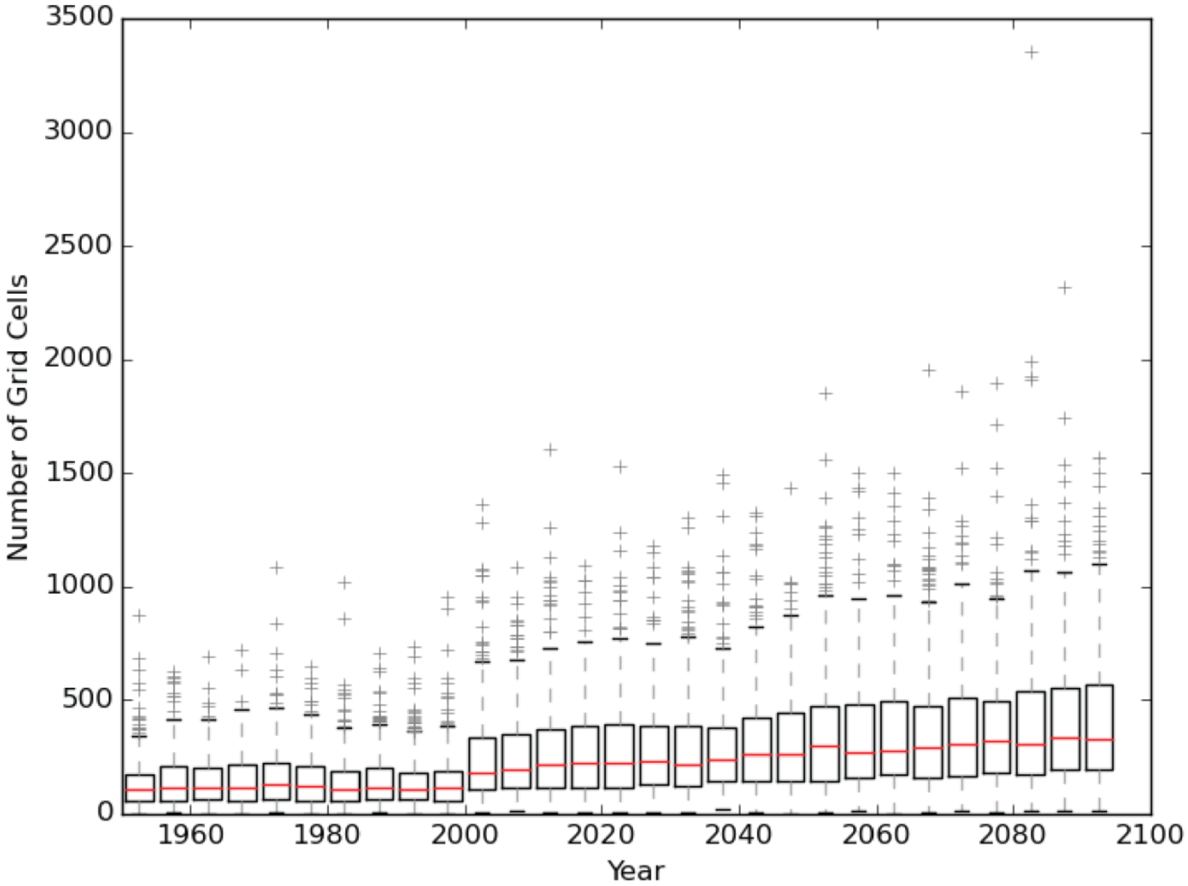

Figure 3: Number of BCSD grid cells in CONUS experiencing their maximum daily precipitation in each year between 1950 and 2100 per model. Box and whiskers represent spread across all of the individual models used in the flow simulations. The step in the year 2000 ~~(black arrow)~~ is an artifact of the BCSD method (~~t-test~~ p value <0.00~~000000~~1). ~~Light grey shading shows period used to calculate "b~~"Baseline" 1% AEP event was calculated using the years 2001-2020.

