Author's final response- Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C

C.F. SCHLEUSSNER ET AL.
ESD-2015-68

Reviewer 1

We thank the reviewer for the in-depth review of our manuscript and the very detailed comments that substantially helped to improve our manuscript.

General Comment 1:

> One general comment is that I think there needs to be a bit more detail about the temperature limits. As much of the paper is phrased, 2◦C (or 1.5◦C) is seen as the upper limit of global mean temperature rise. However, those numbers are fundamentally heuristic, not hard limits. It could be that 1.9◦C is already dangerous, and 2◦C is even more dangerous (the authors find that something along these lines is indeed the case). I would appreciate it if the authors would go through their arguments (particularly the introduction and conclusions) and ensure that their presentations of the global mean temperature limits of 1.5◦C and 2◦C are presented appropriately, as useful heuristics instead of hard limits.

Response:

> We thank the Reviewer for her comment and we fully agree that 1.5°C and 2°C should not be characterized as "scientifically determined" thresholds of dangerous anthropogenic interference with the climate system, but rather "focal points" determined by policy makers based on value judgments and world views. We modified our manuscript accordingly to take full account of this remark.

General Comment 2:

> Another general comment refers to Section 5. It would be useful to see some context. For example, what does a 6% reduction in local yield mean? Is this catastrophic for nobody, a farmer, a region, a nation, etc.? Can it be compensated for? It's hard to say "that's really bad" or "that's not so bad" (or somewhere in between) if only the result is reported.

Response:

We very much agree with the reviewer that only a placing these results in context can truly inform about the importance of these changes. This has been highlighted also in the recent IPCC AR5 that clearly distinguishes between climate hazards, vulnerability and exposure that together constitute the severity of the climate impact. We currently do not account for the latter (e.g. this would become possible once the the recent shared socio-economic pathways are available in their full extent), and hence cannot provide a thorough assessment of what these projections actually "mean". Clearly, we could use present day "climate analogues" for this purpose, but such analogues have to be chosen very carefully without being misleading. On P. 2474, 23ff we qualitatively discuss our findings in the light of countries vulnerabilities also specifically with regard to yield changes P. 2474, 23-29:

> *"The risks posed by extreme heat and potential crop yield reductions in tropical regions in Africa and South East Asia under a 2 ◦C warming are particularly critical given the projected trends in population growth and urbanization in these regions (O'Neill et al., 2013). In conjunction with other development challenges, the impacts of climate change represent a fundamental challenge for regional food security (Lobell and Tebaldi, 2014) and may trigger new poverty traps for several countries or populations within countries (Olsson et al., 2014)."*

From our perspective, a more quantitative assessment of what certain projections imply is beyond the scope of what can be provided in this analysis and would require a separate assessment directly involving trajectories and vulnerabilities.

Specific Comment 1:

Page 2452, first paragraph: I understand why the authors chose two different reference periods, but it makes the presentation a bit confusing and raises some questions. How much do the deviations from past climate affect your results? Could you provide some quantitative evidence that indeed it's not a good idea to make all of your comparisons relative to preindustrial?

Response:

We understand the reviewer's concern about the apparent use of two different base periods, although we would like to highlight that in fact we do not. We derive all model projections (including GMT increase) from the 1986-2005 reference period, but since the policy targets are derived with respect to pre-industrial warming levels, the impacts analysed for 0.9°C and 1.4°C GMT increase above 1986-2005 are expressed in their absolute warming above pre-industrial (1.5°C and 2°C, respectively). We agree with the reviewer, that the current manuscript is not sufficiently clear in this regard and modified P. 2452, 10 accordingly to:

"All our results are given with respect to this common reference period, although for consistency with the respective policy targets we express the GMT differences of 0.9°C and 1.4°C by the implied pre-industrial warming of 1.5°C and 2°C. "

Specific Comment 2:

Page 2452, line 27 to Page 2453, line 10: I'm a bit dissatisfied with this paragraph, in that I don't think there is any reason one would have confidence in individual grid box results in the first place. In addition to natural variability, there could be numerical errors on such small spatial scales. I take it as a foregone conclusion that aggregation or some other kind of filtering is necessary to obtain robustness.

Response:

We agree with the reviewer's comment and modified the respective paragraph accordingly to:

"In addition to the anthropogenic forcing, natural variability is a dominant driver of the climate signal on multi-annual time scales for time-averaged quantities such as mean temperature and precipitation change (Knutti and Sedlácek, 2012; Marotzke and Forster, 2014) and in particular for extreme events (Kendon et al., 2008; Tebaldi et al., 2011). This finding has been further consolidated by experiments with perturbed-initial condition ensemble simulations (Fischer et al., 2013). Thus, natural variability may mask an already present climate change signal and consequently lead to a delayed detection of the imprints of climate change (Tebaldi and Friedlingstein, 2013). To overcome this limitation, Fischer et al. (2013) proposed a spatial aggregation approach that allows for a robust detection of an anthropogenic footprint in climatic extremes despite natural variability – an approach that has also been successfully applied to the observational record (Fischer and Knutti, 2014). Here, we adopt and extend this spatial-aggregation approach."

Specific Comment 3:

Page 2453, line 20: Did you check the robustness for more stringent significance levels? It could be that you get similar results for (say) 99% significance, which reduces the chances of obtaining false positives or negatives in your test.

Response:

Clearly, higher significance levels would increase the test's performance in reducing Type 1 errors ("false positives"). At the same time, this increased rate, however, comes at an increased rate of Type 2 errors ("false negatives"). Therefore, a trade off between the two error levels has to be considered when determining the significance level. In our case, we do not focus on singular model output, but rather an ensemble result when speaking about the robustness of our findings (e.g. more than 66 % of the models reject the null hypothesis of the KS test at the 95 % significance level). Given the minimum number of 11 models, this translates to 7 models and the probability of all the individual KS-tests being false positives is negligible. Therefore, we think that by choosing a 95% significance threshold, our overall test-scheme is already very robust and an increased significance level on the individual model basis will only lead to less discriminatory power of the test.

Specific Comment 4:

Page 2455, lines 12-13: Why did you only choose 11 and 14 models, respectively? Why did you choose the models that you did? Are the models that you chose significantly different from each other? A bit of transparency would be helpful.

Response:

We agree with the reviewer's suggestion that the choice of the model ensemble should be fully transparent to the reader. In our case, there is really not much to it. The choice of the model ensemble was based on data availability and we decided to always include the maximum number of models available for each respective analysis. We did not have access to the required combination of RCP8.5 and historical runs for the respective variables for more than 11 models for extreme temperature and more than 14 for precipitation related changes. We modified the respective paragraph to clarify this point.

Specific Comment 4:

Page 2457, lines 9-10: I know these are cited, but I would say that the point itself is arguable. I would like to see something less strongly phrased.

Response:

We understand the reviewer's reservations against the expression used and have revised it accordingly.

> *"It is the regional natural climate variability that arguably determines a ''climate normal'' to which human systems as well as ecosystems might be adapted to."*

Specific Comment 5:

Page 2459, line 14: It would be nice to have more description so that the reader doesn't have to read Schewe et al. (2013) to understand what you did.

Response:

We thank the reviewer for this comment and updated the respective paragraph to be more explicit with regard to the input data used and the intercomparability to the CMIP5 results presented above.

> *"Projections are based on 11 global hydrological models (GHM) that participated in the ISI-MIP intercomparison project. These are forced with bias--corrected climate simulations from five CMIP5 GCMs (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M, see Hempel et al. (2013) for further details on the bias--correction methodology). Each of GCM-GHM combinations is treated as an individual ensemble member resulting in a N=55 ensemble as a basis for the KS tests described above."*

Specific Comment 6:

I don't think a separate Section 4.1 is necessary if you only have one subsection. Just put everything in Section 4.

Response:

We deleted this subsection as suggested by the reviewer.

Specific Comment 7:

Either in Section 4 or Section 5, it would probably be useful to talk about sea level rise and consequent saltwater intrusions. This will certainly exacerbate water availability for coastal cities/regions.

Response:

We thank the reviewer for this helpful suggestion and included the following paragraph:

> *"In addition to changes in fresh water availability as a consequence of changes in the hydrological cycle, saltwater intrusion resulting from rising sea-levels or extreme coastal flooding has to be considered (Werner et al., 2013). Although strongly dependent on local circumstances including regional water management and coastal protection, saltwater intrusion might present a substantial challenge, in particular for low-lying coastal areas and small island states (Cisneros et al. 2014)."*

Specific Comment 8:

Page 2461, line 29 to Page 2462, line 3: Choosing to plot relative changes makes sense, but it might also be helpful to mask out regions with small absolute change, thus reducing this amplification problem.

Response:

We thank the reviewer for this suggestion and would like to highlight that we already apply such a masking on the regional level for Alaska, East Canada and Northern Europe for different crop types to avoid the amplification problem the reviewer mentions. However, in particular the North Asian region is a major crop producer for all crop types except rice (compare Fig. S5, Northern Europe is relevant for wheat) that should not be masked out of our analysis. We are furthermore of the view that applying a masking on the individual grid cell level will not help to make our results more accessible, but quite to the contrary make our analysis less transparent. If we take North Asia again as an example: While the individual grid cell productivity might be comparably low in this region, it will however in total amount to a change relevant on the global level that should not be neglected. Therefore, we refrained from applying filters on the grid cell level beyond the regional filters we have already in place.

Specific Comment 9:

Section 5.2.4: I don't understand why there isn't any difference between the two different warming levels in the CO2 ensemble. Some insight would be useful.

Response:

We are not sure, if we understand the reviewer's comment correctly, but we assume that she refers to the statement 2465, L9: *"While differences between warming levels are apparent for some regions and the CO2-ensemble, these display comparably low confidence levels."* What we actually refer to here is the minor difference between the percentage change assessed under 1.5°C (6.8% [-16.6,24.5]) and 2°C (6.8% [-14.3,26.8]), in particular displaying the very same median. We are not equipped to look into greater detail on this, but as this is a unique phenomenon for the rice global median value and does not occur for any other crop type, we can only assume that this is indeed by chance. However, we cannot rule out that our applied kernel density function affects the overall shape of our fitted pdf that underlies this.

However, what we find remarkably consistent over all crop types is that although the full-CO2 ensemble shows median gains for some crop types under 1.5°C, no further increase (or even a sign reversal) is projected between 1.5°C and 2°C, indicating that climatological factors are substantially increasing between 1.5°C and 2°C thereby overcoming the benefits of increased CO2-concentrations.

Specific Comment 10:

Page 2466, lines 9-10: I don't think it's very helpful to specifically call out 2030. This comes across as predicting the future.

Response:

Although we of course do not intend to predict 2030 warming levels, a warming of around 1.5°C is inevitable reached around 2030s under all RCPs and also scenarios implied by the Paris Agreement. Thereby, we think that our statement *"Given that a 1.5°C warming might be reached already around 2030, our findings underscore the risks of global crop yield reductions due to climate impacts outlined by Lobell and Tebaldi (2014) "* is justified, in particular as we do not predict 2030 temperature levels.

Specific Comment 11:

Page 2466, lines 25-26: Say more about how this is consistent with the assessment of climate sensitivity. Does it span the same range? Does it have the same mean? Are you talking about median warming?

Response:

The energy-balance carbon-cycle climate model MAGICC6 (Meinshausen et al 2011a, 2011b) is constrained to historical forcing estimates, and observations of hemispheric temperatures and ocean heat uptake, while sampling the parameter space in a way such that the posterior distribution of Equilibrium Climate Sensitivity (ECS) reflects the ECS estimates from IPCC AR5 WG1. This model is well-established and documented in the literature (e.g. underlying the temperature estimates from emission pathways in the AR5 WG3 report), and we thus kept this explanation rather brief. However, we see the reviewers point and updated the respective paragraphs to:

> *"For both scenarios, temperature projections are derived with the reduced complexity carbon- cycle and climate model MAGICC (Meinshausen et al., 2011) in a probabilistic setup (Meinshausenet al., 2009), which has been calibrated to be in line with the uncertainty assessment of equilibrium climate sensitivity of the IPCC AR5 (Rogelj et al., 2012, 2014). Each probabilistic setup ensemble consists of 600 individual scenario runs. "*

Specific Comment 12:

Section 6.1: How do your generated scenarios compare with the CMIP models? Do they replicate any other scenarios?

Response:

As described in section one, the scenarios used here in this study are specifically designed for the purpose to study SLR and coral reef estimates for scenarios that exhibit a median warming of 1.5°C and 2°C. However, given uncertainties in the climate response to anthropogenic perturbations, there's some uncertainty in the GMT projections connected to these scenarios, which propagates through the impact assessments (compare Fig. 13 and 14). Neither the CMIP3 nor the CMIP5 model ensemble (based on the SRES or the RCP framework) included scenarios directly targeted at such levels, whereas the RCP2.6 scenario exhibits a median warming of about 1.6°C. In section 6.2, some discussion of our results in the context of the RCP framework is given.

Specific Comment 13:

Section 8: It would be helpful if you summarized the first few paragraphs in a table so that the reader can easily see the whole picture.

Response:

We very much appreciate the reviewer's suggestion and have included an overview figure (Fig. 15), which highlights key findings of our study.

Specific Comment 14:

Can "not unlikely" be a number?

Response:

We have corrected the wording.

Specific Comment 15:

Page 2474, lines 4-15: This paragraph feels a bit hand-wavy. Is it possible in Section 6 to assess the contribution to SLR of the collapse of the Greenland ice sheets in your two simulations?

Response:

As our simulations only address sea-level rise over the 21^{st}, we do not assess any non-linearities connected to ice-sheet disintegration that operate on much longer time scales. However, we agree that this paragraph is a bit repetitive as it is not directly related to the findings presented in that manuscript. Therefore, we shortened it considerably.

Specific Comment 16:

Page 2475: Mentioning Paris might not be a good idea, as the results from Paris will be clear well before this paper is published.

Response:

In the light of the Paris Agreement and the explicit reference to 1.5°C there, parts of the introduction and the discussion have been rewritten substantially.

Specific Comment 17:

Figures 2, 3, 5, 6, 8-12: It's really hard to discern much useful information from these figures. They're very crowded, and the individual "panels" are small. I'm not quite sure how to improve these, but something really doesn't work here.

Response:

We agree that these figures are crowded and might not be straight-forward to read an assess as CDFs are not widely used in such a context. However, we see some merit in them as they display a wealth of information related to the exposure of land-area to changes in climate and climate impact signals beyond what can easily be displayed in a table or in any kind of other map. In addition, they provide a common framework to address very different impacts and to visualize key differences between a 1.5°C and a 2°C warming on a global and regional basis. As the individual panels are small, they are provided in a high resolution so that assessing all the information on a regional basis is possible.

In addition, we now added regional overview figures that display all relevant impact panels for the respective regions in the supplementary material. These fill a single page each and thus allow to assess the regionally relevant information much more directly than the overview figures in the main body of the manuscript.

Specific Comment 18:

I don't understand the top row of Figure 13. If warming caps at 1.5°C, how can there be any results above this value?

Response:

We hope that our additional explanation given above at Comment 11 does help to clarify this point. As we use probabilistic projections that reflect the IPCC AR5 WG1 climate sensitivity assessment with a 600-member ensemble based on emission scenarios that show a median (50^{th} percentile) warming of 1.5°C and 2°C, half of the 600 ensemble members will thus exhibit a warming above 1.5°C or 2°C.

Specific Comment 19:

Figure S5: I assume this is percent?

Response:

Indeed. We thank the Reviewer for spotting that.

Reviewer 2

We thank the reviewer for her positive perception of our manuscript and her detailed comments in particular regarding our methods section.

General Comment 1:

The methods described in Section 2 are very similar to those used by the impacts community in pattern scaling, particularly in regards to the relationship between GMT and climate variables. This type of scaling was mentioned in section 6, but not explicitly. There is a wealth of information (and studies) that use pattern scaling to look at regional impacts through impact assessment models (IAMs). Tebaldi and Arblaster, 2014, give a thorough critique of such methods.

Response:

We thank the Reviewer for that helpful comment and pointing us to that reference. Referencing to the broad literature on pattern scaling is so far missing from our manuscript and while our approach differs in many regards from pattern scaling approaches, there are also some key similarities that would be worth pointing out.

Firstly, as in pattern scaling approaches we assume that most impacts scale with the magnitude of warming and that "changes in the climate and climate impact signals studied here are dominantly driven by changes in GMT". Clearly, this is limited to continuously increasing warming signals as are pattern scaling approaches. Tebaldi and Arblaster discuss in greater detail the limitations of such an approach for stabilizing scenarios as oceanic processes and large-scale circulation changes continue long after temperatures stabilize.

However, our time-slice approach differs from classical pattern scaling approaches as we don't assume a continuous scaling of impacts with temperature. This is in particular appropriate as we're looking into climate extremes and the hydrological cycle as well as into climate impacts like water availability and crop yields depending on those. Quoting from Tebaldi and Arblaster: *"Pattern scaling is likely to be more limited for extreme events (Lustenberger et al. 2013), or in cases where certain feedbacks (e.g. the drying of the Mediterranean) lead to an amplification of some types of events..."*

Similar limitations of the pattern scaling approach have been discussed e.g. in Lopez et at. (2013) or Chadwick & Good (2013). Our time-slice approach is not based on such an assumption of linear scaling and capable of including non-linear increases. And in our results we find clear evidence for such non-linear increases in extreme event indices and climate impacts e.g. for South Asian extreme precipitation or Mediterranean water availability.

To outline similarity and differences between our time slice approach and pattern scaling we introduced the following paragraph:

Traditional approaches that analyze impacts over a given time period for all models in a model ensemble and relate this to a median GMT increase across the model ensemble do not account for this ensemble-intrinsic spread of global warming levels and will consequently overestimate the ensemble uncertainty of the GMT-dependent indices studied. Such a time-slice centered approach has been shown to provide better accuracy then traditional pattern scaled approaches (Herger et al., 2015). Although relying on the debatable assumption of scenario-independence of the projected signals that does not fully hold in climate stabilization scenarios (Tebaldi and Arblaster, 2014), time-slicing avoids known short-comings of classical pattern scaling analysis. In particular, it allows to capture non-linearities in extreme event and precipitation related signals that relate to non-linear local feedbacks (Lopez et al., 2013) or large-scale circulation changes (Chadwick and Good, 2013; Hawkins et al.,2014).

Specific Comment 1:

Introduction, page 2450, lines 15-20: The argument that global temperature scales with local impacts should be made clearer in the introduction. Reference should be made to Held and Soden, 2006. Briefly describing the thermodynamic relationship between temperature and the hydrological cycle would add value to the method section(s). This is briefly discussed on page 2452, lines 13-20, but the physical mechanism is not mentioned.

Response:

We agree that outlining the relevance of the scaling of local impacts with GMT increase would be helpful in the introduction of our manuscript. Therefore, we added the following statement:

"The assessment of such differences would greatly profit from a regional and impact - centered approach that allows for a more differentiated picture than globally aggregated metrics (Seneviratne et al., 2016). In particular, changes in the hydrological cycle as a result of temperature increase will be regionally dependent (Held and Soden, 2006)."

Specific Comment 2:

Section 2, page 2452, lines3-7: How do the models used compare against observations? I understand that a pre- industrial baseline from observations is not possible, but I didn't think there was a clear surface temperature trend in the observations. Also, was the preindustrial scenario used or was this a period in the historical scenario? Is the pre-industrial period mentioned here the same as in section 6 (1850-1875)?

Response:

Clearly, the reference to the reference pre-industrial period should be made which is 1850–1900 as in the IPCC AR5. We have added this reference accordingly. The warming between 1850-1900 and the reference period 1986–2005 was 0.6°C. By deriving all changes relative to this reference period (which translates to a 0.9°C and 1.4°C warming above 1986-2005) we correct from any possible deviations of the GCMs over the historical period.

Specific Comment 3:

Section 2, page 2452, line 8: I am unclear as to what the "X" means in Table S1. The dates listed in Table S1 are the centered dates around which a 20-year running average GMT reaches a specific threshold? I am not sure this information is needed.

Response:

One characteristic of the time-slice approach is that GCM-specific slices centered around certain warming targets (in our case 1.5°C and 2°C) are chosen. As these slices can differ considerably (up to nearly 20 years for 2°C) this information is given in the supplementary material. In addition, not all model data has been available for all assessments. The availability for the Temperature, Precipitation and ISIMIP analysis is indicate by an 'x' in Table S1, which we explain in the table caption.

Specific Comment 4:

Section 2, page 2453, line 20-27: Because there is the assumption of stationarity, you could do a Priestly-Subba-Rao test of stationarity to support the null hypothesis.

Response:

We are not fully clear what stationarity assumption the reviewer is referring to here. The underlying data is already time-averaged on a grid-cell basis and then aggregated regionally. Thereby, from our understanding no test for stationarity of our two KS distributions would be required here.

Specific Comment 5:

Section 3, page 2454, line 16: The assumption is that climate variables and extremes have a relationship with GMT has been examined in many papers. The relationship of GMT and precipitation should be referenced with the Held and Soden, 2006, and/or Liu and Allen, 2013. Also, you could reference the Sillmann et al, 2013, paper to show that the models show good agreement with reanalysis for the ETCCDI variables.

Response:

We fully agree with the reviewer that the relation between climate (extreme) variables and their change with increased radiative forcing is a subject of intense research. Our statement is thereby referencing the most recent IPCC AR5 WG1 report that from our perspective represents the most comprehensive review of the scientific literature on the matter. We also thank the reviewer for pointing out that a reference to the Sillmann et al. (2013) paper highlighting good model agreement with observational data is relevant here and we have included this reference accordingly.

Specific Comment 6:

Section 3, page 2455: Why was a land mask applied for the ETCCDIs? I would have liked to see the results (i.e. maps) over the oceans as well.

Response:

We agree with the reviewer that for model intercomparisons our analysis of changing patterns in large-scale circulations, analysis of oceanic signals is of great relevance. However, in the approach we pursue here, we focus on a regional analysis of the SREX-regions of specific land-areas. Thereby, we applied a land mask to our analysis and also to the figures presented as this is the main purpose of our analysis.

Specific Comment 7:

Section 3, page 2458, lines 10-14: As with the King et al, 2015, paper, regions of complex topography show little significance in changes in extreme precipitation. Aggregating to large regions is likely to mask significant changes in precipitation extremes.

Response:

We take this as a general comment on the work presented here, as we cannot identify, to what specific statement in Section 3, page 2458, lines 10-14 this comment refers. In particular, we checked the King et al. 2015 reference for corresponding statements on that and were not able to identify the findings the reviewer is referring to here.

Specific Comment 8:

Section 7, page 2471, line 9: The reference period (1980-2000) is different from reference period used in prior sections. Why?

Response:

The methodology for the coral reef analysis is based on a paper by Frieler et al. (2012) that chose this reference period for their analysis. Thereby, several aspects might differ from the newly developed approaches for the CMIP5 and ISIMIP analysis presented above. This include the reference period, but also the AOGCM ensemble underlying this analysis, which in this case is CMIP3 as outlined in section 7.1

Specific Comment 9:

Section 8, page 2475, lines 10-14： Will this sentence be revised due to the outcomes of the Paris 2015 meeting?

Response:

Clearly, this section is outdated now after the Paris Agreement and has been fully rewritten together with parts of the introduction to fully reference the Paris Agreement and the long-term global temperature goals of 1.5°C and 2°C included therein.

Specific Comment 10:

Figure 2: Is this for TXx? It doesn’t say this in the figure caption.

Response:

We thank the reviewer for pointing this out and indeed, this figure displays TXx.

Manuscript prepared for Earth Syst. Dynam.
with version 2014/09/16 7.15 Copernicus papers of the LaTeX class copernicus.cls.
Date: 11 March 2016

Differential climate impacts for policy-relevant limits to global warming: The case of 1.5° C and 2° C

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Abstract.

Robust appraisals of climate impacts at different levels of global-mean temperature increase are vital to guide assessments of dangerous anthropogenic interference with the climate system. ~~Currently, two such levels are discussed in the context of the international climate negotiations as long-term global temperature goals: a~~ The 2015 Paris Agreement includes a two-headed temperature goal: ”holding warming well below 2°C ~~and a~~ above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5°C~~limit in global-mean temperature rise above pre-industrial levels~~”. Despite the prominence of these two temperature limits, a comprehensive ~~assessment~~ overview of the differences in climate impacts at these levels is still missing. Here we provide an ~~assessment~~ overview of key impacts of climate change at warming levels of 1.5°C and 2°C, including extreme weather events, water availability, agricultural yields, sea-level rise and risk of coral reef loss. Our results reveal substantial differences in impacts between a 1.5°C and 2°C warming that are highly relevant for the assessment of dangerous anthropogenic interference with the climate system. For heat-related extremes, the additional 0.5°C increase in global-mean temperature marks the difference between events at the upper limit of present-day natural variability and a new climate regime, particularly in tropical regions. Similarly, this warming difference is likely to be decisive for the future of tropical coral reefs. In a scenario with an end-of-century warming of 2°C, virtually all tropical coral reefs are projected to be at risk of severe degradation due to temperature induced bleaching from 2050 onwards. This fraction is reduced to about 90 % in 2050 and projected to decline to 70 % by 2100 for a 1.5°C scenario. Analyses of precipitation-related impacts reveal distinct

regional differences and ~~several~~ hot-spots of change emerge. Regional reduction in median water availability for the Mediterranean is found to nearly double from 9 % to 17 % between 1.5°C and 2°C, and the projected lengthening of regional dry spells increases from 7 % ~~longer~~ to 11 %. Projections for agricultural yields differ between crop types as well as world regions. While some (in particular high-latitude) regions may benefit, tropical regions like West Africa, South-East Asia, as well as Central and Northern South America are projected to face substantial local yield reductions, particularly for wheat and maize. Best estimate sea-level rise projections based on two illustrative scenarios indicate a 50 cm rise by 2100 relative to year 2000-levels ~~under~~ for a 2°C ~~warming, which is~~ scenario, and about 10 cm lower levels for a 1.5°C scenario. A 1.5°C scenario would also reduce the rate of sea-level rise by about 30 % compared to a 2°C scenario. Our findings highlight the importance of regional differentiation to assess both future climate risks ~~as well as~~ and different vulnerabilities to incremental increases in global-mean temperature. The article provides a consistent and comprehensive assessment of existing projections and a ~~solid foundation~~ good basis for future work on refining our understanding of ~~warming-level dependent climate impacts~~ the difference between impacts at 1.5 °C and 2 °C warming.