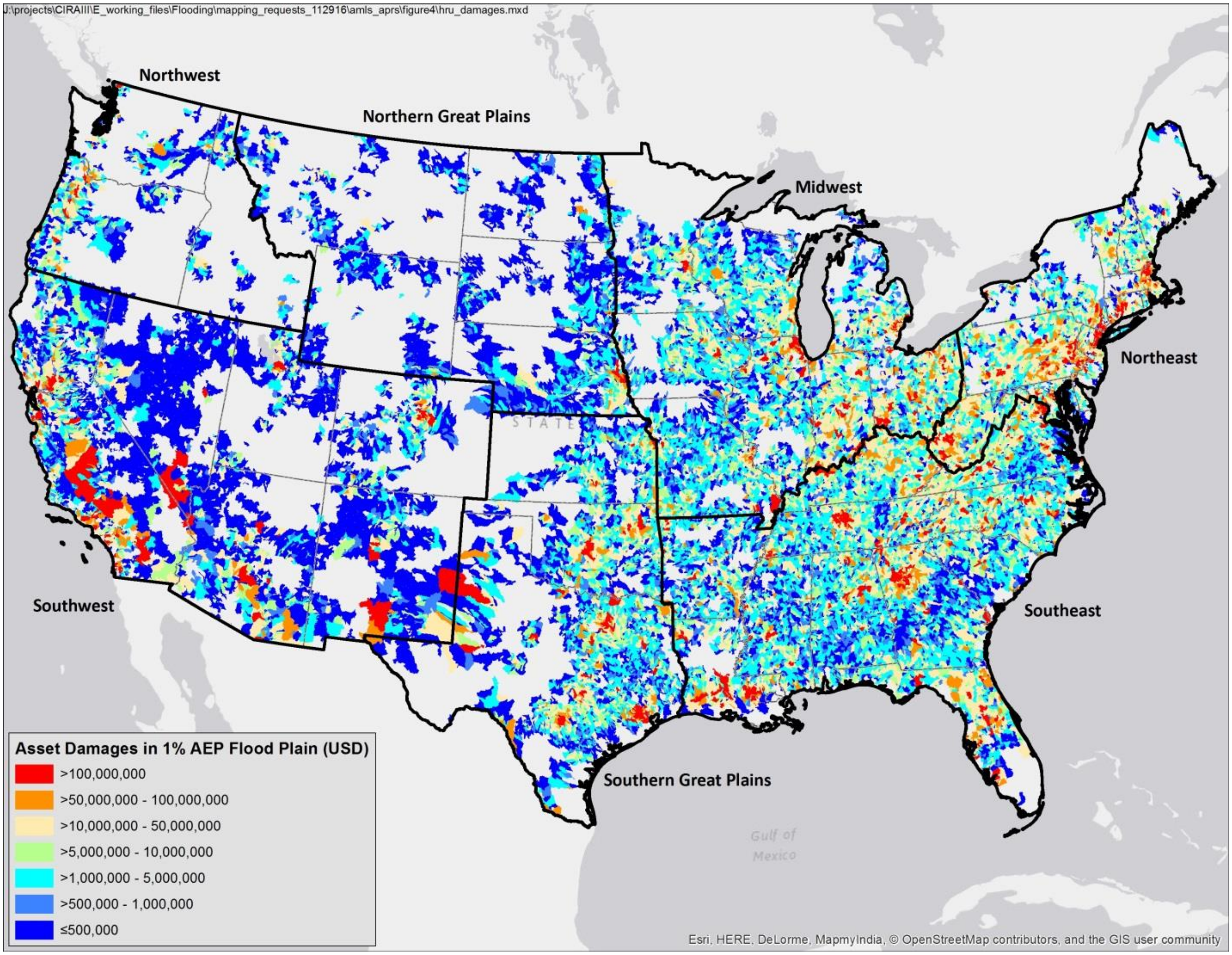

Figure 4: Total ~~expected~~ asset damages from a 1% AEP flood event in each of the HRUs in the CONUS. Values in 2014 dollars.