1 Introduction

Recent decades have seen increasing climate impacts, many of which science is now able to attribute to anthropogenic carbon dioxide emissions and consequent global warming (IPCC, 2013; King et al., 2015). On-going temperature increase will escalate these impacts on ecological and human systems (IPCC, 2014a), which has made climate change a political issue of ~~utmost importance. Already in 1992, the international community established the~~ central importance. The response of the global community to that challenge laid out in the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) ~~with the objective of~~ provides a promising framework for global climate protection (UNFCCC, 2015). Specifically, the Agreement includes two long-term global goals (LTGGs): "holding warming well below 2°C above pre-industrial levels, and pursuing efforts to limit the temperature increase to 1.5°C, recognizing that this would significantly reduce the risks and impacts of climate change". LTGGs have been proven useful to guide climate action (SED, 2015) and their inclusion aims to operationalize the "ultimate objective" of the UNFCCC of a "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992). ~~The extent and level of such a "dangerous anthropogenic interference ", however, remains a topic of debate until today.~~

~~To operationalize this convention in terms of a long-term global temperature goal to guide mitigation action, the parties under the UNFCCC agreed in 2010 "to hold the increase in global average temperature below 2°C above pre-industrial levels"(**?**), while recognizing the need to review this~~

goal on the basis of the Although the assessment of levels of dangerous interference is primarily a political process that requires value judgements and depends on different world views (Knutti et al., 2015), it needs to be informed by the best available science and exploring limiting global temperature increase to 1.5°C (?). A outlining the impacts of climate change and mitigation efforts implied by different LTGGs. Based on the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), a recent expert assessment reviewing focussing on the adequacy of the long-term global goal LTGGs in light of the ultimate objective of the convention concluded that "significant climate impacts are already occurring [. . .] and additional magnitudes of warming will only increase the risk of severe, pervasive and irreversible impacts" (SED, 2015), stressing the fact that . While the report emphasized that a warming of global mean surface air temperature (GMT) of 2°C of global warming should above pre-industrial levels should not be seen as an upper limit, and not a 'safe' limit. While a below level, it also concluded that substantial research gaps exist regarding the differences in climate impacts between a 1.5°C and 2°C-goal has been agreed politically, scientific evidence indicates that severe and potentially irreversible impacts of climate change may already occur for lower levels of warming (IPCC, 2014a). As yet, such evidence remains fragmented, and C temperature increase (SED, 2015). In particular, comprehensive, multi-sectoral assessments of differences in climate impacts between a 1.5°C and 2°C temperature increase warming are lacking. The assessment of such differences would greatly profit from a regional and impact - centered approach that allows for a more differentiated picture than globally aggregated metrics (Seneviratne et al., 2016). For example, changes in the hydrological cycle as a result of temperature increase will be regionally dependent (Held and Soden, 2006).

The "Turn down the heat" - report series issued by the World Bank (Schellnhuber et al., 2012, 2013, 2014) assessed climate risks for a 2°C and a 4°C warming above pre-industrial levels for different world regions. The report of the Working Group 2 (WG2) of the Fifth Assessment Report (IPCC AR5) of the Intergovernmental Panel on Climate Change (IPCC) includes both, chapters on specific impacts as well as on specific regionsimpact and region specific chapters, and provides warming level dependent information on impacts where available. The range of emission scenarios which provide the basis for the climate impact projections in the IPCC AR5, the Representative Concentration Pathways (RCPs), however, do not allow for a straight-forward differentiation between impacts for warming levels of 1.5°C and 2°C. Only the lowest emission pathway RCP 2.6 is in line with keeping global-mean surface-air temperature (GMT) GMT increase above pre-industrial levels to below 2°C with a likely chance (66 % probability, IPCC, 2013) and no pathway in line with a 1.5°C limit is assessed in the AR5. Still, the IPCC AR5 WG2 report provides an expert assessment of key impacts at different levels of warming, summarized in five "Reasons-for-Concern" (RFCs, Oppenheimer et al., 2014). The risks for three out of five of these RFCs are assessed as at least moderate at 1.5°C GMT increase above pre-industrial levels, and as high at at least moderate-high at 2°C. Moderate risks hereby mean In the RFC frameworj, moderate risks imply that associated impacts are both detectable and attributable to climate change with at least medium confidence, whereas high risks are associated with severe and widespread impacts (Oppenheimer et al., 2014). Among the three RFCs that show high risks at 2°C are *Risks to unique and threatened systems* (RFC1) that include coral reefs and other highly vulnerable human systems as well as ecosystems, *Risks associated with extreme weather events* (RFC2) and *Risks associated with the distribution of impacts* (RFC3).

Based on the data archives of the Coupled Model Intercomparison Project 5 (CMIP5, Taylor et al., 2011) and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, Warszawski et al., 2013), this article provides an extensive assessment of regionally differentiated climate impacts at levels of 1.5°C and 2°C global mean surface-air temperature increase (GMT) GMT increase above pre-industrial levels (hereinafter henceforth 1.5°C and 2°C) for different climate impacts, including increases in climatic extremes extreme weather events (Section 3), changes in water availability (Section 4), crop yield projections (Section 5), sea-level rise (SLR, Section 6) and coral reef degradation (Section 7).

The following Section (2) outlines the common methodological approach taken our methods for the assessment of changes in climate extremesextreme weather indices, water availability and agricultural impacts. Consequently, regionally differentiated results for the specific impacts listed above at 1.5°C and 2°C warming are presented. Analyses of sea-level rise and impacts on coral reefs contain additional details on sector-specific methods. Where impact-specific additional methodological specifications are needed, these are given in the respective section, followed by a presentation of the main results and a short discussion. A summarizing discussion as well as some and conclusions finalize this contribution in Section 8. The Supplementary Material (SM) provides additional methodological information as well as further impact mapsand summary impact , regional overviews and summary tables.

2 Methods

This section provides an overview of the methods applied for the assessment of climate extremesextreme weather indices, water availability and agricultural impacts. The individual subsections provide additional information on sector- and impact-specific methods as well as on the data analyzed. The meteorological extreme indices are derived from an ensemble of general circulation models (GCMs) of from CMIP5 (Taylor et al., 2011) while our assessment of water availability and agricultural impacts at 1.5°C and 2°C is based on the ISI-MIP Fast Track data Warszawski et al. (2013); Frieler et al. (2015)(Warszawski et al., 2013; Frie

For both data archives, the impacts for a GMT increase of 1.5°C and 2°C above pre-industrial levels are derived for 20-year time slices around the respective time-averaged with the respective mean warming for each model separately. To account for model deviations from observations over the historical period, the warming levels are derived relative to the reference period 1986-2005, (this reference period lies is 0.6°C above warmer than pre-industrial levels (1850 — 1900) , IPCC (2013)), which translates to a warming of 0.9°C and 1.4°C above reference period levels for the 1.5°C and 2°C limit, respectively. All time slices are derived from the RCP8.5 scenario (the time slices for the individual GCMs are given in the SM Tab. S1). 1986-2005 is also the common reference period to assess projected changes in extreme indices and ~~and~~ climate impacts. ~~Therefore, where results speak of impacts at~~

All our results are calculated with respect to this common reference period. For consistency with the respective policy targets, however, we express the GMT differences of 0.9°C and 1.4°C by their implied pre-industrial warming of 1.5~~°~~°C and 2 ~~°C, the GMT increase refers to pre-industrial temperature, while the impact signal is derived relative to the reference period~~°C.

Analyzing time-slices centered around a specific level of warming relies on the assumption that the changes in the climate and climate impact signals studied here are dominantly driven by changes in GMT and that the effect of changes in time-lagged systems such as large-scale ocean circulations (Schleussner et al., 2014a, b) on the quantities studied are of minor importance. In addition, this approach does not account for the effect of other anthropogenic climate forcers that may differ for the same level of total radiative forcing such as aerosols (Zopa et al., 2012). It comes, however, also with several advantages. In particular, it eliminates the spread due to different transient climate responses across the model ensemble, which can deviate by up to a factor of two (Flato et al., 2013). Traditional approaches that analyze impacts over a given time period for all models in a model ensemble and relate this to a median GMT increase across the model ensemble do not account for this ensemble-intrinsic spread of global warming levels and will consequently overestimate the ensemble uncertainty of the GMT-dependent indices studied. The time-slice approach has furthermore been shown to provide better accuracy then traditional pattern scaled approaches (Herger et al., 2015). Although also relying on the debatable assumption of scenario-independence of the projected signals, which does not fully hold in climate stabilization scenarios (Tebaldi and Arblaster, 2014), time-slicing avoids known short-comings of classical pattern scaling analysis. In particular, it allows to capture non-linearities in extreme indices and precipitation related signals that relate to non-linear local feedbacks (Lopez et al., 2013) or large-scale circulation changes (Chadwick and Good, 2013; Hawkins et al., 2014).

In addition to the anthropogenic forcing, natural variability is a dominant driver of the climate signal on multi-annual time scales for time-averaged quantities such as mean temperature and precipitation change (Knutti and Sedláček, 2012; Marotzke and Forster, 2014) and in particular for extreme weather events (Kendon et al., 2008; Tebaldi et al., 2011). ~~This finding has been further consolidated by perturbed-initial condition ensemble simulations (Fischer et al., 2013).~~ Thus, natural variability may mask ~~the effect of climate change on an individual grid cell basis~~ an already present climate change signal and consequently lead to a delayed detection of the imprints of climate change (Tebaldi and Friedlingstein, 2013). To overcome this limitation, Fischer et al. (2013) ~~have~~ proposed a spatial aggregation approach that allows for a robust detection of ~~changes~~ an anthropogenic footprint in climatic extremes despite the substantial effect of natural variability on an individual grid-cell level natural variability – an approach that has also been successfully applied to the observational record (Fischer and Knutti, 2014). Here, we adopt and extend this spatial aggregation spatial-aggregation approach.

As in Fischer et al. (2013), we consider the distribution of changes in the selected impact indicator at each grid point over the global land-mass between 66°N and 66°S (for the sake of simplicity henceforth referred to as global land-mass) and additionally analyze changes for 26 world regions (as used in IPCC, 2012, see Tab. 1 for details). This yields distributions for 1.5°C and 2°C for each of the ensemble members and regions, where the sample size is given by the number of grid points included . This allows for a pair-wise assessment in the respective regions. In a next step, the statistical significance of differences between the 1.5°C and 2°C distributions is assessed for each region and ensemble member. This is done using a two-sample Kolmogorov–Smirnov (KS) test with the null hypothesis that both distributions for 1.5°C and 2°C are drawn from the same probability distribution.

A rejection of the test's null-hypothesis at a significance level of 95 % indicates is taken as a robust difference in projections between these two warming levels. This pairwise test, based on the individual models used for the assessmentmodel ensemble members analyzed, allows for robust statements about differences in impacts between the two warming levels, even if there is substantial overlap of uncertainty bands in the model ensemble. For GCMs that provide multiple realizations, the distributions are combined for each warming level leading to larger samples and higher discriminatory power of the KS test. Please note that this approach is only applied for the KS test and not for the ensemble projections. For the latter, the averaged signal over multiple realizations of a single GCM is included in the ensemble analysis ensuring equal weight to all GCMs investigated (see SM Section 1 for further detail on the methodology applied methods and the treatment of multiple realizations). A similar approach has been applied recently to investigate the timing of anthropogenic emergence in simulated climate extremes (King et al., 2015).

Based on the regionally specific distributions, cumulative density functions (CDF) of changes in the impact indices over the land area of the respective region are derived. As in Fischer et al. (2013), we fit a probability density function to the empirical distribution of the climate signal using a Gaussian kernel density estimator. Individual grid-cells are weighted according to their latitude-dependent area. These CDFs are derived for each ensemble member (GCM or GCM-impact model combination) and the ensemble median as well the likely range (66 % of the ensemble members are within this range) are given. This land-area focused approach allows to directly assess not only the median change over a region, but also changes for smaller fractions of the land area. At the same time, the uncertainty estimates based on the model ensemble spread can be directly visualized.

Table 1. Overview of the world regions used as well as the respective acronyms based on IPCC (2012). Please note that the Central American (CAM) region has been extended eastwards to also include the Caribbean.

ALA	Alaska, North-West Canada	NEB	North East Brazil
AMZ	Amazon	NEU	North Europe
CAM	Central America, Mexico, Caribbean	SAF	South Africa
CAS	Central Asia	SAH	Sahara
CEU	Central Europe	SAS	South Asia
CGI	East Canada, Greenland, Iceland	SAU	South Australia, New Zealand
CNA	Central North America	SEA	South-East Asia
EAF	East Africa	SSA	South-East South America
EAS	East Asia	TIB	Tibetan Plateau
ENA	East North America	WAF	West Africa
MED	Mediterranean	WAS	West Asia
NAS	North Asia	WNA	West North America
NAU	North Australia	WSA	West Coast South America

3 ~~Climate extremes indices~~Extremes Weather Events

There is a growing body of evidence showing that the frequency and intensity of many ~~climatic extremes~~ extreme weather events has increased significantly over the last decades as a result of anthropogenic climate change, but confidence in the significance of the trend and attribution to anthropogenic origin differ substantially between types of extreme weather events and regions (IPCC, 2013). With on-going warming, these trends are projected to continue (IPCC, 2012). Impacts of ~~climate extremes~~ extreme weather events will particularly, but not exclusively, affect the most vulnerable with the lowest levels of adaptive capacity and represent one of the biggest threats posed by climate change (IPCC, 2014b). In this Section, the difference in impacts between a warming of 1.5°C and 2°C for four different types of meteorological extreme event indices are assessed. ~~The definition of these indices~~ Good agreement between the CMIP5 model ensemble median estimates of extreme event indices and observational indices data sets has been reported by Sillmann et al. (2013a). The indices used follow the recommendations of the Expert Team on Climate Change Detection and Indices (Zhang et al., 2011) and are derived on an annual basis:

- Intensity of hot extremes (**TXx**): Annual maximum value of daily maximum temperature.
- Warm spell duration indicator (**WSDI**): Annual count of the longest consecutive period in which the daily maximum temperature for each day exceeds the 90 % quantile for this day over the reference period. The minimum length is six consecutive days.

– Dry spell length or consecutive dry days (**CDD**): Annual maximum number of consecutive days for which the precipitation is below 1mm per day.

– Heavy precipitation intensity or maximum accumulated five-day precipitation (**RX5day**): Absolute annual maximum of consecutive 5-day precipitation.

3.1 Methods and Data

Projected changes in climate extreme indices are assessed using an ~~11-member model ensemble of CMIP5~~ ensemble of 11 CMIP5-models for TXx and WSDI and ~~a 14-member model ensemble of CMIP5~~ 14 for RX5day and CDD ~~, based on~~ and follows the methods outlined in Section 2. The model selection was done based on data vailability. All available GCMs are assessed on a uniform grid with a 2.5° x 1.9° resolution. Multiple realizations of scenario runs for individual models are included when available, and in that case allow to estimate CDFs for natural variability that are derived based on pairwise realizations of model runs over the reference period (see SM Section 1.2 for further detail on the methodology applied).

We assess the changes in TXx and WSDI for a warming of 1.5°C and 2°C and derive changes of 20-year averages of extreme indices for the model dependent warming-level time-slices at each land grid point relative to the 1986-2005 reference period. Changes in precipitation-related indices are described as relative changes while we consider absolute changes for the other indicators. For the CDF analysis for TXx, the absolute signal is normalized by the standard deviation over the reference period.

3.2 Results

3.3 Heat Extremes

Substantial increases of 3°C and more in TXx over large parts of the Northern Hemisphere, Central South America and South Africa as well as increases in warm-spell durations (WSDI) of 3 months and more are projected under a warming of 2°C. Fig. 1 depicts changes in TXx (left) and WSDI (right) for a 1.5°C (top) and 2°C (middle) GMT temperature increase, as well as the differences between the two warming levels (bottom) on a grid-cell basis. Particularly strong increases in WSDI are found in some tropical coastal areas, which we attribute to a large share of ocean surface in the respective grid cells that lead to an amplification of the effect compared to pure land grid cells and should not be over-interpreted. We excluded these grid-cells for the CDF analysis for the respective regions. The majority of GCMs agree on a robust increase in these heat-related indices and show significant differences between the two warming levels. The impacts are robustly smaller at 1.5°C warming in both cases (see results for the KS test listed in Tab. S2).

Globally and regionally resolved CDFs for TXx, normalized to the standard deviation (σ) over the reference period, are given in Fig. 2 and median values are listed in Tab. S2. 50 % of the global land-

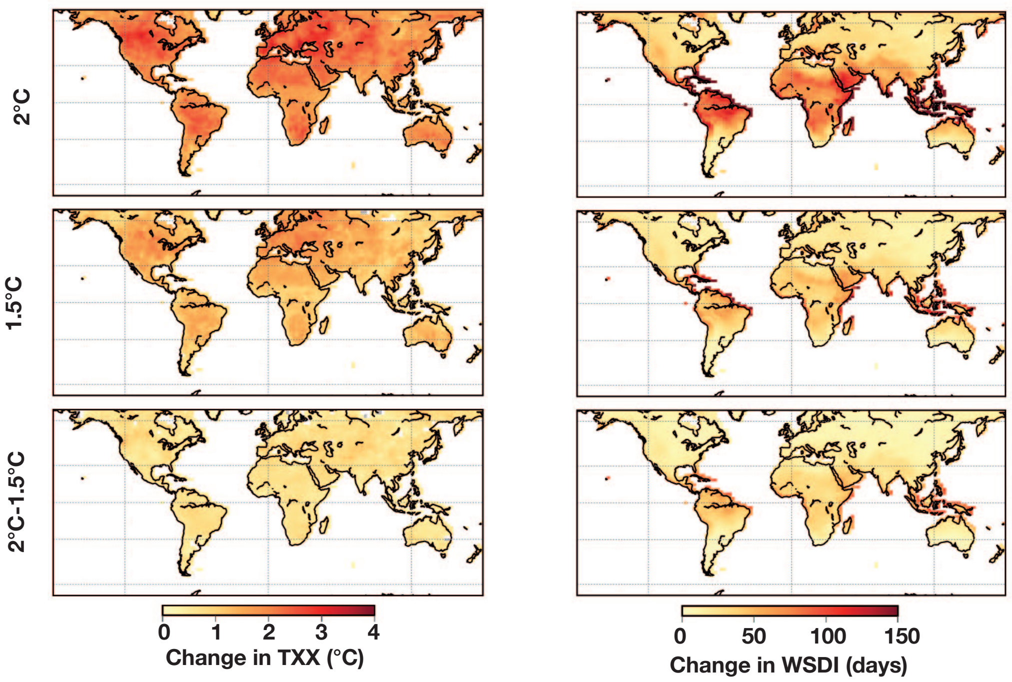

Figure 1. Median changes of TXx (left panels) and WSDI (right panels) for a warming of 2°C (upper panels), 1.5°C (middle panels) and the difference between the two warming levels (lower panels). Changes in TXx are given in °C, whereas changes in WSDI are given in days.

mass will experience a median TXx increase of more than 1.2 (1.8) standard deviations relative to the reference period for a warming of 1.5°C (2°C) above pre-industrial levels. The regional assessments indicate that the tropical regions in Africa, South America and South East Asia are projected to experience the strongest increase in land area covered by heat extremes relative to the regional natural variability, where 3-σ events become the new normal under a 2°C warming.

The pattern of a strong tropical signal is mainly due to the small natural variability of TXx in tropical regions. This is also apparent for the WSDI CDFs resolved in Fig. 3. For a warming of 1.5°C, a median increase in WSDI length by about one month is projected for 50 % of the global land area that increases by 50 % for a 2°C warming. Since this index is derived relative to natural variability over a reference period, the signal again is greatly amplified in tropical regions, where a median WSDI of up to three month is projected for Amazonia, East and West Africa and South-East Asia (see Tab. S2). Given that the WSDI only measures the longest consecutive interval, such an increase can be interpreted as entering a new climate regime for these tropical regions (Diffenbaugh and Scherer, 2011; Mora et al., 2013; King et al., 2015).

A meaningful assessment of impacts requires not only an assessment of absolute changes, but these also have to be interpreted in the light of regional climate conditions. It is the regional natural

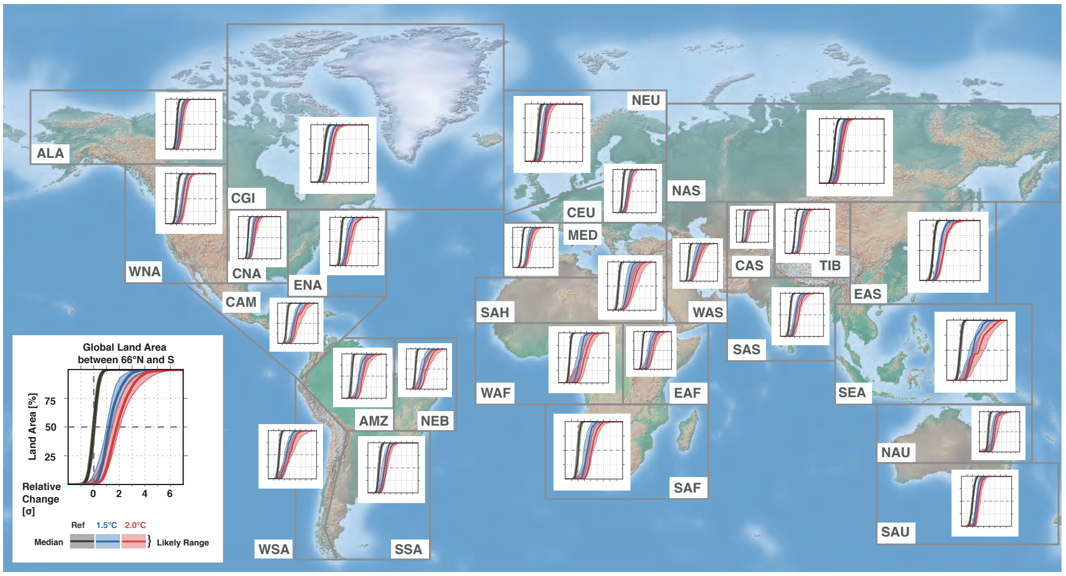

Figure 2. CDFs for projected regional aggregated changes in TXx (relative to the standard variation over the reference period) for the global land area between 66 °N and 66 °S (lower left corner) as well as resolved for 26 world regions separately (see Section 2 for further details). Changes are given relative to the standard deviation over the 1986-2005 reference period. Note that a change in 2 (3) standard deviations implies that events with a reference return time of several decades (centuries) become the new normal, whereas a new normal of 4-σ refers to an event that would be extremely unlikely to occur in a reference period climate. Region impact overviews are provided in the Supplementary Material.

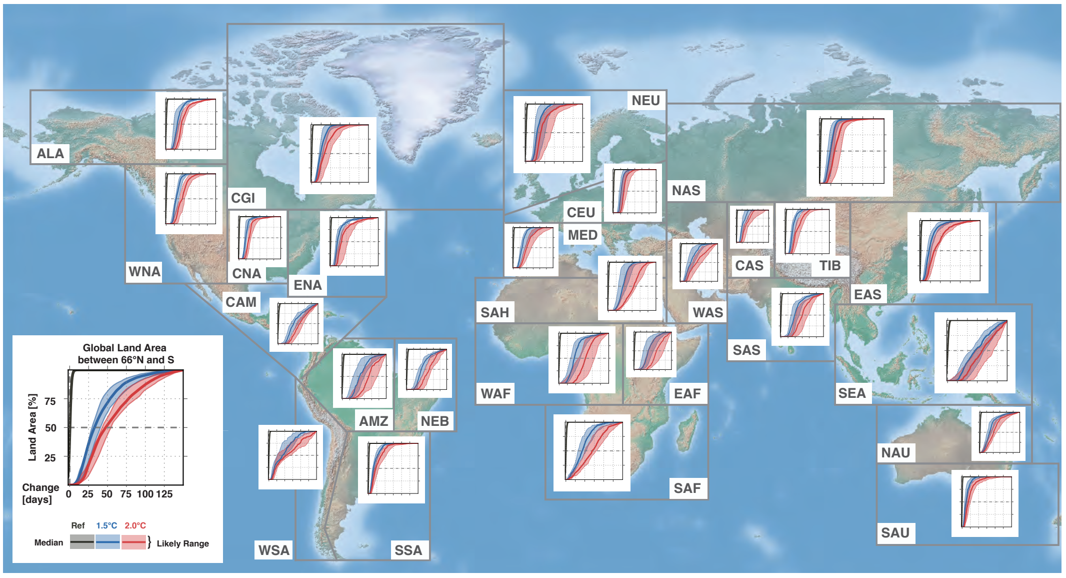

Figure 3. Same as Fig. 2, but for WSDI in days.

climate variability that arguably determines a "climate normal" to which human systems as well as ecosystems ~~are adapted~~ might be adapted to (Hansen et al., 2012; Coumou and Robinson, 2013). While this may hold as a general assumption for a range of impacts concerning human health as well as ecosystems, it is important to note that the severity of certain climate impacts may also depend on the exceedance of absolute thresholds, as has been shown for temperature effects on crop yields, for example (Deryng et al., 2014; Smith et al., 2014). The choice of an either relative or absolute representation of changes in climate impacts thus has to be made in ~~the~~ light of the impact of interest. In addition, a normalization by the standard deviation similar to the one applied here has been shown to introduce statistical biases arising from a limited sample size of the reference period (Sippel et al., 2015) that we do not account for in the results presented here.

Our findings are in line with previous assessments of projected changes in extreme temperatures and heat-waves (Orlowsky and Seneviratne, 2012; Sillmann et al., 2013; Kharin et al., 2013) and illustrate the substantial increase in the likelihood of heat extremes between 1.5°C and 2°C warming above pre-industrial levels, in particular when putting these changes in perspective to regional natural climate variability (Diffenbaugh and Scherer, 2011; Coumou and Robinson, 2013).

3.4 Extreme Precipitation and Dry Spells

Uncertainty in model projections of precipitation extremes is considerably larger than that of temperature related extremes. Fig. 4 depicts the median projections for RX5day (Maximum accumulated five-day precipitation, left) and CDD (Dry spell length, right), which exhibit contrasting patterns in terms of signal strength and robustness. The KS test ~~reveals~~ illustrates the additional merit of a regional analysis of ~~these~~ precipitation-related extremes (see Tab. S3). While all models in the ensemble indicate a robust difference between a 1.5°C and 2°C warming for both indices for the global land mass, the analysis for the separate world regions reveals different patterns.

A robust indication (more than 66 % of the models reject the null hypothesis of the KS test at the 95 % significance level, see Tab. S3) of a difference in RX5day is projected in particular for the high northern latitude regions, East Asia, as well as East and West Africa. While the high northern latitudes are also among those regions experiencing the largest increase in RX5day between the assessed warming levels (up to 7 % and 11 %, median estimates for 1.5°C and 2°C, respectively), projections for other regions that experience a considerable increase under a 1.5°C warming do not indicate a significant difference between the warming levels. This is in particular noteworthy for the Amazon region and North-East Brazil, where precipitation extremes are likely related to the South American monsoon systems (Boers et al., 2014) and to a lesser extent for West Africa (see Fig 5 and Tab. S3).

A different picture emerges for CDD as an indicator for dry spell length. For the majority of the global land area, little to no differences in CDD are projected relative to the reference period (see Fig. 4). However, about 40 % of the global land area in the subtropical and tropical regions experi-

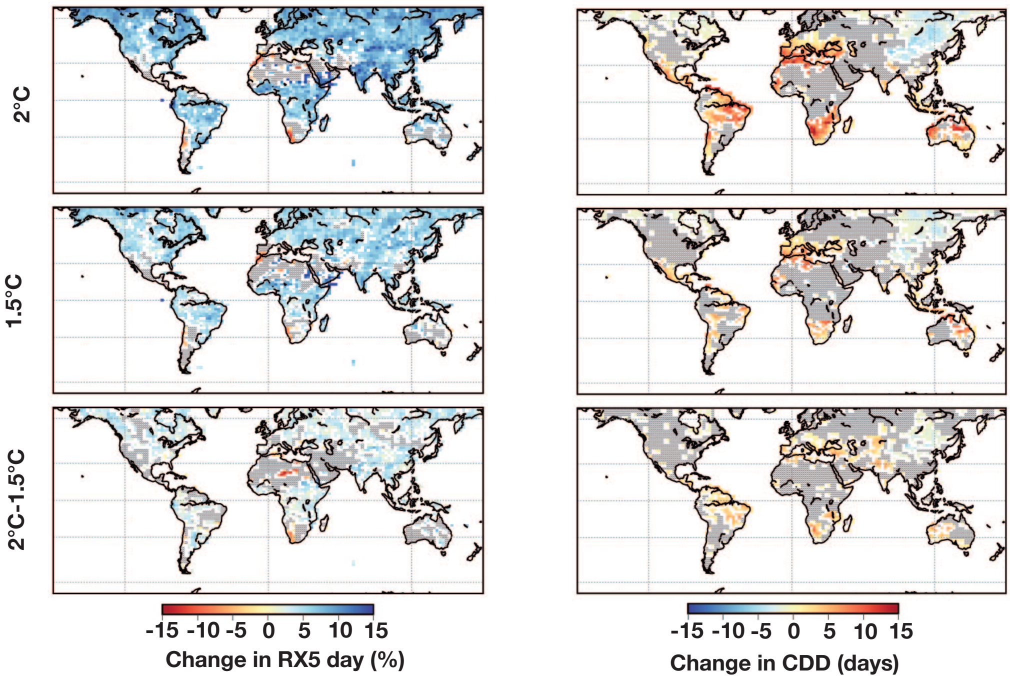

Figure 4. Same as Fig. 1, but for RX5day and CDD. Hatched areas indicate regions, where less than 66 % of the models in the ensemble agree with the sign of change of the median projections.