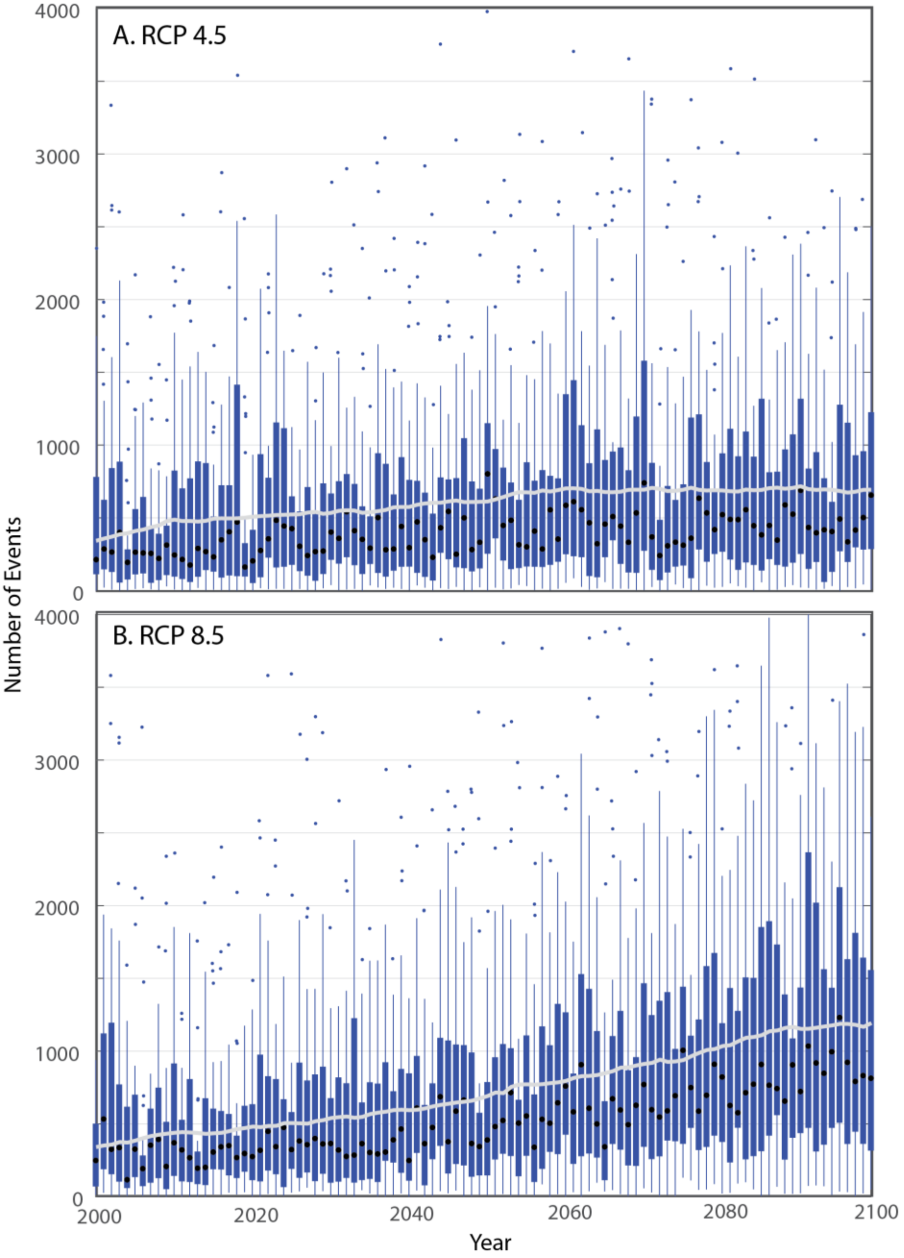

Figure 5: Number of floods throughout CONUS in each year of the 21st century, across all 29 GCMs in A) RCP4.5 and B) RCP8.5. In each plot, black dots are the median value across all 29 GCMs, thick blue bars are the middle 50% of models, whiskers extend to the 95th percentile of values, and dots represent outliers. The thick grey line is the five-year moving mean across all models. Light grey shading in background shows period used to calculate "baseline" 1% AEP event.