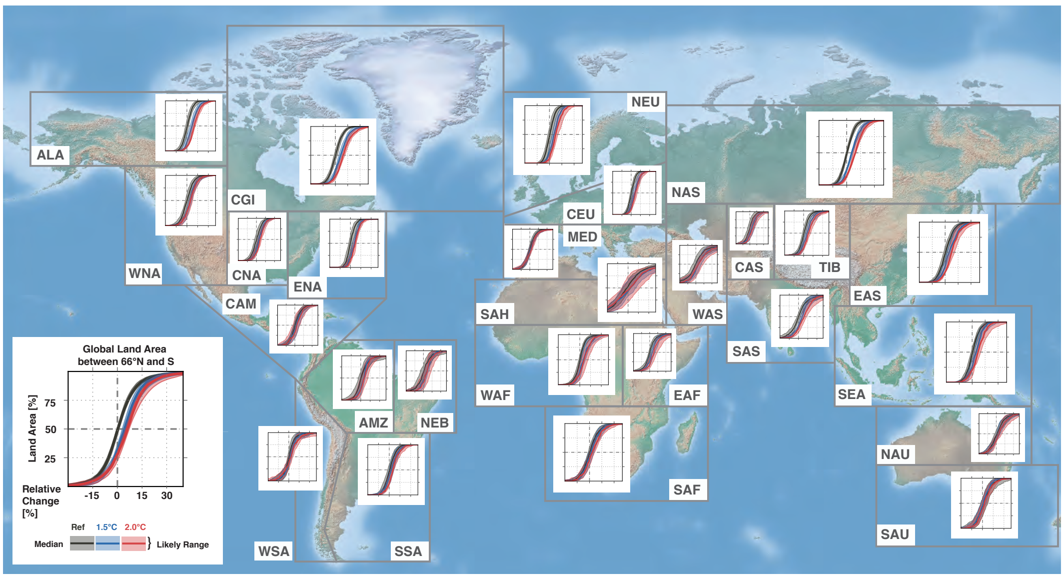

Figure 5. Same as Fig. 2 but for RX5day. Changes are given relative to the 1986-2005 reference period.

ence an increase in CDD length, including the Mediterranean, Central America, the Amazon as well
305 as South Africa (compare Fig. 4 and Fig. 6). In these regions, the KS test also reveals robust indica-

tions for differences in impacts between 1.5°C and 2°C. This difference is particularly pronounced for the Mediterranean region, where the median CDD length increases from 7 % (likely range 4 to 10 %) to 11 % (likely range 6 to 15 %) between 1.5°C and 2°C.

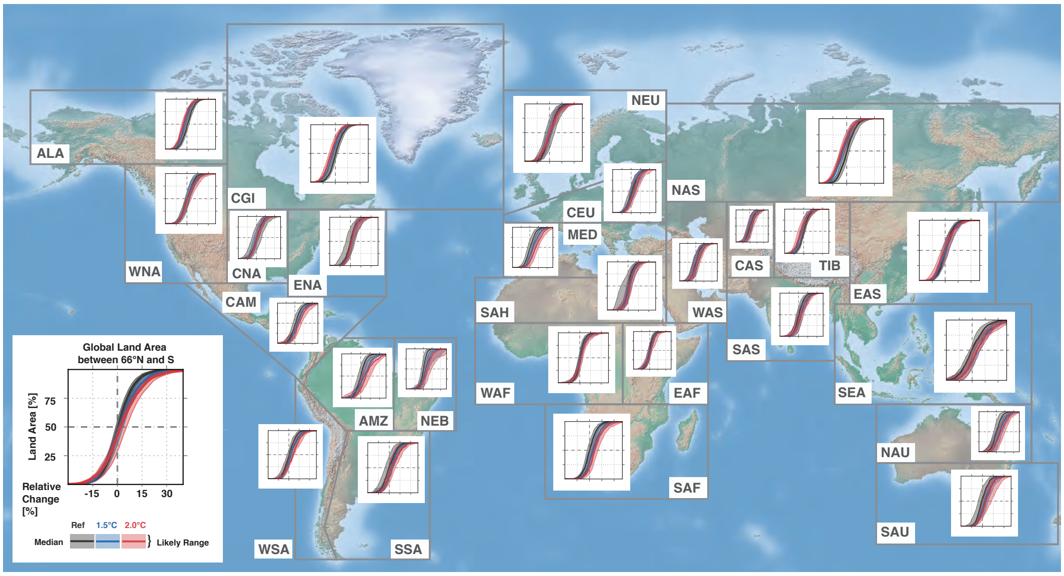

Figure 6. Same as Fig. 2 but for CDD. Changes are given relative to the 1986-2005 reference period.

It is important to highlight that CDD is only an indicator for dry spell length and does not account for changes in evapotranspiration and soil-moisture related effects. It should hence not be interpreted as a direct indicator for agricultural or hydrological (streamflow) drought (Mueller and Seneviratne, 2012; Orlowsky and Seneviratne, 2012). Furthermore, CDD is a metric for short dry spells, which represent only a snapshot of the overall changes in dryness (IPCC, 2012), while high-impact drought events like the Big Dry in Australia (Kiem and Verdon-Kidd, 2010) or the ~~ongoing~~ recent California drought stretch over month and potentially years (Ault et al., 2014). Nevertheless, CDD as well as RX5day can be seen as proxies for the precipitation-related component when assessing drought and flooding risks, respectively, and the results and impacted regions identified here are broadly consistent with projections based on more comprehensive indicators for droughts (Dai, 2012; Prudhomme et al., 2013) and flooding risk (Hirabayashi et al., 2013) alike.

4 Water Availability

Already today, water scarcity is among the biggest challenges for ecosystems and human societies in many regions globally. To assess changes in water availability (assessed here as the annual mean surface and subsurface runoff – QTOT) at 1.5°C and 2°C, we follow the approach outlined above in Section 2. Projections are based on 11 global hydrological models (GHM) that participated in the ISI-MIP intercomparison (Schewe et al., 2013). These are forced with bias–corrected climate simulations from five ~~GCMs (Hempel et al., 2013) used in ISI-MIP, as described in Schewe et al. (2013)~~CMIP5 GCMs (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M, see Hempel et al. (2013) for further details on the bias–correction methodology applied). Each of GCM-GHM combinations is treated as an individual ensemble member resulting in a N=55 ensemble as a basis for the KS tests described above. Unlike for the CMIP5 ensemble, only one realization of each experiment is available and as a consequence the effect of natural variability cannot be assessed. ISI-MIP impacts are assessed at a 0.5° by 0.5° resolution.

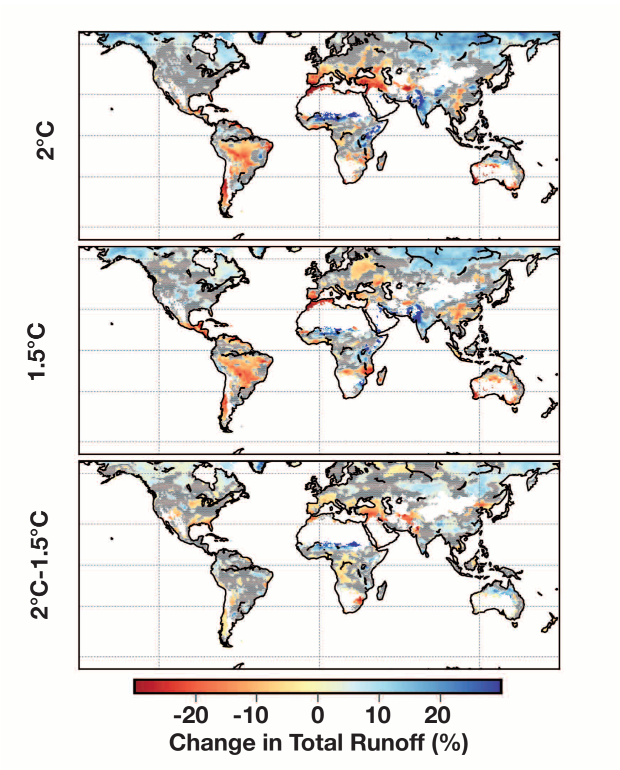

Figure 7. Median projections for changes in annual mean runoff for a warming of 2°C (upper panel), 1.5°C (middle panel) and the difference between both levels (lower panel) relative to the 1986-2005 reference period. The projections are based on the ISI-MIP GCM-GHM model ensemble. Grid cells where less than 66 % of all GCM-GHM pairs agree with the median sign of change are hatched out. Grid cells with an annual mean runoff of less than 0.05 mm/day are masked white.

4.1 ~~Results~~

For a warming of 2°C, reductions in water availability of up to 30 % are projected in several – mainly subtropical – regions, in particular affecting the Mediterranean, South Africa, Central and Southern South America and South Australia (Fig. 7). A relative increase in runoff is projected in much of the high northern latitudes, as well as in parts of India, East Africa and parts of the Sahel. While many of these findings are consistent with earlier studies (James and Washington, 2013; Schewe et al., 2013), some may depend on the five GCMs chosen here and may be less robust in larger CMIP5 GCM ensembles (Knutti and Sedláček, 2012).

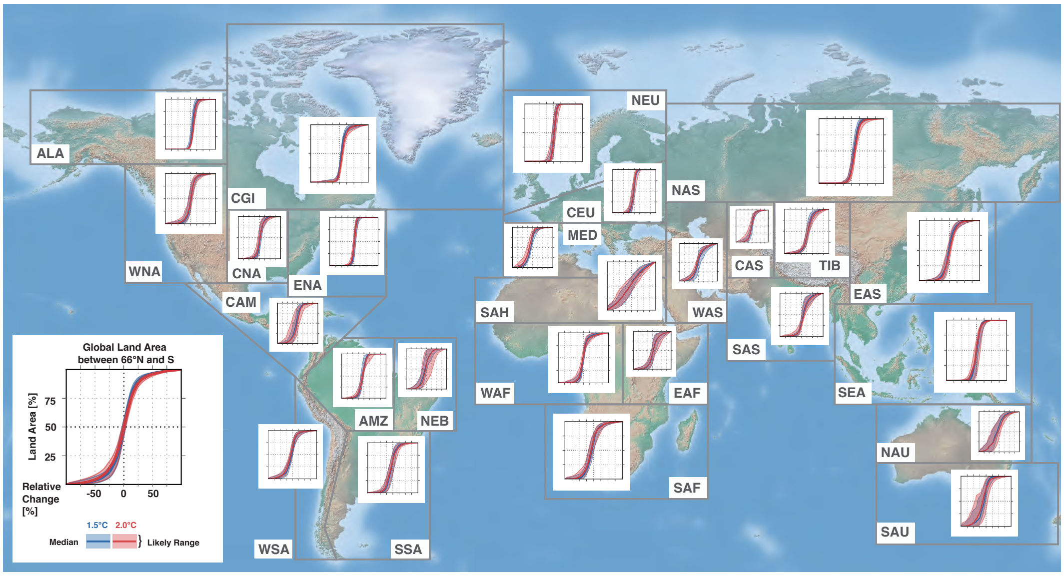

Figure 8. Same as Fig. 2 but for total annual runoff. Changes are given relative to the 1986-2005 reference period.

Fig. 7 (lower panel) and Fig. 8 illustrate the difference between a 1.5°C and 2°C warming. Differences are most prominent in the Mediterranean region where the median reduction in runoff almost doubles from about 9 % (likely range: 4.5 % – 15.5 %) at 1.5°C to 17 % (8 % – 28 %) at 2°C. For several other world regions such as Central America and Australia, there is an increasing risk of substantial runoff reductions exceeding 30 % for the upper limit of the 66 % quantile, although projections are highly uncertain (Tab. S4 and Fig. 8). The differences between 1.5°C and 2°C are smaller for many other regions, but the KS-test reveals that they are statistically significant for all world regions assessed (Tab. S4). These runoff results are also consistent with the findings on precipitation related extremes presented in Section 3.4.

In addition to changes in fresh water availability as a consequence of changes in the hydrological cycle, saltwater intrusion resulting from rising sea-levels or extreme coastal flooding has to be considered (Werner et al. , 2013). Although strongly dependent on local circumstances including regional water management and coastal protection, saltwater intrusion might present a substantial challenge in particular for low-lying coastal areas and small island states (Jiménez Cisneros et al., 2014).

5 Assessing agricultural risks

5.1 Methods and Data

~~To assess projections of~~ We assess future agricultural crop yields in a 1.5°C and 2°C warmer world ~~, we base our analysis of climate change impacts on the yields~~ for the four major staple crops maize, wheat, rice and soy ~~in~~ based on projections from the ISI-MIP Fast Track database (Warszawski et al., 2013; Rosenzweig et al., 2013). Projections for agricultural production depend on a complex interplay of a range of factors, including physical responses to soils, climate and chemical processes, or nutrient and water availability, but are also strongly determined by human development and management. The representation of these processes differs strongly between different agricultural models. While studies suggest an increase in productivity for some crops as a result of higher CO_2-concentrations, large uncertainties remain with regard to temperature sensitivity, nutrient and water limitations, differences in regional responses and also the interactions between ~~those~~ these different factors (Rosenzweig et al., 2013). According to their metabolic pathways of carbon fixation in photosynthesis, main crops can be categorized as C3 and C4 plants. C4 plants such as maize, sorghum and sugar cane have a high CO_2 efficiency and as a consequence profit little from increased CO_2-concentrations, whereas for C3 plants including wheat, rice and soy a positive CO_2 -fertilization effect is to be expected. At the same time, increased CO_2-concentrations may lead to improved water use efficiency (Eamus, 1991). However, the effect of elevated CO_2 concentrations on plant growth is highly uncertain (McGrath and Lobell, 2013) and the representation of this effect greatly differs between different agricultural models. As a consequence, the ISI-MIP protocol has been conducted with and without accounting for CO_2-fertilization effects (further referred to as the CO_2-ensemble and noCO_2-ensemble, respectively). Recent findings also underline the importance of elevated temperatures and heat extremes (Gourdji et al., 2013; Deryng et al., 2014), ozone concentrations (Tai et al., 2014) as well as the potential of increasing susceptibility to disease as a consequence of elevated CO_2 levels (Vaughan et al., 2014) for agricultural yields, which may counteract potential yield gains by CO_2-fertilization (Porter et al., 2014). Results for the CO_2 and noCO_2-ensembles are presented separately, showing the range of potential manifestations and the additional risks of regional yield reductions, if effects of CO_2-fertilization turn out to be lower than estimated by the model ensemble.

The ISI-MIP ensemble contains simulations based on seven Global Gridded Crop Models (GGCM) for wheat, maize and soy and six GGCM for rice, run with input from five CMIP5 GCMs (for further information see Rosenzweig et al., 2013). For the CO_2-ensemble, all model combinations are available (35, and 30 for rice), while for the noCO_2-ensemble runs have been provided for 23 (18 for rice) GGCM-GCM combinations. We restrict future crop growing areas ~~(Monfreda et al., 2008)~~ to present day agricultural areas (based on Monfreda et al., 2008) and assume no change in management type, meaning that "rainfed" and "irrigation" conditions are kept constant as well.

As in previous Sections, the results presented here are based on 20-year time slices from the RCP8.5 simulations and changes are given relative to the 1986-2005 reference period. The choice of displaying relative changes comes with several advantages, but will also lead to a disproportional visual amplification of minor absolute changes for regions with small present day yields, in particular in the high northern latitudes. An overview of the regionally resolved present day share in global production is given in Fig. S5.

Since agricultural impacts depend both on climatological changes and changes in the atmospheric CO_2-concentrations, the assumption of time-independent impacts underlying the time-slice-approach as discussed above does not fully hold for agricultural projections accounting for the effects of CO_2-fertilization (the CO_2-ensemble) and will lead to increased inner-ensemble spread as a consequence. Please note that the regional aggregation for agricultural yields is not based on absolute yield change but on land area, as for the other indicators studied above. Since societal impacts of changes in agricultural production go beyond mere changes in yield, but also include for example local livelihood dependencies (Schellnhuber et al., 2013; Olsson et al., 2014), our assessment of local yield changes (on a grid-cell level) supplements and extends previous yield-centered analysis (Rosenzweig et al., 2013). Maps for the projected differences of yield changes on a grid-cell basis are provided in the supplementary information.

5.2 Results

5.2.1 Wheat

Our analysis reveals very small local median yield changes for 50 % of the global land area for a 1.5°C and 2°C warming. However, the uncertainties of these projections are substantial and reductions of about 6 % and 8 % for 1.5°C and 2°C, respectively, mark the lower end of the likely range (compare Tab. S5). For the noCO_2-ensemble, we find substantial median reductions in local wheat yields of 14 % at 1.5°C, with a statistically significant higher decrease of 19 % at 2 °C and potential reductions of up to 20 % (1.5°C) and 37 % (2°C) as lower limits for the likely range. The results of the KS-tests based on individual model combinations are given in Tab. S5 and for the global level as well as most regions, more than 83 % (90 %) of all ensemble members indicate a robust difference between projected impacts at 1.5°C and 2°C for the CO_2 (noCO_2)-ensemble.

~~Local~~ Best estimate local yield reductions are projected for ~~most tropical regions. A median reduction of 13~~the tropical region of about 9 % (~~19~~15 %) ~~is projected for 50 % of the West African agricultural area for~~ for 1.5°C (2°C) ~~and more than 6 % for East Africa. Both,~~ that are particularly pronounced in West African (median reduction of 13 % (19 %)). Under a 1.5 °C (2°C) warming, reductions of up to 25 % (42 %) are within the likely range of the CO_2 ~~and no~~ensemble projections and for the noCO_2-ensembles~~, project wheat yield increases of over 40 % in some high latitude regions relative to a comparably low baseline (compare Fig. S5)~~, median reductions of 28 % (35 %)

would be projected. ~~Similarly, the projected drastic relative reductions of over 60 % for a 2°C warming in the Amazon region, may not directly affect regional food security, as wheat is not the main regional staple crop (about 1 %of global wheat are produced in the region) .~~

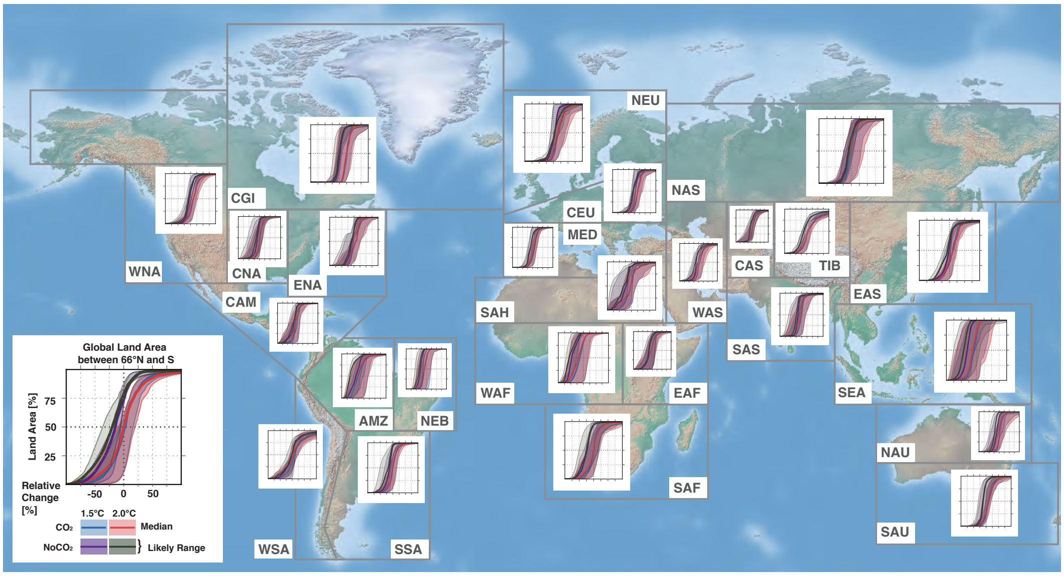

Figure 9. Same as Fig. 2 but for changes in wheat yields. Changes are given relative to the 1986-2005 reference period and ensemble projections excluding the effect of CO_2-fertilization are ~~singled out explicitly~~shown separately. The CDFs are derived only over the present day growing areas of the crop~~(Monfreda et al., 2008)~~.

5.2.2 Maize

The effects of elevated CO_2 concentrations affect maize yields to a much lesser extent, as conditions are mostly saturated at present levels (see e.g. Leakey et al., 2006). Differences between runs are thus less pronounced for maize yields, where yield reductions are projected for both the CO_2 and the noCO_2-ensemble. As the number of runs differ between the two ensembles (see Methods), the small differences are likely due to the different ensemble size. Thus, we only discuss results for the CO_2-ensemble here. Differences between the warming levels are significant (all ensemble members indicate a significant difference for the global crop area, see Tab. S6), with median local yield reductions experienced by 50 % of the global crop area of around 1.5 % and 6 % for 1.5°C and 2°C warming, respectively. Risks of reductions of up to 26 % at 1.5°C and 38 % at 2°C are within the likely range globally (compare Fig. 9 and Tab. S6).

As apparent in Fig. 9, the likely range is deferred towards stronger reductions. Similar regional patterns compared to wheat projections are apparent. Again, the highest relative median changes occur in regions with a relatively low share of global production. For central North America, where at present about 10 % of global maize is produced, substantial differences between the two warming levels are projected, and risks for a strong negative effect in this region more than double between 1.5°C and 2°C warming from 15.5 % to 37 % (upper limit of the 66 % range). Tropical regions such as Central America, the Amazon and South-East Asia are projected to experience median local yield reductions exceeding 5 % for 1.5°C and up to and more than 10 % for 2 °C, while projections for the full tropical region do not differ substantially from the global projections.

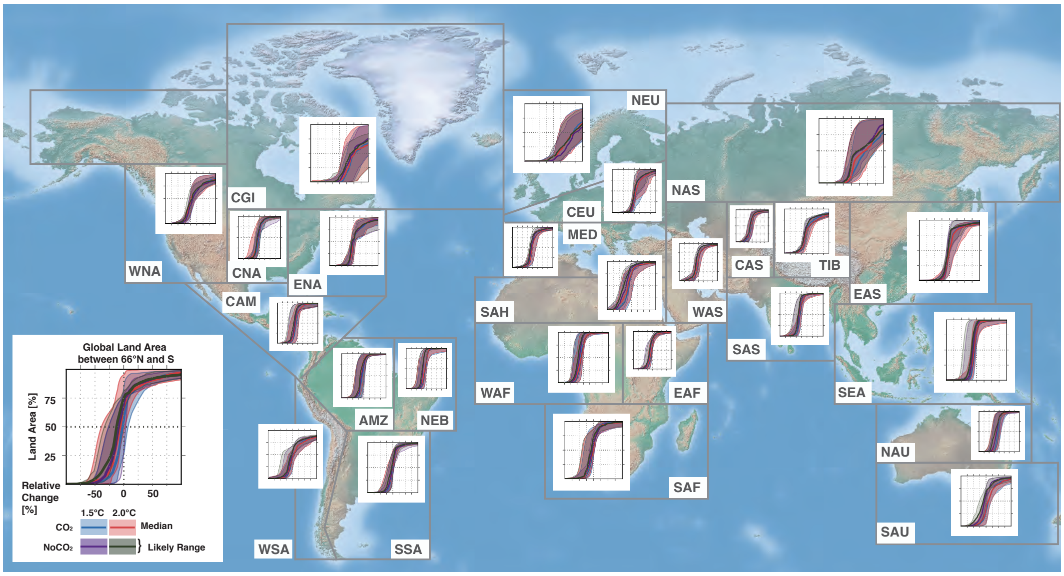

Figure 10. Same as Fig. 9, but for changes in maize yields.

5.2.3 Soy

Projections of changes in soy yields between the two assessed warming levels show robust differences (see Tab. S7). For the CO_2-ensemble, a median increase in global yields of 7 % is projected for 50 % of the global area under a warming of 1.5°C. This median increase vanishes for 2°C. Global differences between warming levels for the noCO_2-ensemble are smaller but nonetheless robust, with median reductions of 10 % and 12 %, respectively.

Regionally, the differences for the noCO_2-ensemble are more pronounced, especially in those regions with a large share in present-day global soy production. Median yields for the Amazon (AMZ) region, currently producing about 7 % of global soy (Monfreda et al., 2008, see also Fig. S5), are projected to reduce from 15 % under 1.5°C to 20 % under 2°C warming. Similar robust differences in yield reductions between 1.5°C and 2°C warming are also projected for the major soy producers in Central North America and South-East South America. For North Asia, where currently over 7 % of soy production takes place, median increases in yields of 28 % and 24 % are projected for a warming of 1.5°C for the noCO_2 and CO_2-ensembles, respectively. However, uncertainties for this region are high and a risk of substantial reductions of 25 % (1.5°C) and 20 % (2°C) in the CO_2-ensemble are within the likely range of the ensemble projections.

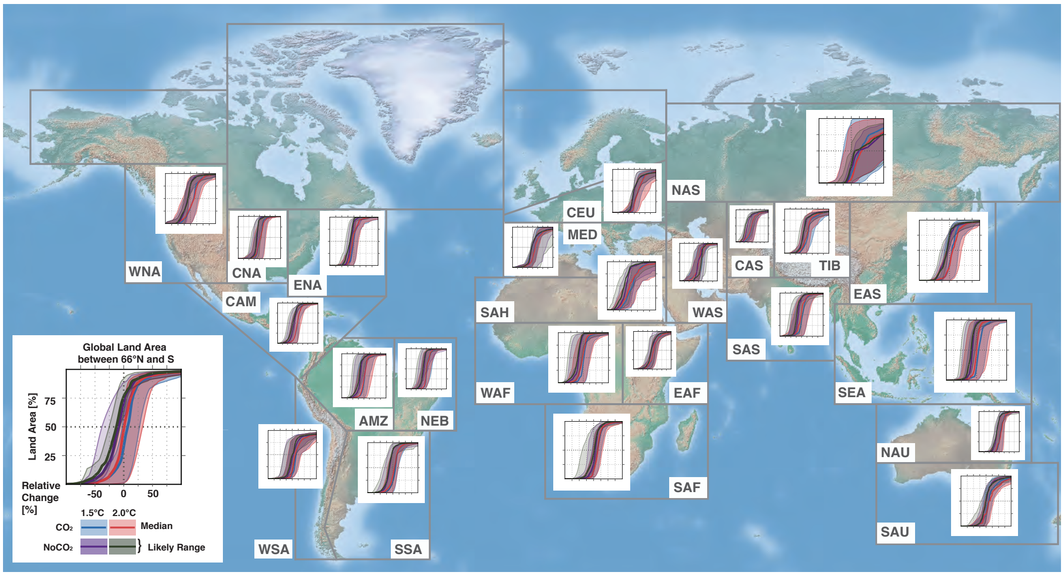

Figure 11. Same as Fig. 9, but for changes in soy yields.