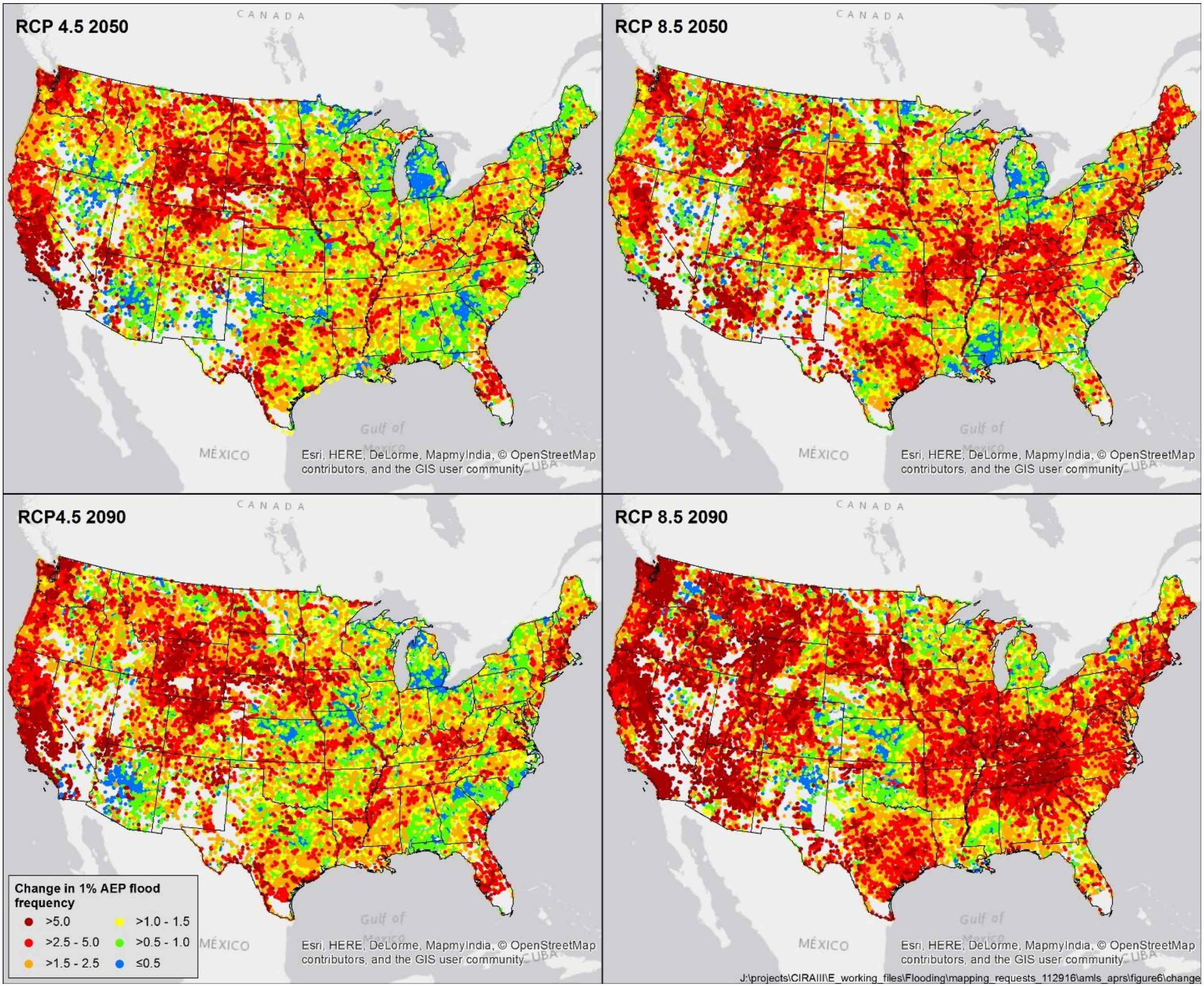

Figure 6: Change in frequency of historical 1% AEP events based on ensemble averages for specified RCP and time periods. Calculations are based on individual stream segments over 20-year periods centered on A) 2050 for RCP4.5, B) 2050 for RCP8.5, C) 2090 for RCP4.5, and D) 2090 for RCP8.5. Values are expressed as ratios (e.g., a value of 2 corresponds to a doubling in frequency of the historical 1% AEP event).

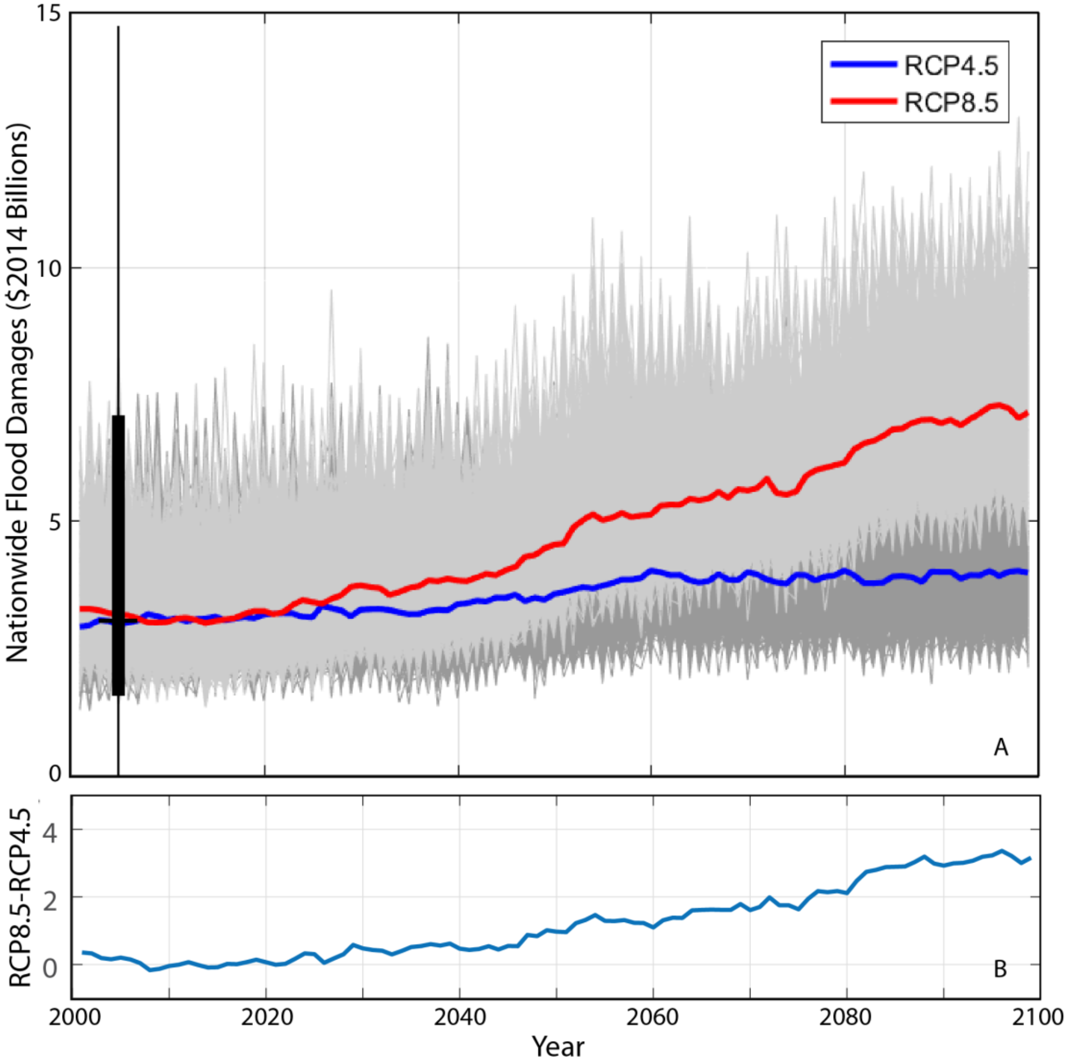

Figure 7: A) Projected national flood damages within 100-year flood zones, in 2014 dollars. Thin grey lines are 1,000 simulations of damages for RCP4.5 (dark grey) and RCP8.5 (light grey). Blue and red lines are means of simulations for the two RCPs. Box and whisker plot at left is the range of historical observed flooding in CONUS between 1903 and 2014 (10 outliers not shown). B) Difference between mean annual flood damages between RCP4.5 and RCP8.5 (billions of 2014 US dollars).