5.2.4 Rice

Median changes in global rice yields for the CO_2-ensemble do not differ between the assessed warming levels, with projected increases of about 7 % although the respective local yield change distributions are significantly different (compare Tab. S8). The distribution of possible developments indicates ~~risks~~ risk of substantial reductions of up to 17 % and 14 % at 1.5°C and 2°C~~of warming~~. For the $noCO_2$-ensemble, reductions of 8 % and 15 % are projected for the two warming levels.

The effects of CO_2-fertilization consistently indicates yield increases across regions for median projections. While differences between warming levels are apparent for some regions and the CO_2-ensemble, ~~these display comparably low confidence~~ global estimates are very similar between both warming levels. For the $noCO_2$-ensemble, robust differences between 1.5°C and 2°C warming are apparent for all major rice producing regions, including all Asian regions where a total of 40 % of rice is produced today (EAS, SAS, SEA, TIB) as well as the Amazon, and South American rice producers. Reductions are projected to double between the two warming levels, for example in South Asia, South-East South America and the Tibetan Plateau. For these regions, median projections are close to the lower end of the likely range (compare Fig. 12 and Tab. S8).

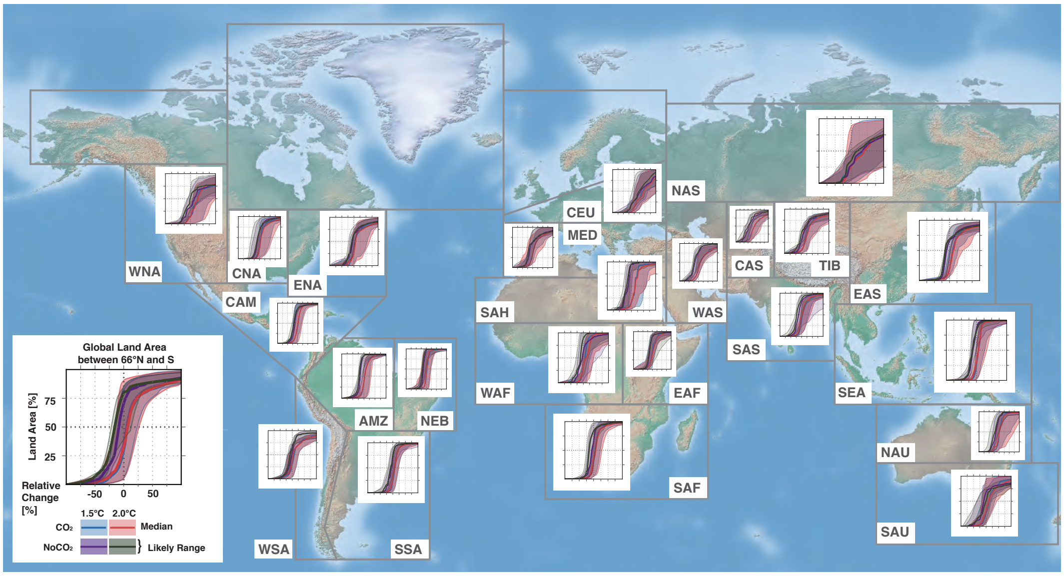

Figure 12. Same as Fig. 9 but for changes in rice yields.

5.3 Discussion of agricultural impact projections

Our projections of local agricultural yields reveal substantial uncertainties in global median regional yield changes (Figs. 9 to 12) with a likely range (66 % - likelihood) comprising zero. For wheat, rice and soy, our projections indicate differences between the CO_2 and noCO_2 assessments, which are generally much larger than those between a 1.5°C and 2°C warming. While substantial uncertainty renders a differentiation between impacts at 1.5°C and 2°C warming difficult in most world regions, a clear signal emerges for the noCO_2-ensemble, that may serve as a high-risk illustration of potential climate impacts on agricultural production. In the noCO_2-ensemble, local yields are projected to decrease between 1.5°C and 2°C for all crop types.

Our results indicate that risks are region and crop specific and are in line with findings of previous model intercomparison studies (Asseng et al., 2014; Rosenzweig et al., 2013). While high-latitude regions may benefit, median projections for local yields in large parts of the tropical land area are found to be negatively affected already at 1.5°Cand risks . Risks increase substantially, if effects of CO_2-fertilization are less substantial or counter-acted by other factors such as extreme temperature response, land degradation or nitrogen limitation (Rosenzweig et al., 2013; Bodirsky and Müller, 2014; Bodirsky et al., 2014). In a statistical analysis of climate impacts on wheat and barley yields in Europe, Moore and Lobell (2015) report an overall negative contribution of climatic factors in line with findings of a meta-analysis by Asseng et al. (2014), which questions the positive effects projected in our CO_2-ensemble for this region and further support the risk framework of assessing future projections including our approach of singling out noCO_2-ensemble projectionsadopted here. Given that a 1.5°C warming might be reached already around 2030, our findings underscore the risks of global crop yield reductions due to climate impacts outlined by Lobell and Tebaldi (2014), while giving further indications for the regional diversity of climate impacts with tropical regions being a hot-spot for climate impacts on local agricultural yields (Müller et al., 2014).

6 Sea-level rise

6.1 Methods

Projections for sea-level rise (SLR) cannot be based on a ~~time-sliced approach due to~~ time-slice approach because of the importance of the time-lagged response of the ocean and cryosphere to the warming signal. Therefore, we selected two multi-gas scenarios illustrative of a 1.5°C and 2°C warming to assess SLR impacts over the the entire 21^{st} century from a large emission scenario ensemble created by Rogelj et al. (2013). These scenarios were created with the integrated assessment modeling framework MESSAGE (the Model for Energy Supply Strategy Alternatives and their General Environmental Impact, Riahi et al., 2007). For both scenarios, temperature projections are derived with the reduced complexity carbon-cycle and climate model MAGICC (Meinshausen et al., 2011) in a probabilistic setup (Meinshausen et al., 2009), which ~~is consistent with the IPCC AR5 assessment of climate sensitivity (Rogelj et al., 2012, 2014).~~ has been calibrated to be in line with the uncertainty assessment of equilibrium climate sensitivity of the IPCC AR5 (Rogelj et al., 2012, 2014). Each probabilistic setup ensemble consists of 600 individual scenario runs. The first scenario keeps GMT to below 2°C relative to pre-industrial levels (1850-1875) during the 21^{st} century with 50 % probability. The second scenario reduces emissions sooner and deeper, and keeps warming to below 1.5°C relative to pre-industrial levels during the 21^{st} century with about 50 % probability and returns end-of-century warming to below 1.5°C with about 70 % probability. See Fig. 13 (upper panel) for median temperature projections for the 2°C and 1.5°C scenario and their associated uncertainty bands. Since the projections for coral reef degradation include a time dependent adaptation scenario, the same approach is taken for the coral reef projections (see Section 7).

SLR projections are based on Perrette et al. (2013), who developed a scaling approach for the various SLR contributions according to an appropriately chosen climate predictor – in this case GMT increase and ocean heat uptake. Coupled with output from the MAGICC model, this allows to emulate the sea-level response of GCMs to any kind of emission scenario within the calibration range of the method that is spanned by the RCPs.

Consistent with the relationship found in CMIP3 and CMIP5 GCMs, ocean thermal expansion is assumed to be proportional to cumulative ocean heat uptake (Church et al., 2013). Mountain glacier melt is computed following a widely-used semi-empirical relationship between rate of glacier melt, remaining surface glacier area, and temperature anomaly with respect to pre-industrial levels. This approach assumes constant scaling between area and volume (Wigley and Raper, 2005; Meehl et al., 2007), with parameters chosen to account for current melt rate and known glacier volume (Eq. 1 and Table 2 in Perrette et al., 2013). As already noticed by Gregory and Huybrechts (2006) (their Fig. 5), the surface mass balance (SMB) anomaly from the Greenland ice-sheet can be approximated with reasonable accuracy as a quadratic fit to global mean temperature anomaly. Here we adopted the same functional form, but calibrated it to more recent projections by Fettweis et al. (2013). Following Hinkel et al. (2014), we scaled up these projections by $20\% \pm 20\%$ to account for missing dynamic processes (elevation feedback $10\% \pm 5\%$, changes in ice dynamics $10\% \pm 5\%$, and $\pm 10\%$ arising from the skill of the SMB model to simulate the current SMB rate over Greenland). The climate-independent land-water contribution has been added for all scenarios following Wada et al. (2012).

Beyond the scaling approach, the ~~real~~ main advancement of our approach compared to the IPCC AR5 (Church et al., 2013) stems from the inclusion of scenario-dependent Antarctic ice-sheet projections following Levermann et al. (2014). Linear response functions were derived from idealized step-forcing experiments from the SeaRISE project ~~Bindschadler et al. (2013)~~ (Bindschadler et al., 2013) as a functional link between the rate of ice shelf melting and dynamical contribution to SLR over four Antarctic sectors and various ice-sheet models. Levermann et al. (2014) further assume linear scaling between global surface air warming, local ocean warming, and ice-shelf melting in each of the sectors. They adopted a Monte Carlo approach with 50,000 samples to combine the various parameter ranges, GCMs and ice-sheet models. To our knowledge, this is the most comprehensive attempt to date to link climate warming and Antarctic ice-sheet contributions to scenario-dependent sea-level rise over the 21^{st} century.

6.2 Results

The results for the 2°C scenario are comparable with projections by Church et al. (2013) and Hinkel et al. (2014) for RCP2.6 (their Tables 13.5 and 4, respectively) that leads to a median GMT increase of about 1.6°C above pre-industrial levels. For this scenario, we project a median SLR of about 50 cm (36 – 65 cm, likely range) by 2100 and a rate of rise of 5.6 (4 – 7) mm/year over the 2081-2100 period. Under our illustrative 1.5°C scenario, projected SLR in 2100 is about 20 % (or 10cm) lower, compared to the 2°C scenario (See Tab. 2). The corresponding reduction in the expected rate of SLR over the 2081-2100 period is about 30 %. More importantly, and in contrast to the projections for the 2°C scenario, the rate for the 1.5°C scenario is projected to decline between mid-century and the 2081-2100 period by about 0.5 mm/year, which substantially reduces the multi-centennial SLR commitment (Schaeffer et al., 2012).

The projected difference in SLR between the 1.5°C and 2°C scenarios studied here is comparable to the difference between the RCP2.6 and RCP4.5 scenarios (Hinkel et al., 2014; Church et al., 2013), while the projected median GMT difference between the two RCP scenarios is about 0.8 °C for the 2081-2100 period. The relatively higher sensitivity of SLR in the 21^{st} century to temperature increase at low climate warming is probably related to the earlier peaking of GMT under such scenarios and thus an already longer adjustment period for the time-lagged ocean and cryosphere. This leads to a larger share of committed multi-centennial SLR to occur in the 21st century. On multi-centennial timescales these scenario dependent differences are expected to vanish. A long-term difference, however, may arise from contributions by mountain glacier melt, which are particularly vulnerable to GMT increase and thus differences in melted mountain glacier volume are higher for lower emission scenarios.

While SLR projections for the two illustrative 1.5°C and 2°C differ substantially, this effect is strongly scenario dependent. In particular, most emission pathways labeled as 1.5°C scenarios allow for a temporal overshoot in GMT and a decline below 1.5°C with a 50 % probability by 2100 (Rogelj et al., 2015), whereas the illustrative 1.5°C scenario used here does not allow for a GMT overshoot, but stays below 1.5°C over the course of the 21st century. For time-lagged climate impacts such as SLR that depend on the cumulative heat entry in the system, the difference between a scenario allowing for a GMT overshoot and one that does not will be significant.

Sea-level adjustment to climate warming has a time scale much larger than a century as a result of slow ice-sheet processes and ocean heat uptake. This means that in all emission scenarios considered, sea level will continue to rise beyond 2100. Levermann et al. (2013) have shown that on a 2000-year time-scale, sea-level sensitivity to global mean temperature increase is about 2.3m per °C. In addition to that, Levermann et al. (2013) report a steep increase in long-term SLR between 1.5°C and 2°C as a result of an increasing risk of crossing a destabilizing threshold for the Greenland ice-sheet (Robinson et al., 2012). The disintegration ~~of this ice-sheet, which~~ process that would lead to 5–7 m global SLR, however, is projected to happen on the time scale of several millennia~~, however~~.

Recent observational and modeling evidence indicates that a marine ice-sheet instability in the West Antarctic may have already been triggered, which could lead to an additional SLR commitment of about 1 m on a multi-centennial time scale. Spill-over effects of this destabilization on other drainage basins and their relation to GMT increase are as yet little understood (Rignot et al., 2014; Joughin et al., 2014; Favier et al., 2014) and there are indications that a destabilization of the full West Antarctic ice-sheet could eventually be triggered (Feldmann and Levermann , 2015). Similarly, Mengel and Levermann (2014) report a potential marine ice-sheet instability for the Wilkens Basin in West Antarctica containing 3–4 m of global SLR. The dynamics of these coupled cryosphere-oceanic systems remain a topic of intense research. Current fine-scale ocean models, suggest increased intrusion of warm deep water on the continental shelf as a result of anthropogenic climate change and thus indicate an increasing risk with increasing warming (Hellmer et al., 2012; Timmermann and Hellmer, 2013). Given the risk of potentially triggering multi-meter SLR on centennial to millennial time scales, this clearly calls for a precautionary approach that is further underscored by evidence from paleo-records, which reveals that past sea-levels might have about 6–9 m above present day for levels for a GMT increase not exceeding 2°C above pre-industrial levels (Dutton et al., 2015).