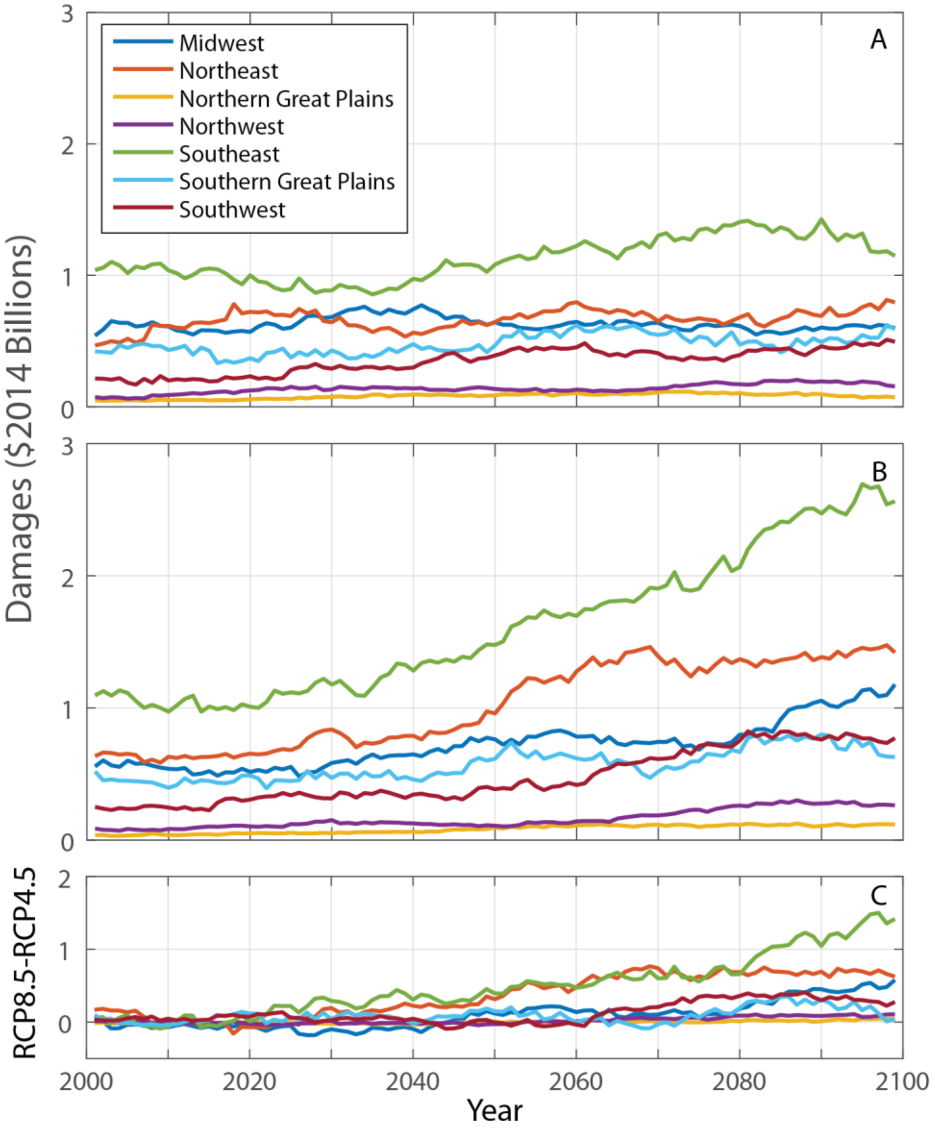

Figure 8: Average annual flooding damages by region for A) RCP4.5 and B) RCP8.5. C) Difference in annual flood damages between RCP4.5 and RCP8.5 by region (billions of 2014 US dollars). See Figure 4 for delineation of regions.