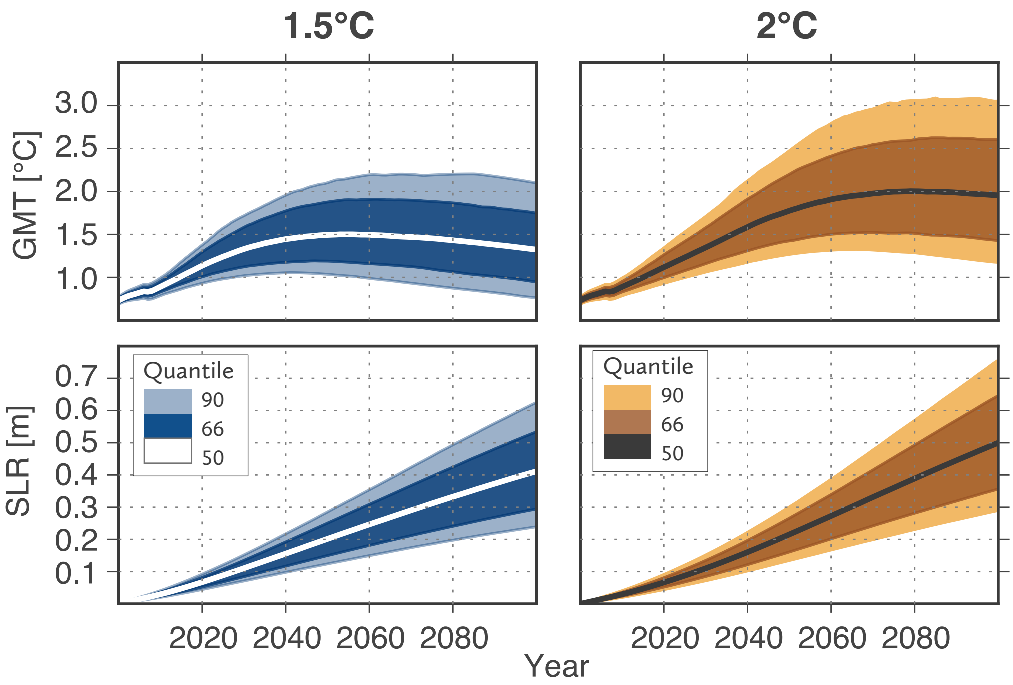

Figure 13. Upper panel: Probabilistic GMT projections for illustrative emission scenarios with a peak warming of 1.5°C (left panels) and 2°C (right panels) above pre-industrial levels during the 21st century. Lower panels: Probabilistic projections of global sea-level rise (SLR) for both scenarios relative to 1986-2005 levels. Uncertainty bands indicate the likely range (66 % probability within this range) and the very likely range (90 % probability), respectively.

Table 2. Projections for sea-level rise above the year 2000-levels for two illustrative 1.5°C and 2°C scenarios (see Fig. 13). Square brackets give the likely (66 %) range.

	$1.5^{\circ}C$	$2^{\circ}C$
SLR 2081-2100 [m]	0.37 [0.27,0.48]	0.44 [0.32,0.57]
SLR 2100 [m]	0.41 [0.29,0.53]	0.5 [0.36,0.65]
Rate of SLR 2041-2060 [mm/year]	4.6 [3.2,5.8]	5.6 [4.0,7.0]
Rate of SLR 2081-2100 [mm/year]	4.0 [2.7,5.5]	5.6 [3.8,7.7]

7 Coral reef systems

7.1 Methods

The projections of the degradation of coral reef sites ~~use a risk assessment framework analogous to~~ uses the coral bleaching model developed in Frieler et al. (2012) based on the two illustrative 1.5°C and 2°C global emission pathways introduced in Section 6.1. The framework applies a threshold-based bleaching algorithm by Donner (2009), which is based on degree heating months (DHMs), to sea surface temperature (SST) pathways of 2160 individual geospatial locations of coral reef sites (see www.reefbase.org) and generates as output the fraction of coral reef locations subject to long-term degradation. DHMs are a measure for the accumulated heat stress exerted on coral reefs due to elevated SST (see Fig. S6 for a graphical illustration of the methodology). Within a four months moving window the monthly SST above a reference value (here the mean of monthly maximal temperatures, MMM) are accumulated and compared to a threshold value (critical DHM threshold) that is associated with mass coral bleaching. The value of the critical DHM threshold depends on the scenario assumptions (see below). In order to translate coral bleaching events into long-term coral degradation, we refer to the assumption that reef recovery from mass coral bleaching is usually very limited within the first five years (Baker et al., 2008). Therefore, we assume a maximum tolerable probabilistic frequency of $0.2yr^{-1}$ (Donner, 2009) for bleaching events causing long-term degradation. The MMM is calculated from a 20-year climatological reference period (1980-2000) individually for every coral location and SST pathway. Thus, the MMM serves as an indicator of temperatures to which the corals of a certain reef location are generally adapted. In order to generate a scenario-independent description of coral reef response to different levels of global warming (e.g. any given global mean air temperature pathway) we apply the algorithm to a large number of SST pathways and reassign the fraction of 2160 mapped coral reef locations subject to long-term degradation back to global air temperature pathways. In total, we use the SST pathways of 19 Atmosphere-Ocean General Circulation Models (AOGCMs) from the multi-model CMIP3 project and seven different emission scenarios leading to 30,728 model years. We also used a wide range of critical DHMs (from 0° to 8°), which allows for the testing of risk scenarios with constant and variable critical DHM thresholds (e.g. thermal adaptation).

The condensed output of the global coral bleaching assessment allows for the implementation of different coral adaptation scenarios. In the standard scenario (*Constant*) a constant DHM threshold of 2°C is assumed. This means that corals can resist a cumulative heat stress of 2°C (accumulated over four month period) above the long-term maximum monthly mean (MMM) sea surface temperature for a given location. It has been demonstrated that this value serves as a good proxy for severe mass coral bleaching (Donner et al., 2005, 2007).

In addition to the constant scenario, an extremely optimistic scenario of strong thermal adaptation of the corals is assessed (*Adaptation*). Under this scenarios, the critical DHM threshold constantly increases from 2°C in the year 2000 up to 6°C in 2100. The assumption of a thermal adaptation of 0.4° per decade appears very ambitious given the long creation times of reef-building corals and the consequently slow rate at which evolutionary adaptation occurs. Furthermore, additional environmental stressors such as ocean acidification (Caldeira, 2005) and disease spreading (Maynard et al., 2015) have to be expected to slow-down coral growth and to reduce the adaptive capacity of tropical coral reefs. As a consequence, this scenario should be seen as an absolute lower boundary for degradation of coral reefs globally.

Finally, a third scenario takes the negative effect of the acidification of the oceans into account which reduces the calcification rates of the corals and thus promotes further degradation of coral reefs (*Saturation*). We derived a transfer function based on atmospheric CO_2 concentrations due to the fact that tropical surface aragonite saturation levels are in equilibrium with atmospheric CO_2 concentrations on a timescale of years to decades (Caldeira, 2005). With an assumption of the effect of the aragonite saturation on the critical DHM threshold (see supporting material of Frieler et al. (2012)) this translates into a measurable increased stress to corals.

7.2 Results

Coral reef systems are slow-growing, complex ecosystems that are particularly susceptible to the impacts of increased CO_2 concentrations, both through warming (and resulting coral bleaching) and ocean acidification (Pörtner et al., 2014). Our analysis re-iterates earlier findings that the risk of coral reefs to suffer from long-term degradation eventually leading to an ecosystem regime shift (Graham et al., 2015) will be substantial as early as 2030 (Meissner et al., 2012; Gattuso et al., 2015; Frieler et al., 2012). We find that this risk increases dramatically until the 2050s, where even under a 1.5°C scenario, 90 % and more of all global reef grid cells will be at risk of long-term degradation under all but the most optimistic scenario assessed (the *Adaptation* case, see Sec. 7.1). However, long-term risks towards the end of the century are reduced to about 70 % of global coral reef cells under a 1.5°C scenario but not under a 2°C scenario (compare Fig. 14 and Tab. 3).

Our approach only includes the effects of increased CO_2-concentrations, but does not account for other stressors for coral reef systems such as rising sea-levels, increased intensity of ENSO-events (Power et al., 2013), tropical cyclones (Knutson et al., 2010), invasive species and disease spreading (Maynard et al., 2015), and other local anthropogenic stressors, which ranks our projections of long-term coral reef degradation rather conservative. These projected losses will greatly affect societies, which depend on coral reefs as a primary source of ecosystem services e.g. in the fishery and tourism sector (Cinner et al., 2015). Teh et al. (2013) estimate that about 25 % of the world's small-scale fishers fish on coral reefs. Chen et al. (2015) report that a loss of less than 60 % of global coral reef coverage, that could very well be reached already in the 2030s, would inflict damages of more than US$ 20 billion annually.

8 Discussion and Conclusions

The findings of our analysis support the IPCC AR5 Working Group 2 RFC assessment of differences in key impacts of climate change between warming of 1.5°C and 2°C above pre-industrial levels: we find that under a 1.5° scenario, the fractions of coral reef cells ~~under~~ at risk of severe degradation are reduced significantly compared to a warming of 2°C (RFC1), that the difference between 1.5°C and 2°C marks the transition between an upper limit of present-day natural variability and a new climate

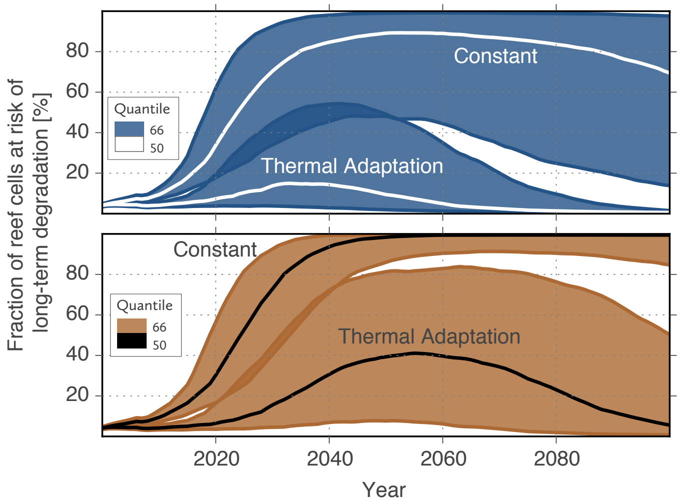

Figure 14. Probabilistic projections of the fraction of global tropical coral reef cells suffering from long-term degradation under two illustrative 1.5°C (upper panel) and 2°C (lower panel) scenarios (see Fig. 13 upper panel) for two different assumptions about ~~the~~ their adaptive capacity ~~following Frieler et al. (2012)~~(see Section 7.1). Median projections and the 66 % range are shown. Note that uncertainties also include uncertainties in the GMT response (see Fig. 13). See Section 7.1 for further details on the methodology. Only the projections for the *Constant* and *Adaptation* scenario are shown, since the projections for the *Saturation* scenario differ only slightly from *Constant*. Tab. 3 gives results for all three scenarios assessed.

Table 3. Fraction of reef cells at risk of long-term degradation due to coral bleaching in 2050 and 2100 for three different assumptions about the adaptive capacity and susceptibility of corals to ocean acidification as described in Section 7.1 in percent. Median projections and the 66 % range (in square brackets) are given, accounting also for uncertainties in global mean temperature projections..

2050	$1.5^{\circ}C$	$2^{\circ}C$
Adaptation	9 [2,49]	39 [8,81]
Saturation	94 [60,100]	100 [95,100]
Constant	89 [48,99]	98 [86,100]
2100		
Adaptation	1 [0,2]	6 [1,50]
Saturation	69 [14,98]	100 [91,100]
Constant	69 [14,98]	99 [85,100]

regime in terms of heat extremes globally (RFC2), and that changes in water availability and local agricultural yields are already unevenly distributed between world regions at 1.5°C and even more so at 2°C (RFC3). Central findings across the different indicators studied are summarized in Fig. 15 and regional summaries are given in the Supplementary Material (Fig. S.7–33)

Water availability reduction and dry spell length (CDD) increase are found to accelerate between 1.5°C and 2°C for several sub-tropical regions, in particular in the Mediterranean, Central America and the Caribbean, South Africa and Australia. Local agriculture production in tropical regions is projected to be strongly affected by ongoing warming, in particular, if effects of CO_2 -fertilization do not play out as current models project them or are counter-balanced by other factors such as nitrogen and phosphor limitations or heat stress, which are not fully included in the models investigated here.

Our analysis of projected SLR reveals differences of about ~~10cm~~ 10c̃m in global mean SLR between ~~a~~ illustrative 1.5°C and 2°C ~~scenario~~ scenarios by 2100. In addition, ~~recent findings outlining evidence~~ the end-of-century rate of sea-level rise for 1.5°C is about 30 % lower than for a 2°C pathway, indicating a substantially lower long-term sea-level rise commitment (Clark et al., 2016). Evidence from the paleo-record (Dutton et al., 2015) and modeling studies (Levermann et al., 2013) further indicate that a multi-meter sea-level of potentially up to ~~9m and is not unlikely~~ 9 m cannot be ruled out under a 2°C warming on multi-millennial time scales. ~~In particular, a maintained warming of 2°C above pre-industrial levels has been found to potentially destabilize large parts of the Greenland ice-sheet (Robinson et al., 2012) and a warming of well-below 2°C might be needed to avoid further destabilization of marine ice-sheets in Antarctica (Winkelmann et al., 2015). We are only beginning to understand the complex ocean - ice-sheet interactions that govern these processes and as a consequence, these thresholds are subject to substantial uncertainty and call for a precautionary approach to keep warming as low as possible.~~

Our assessment based on this limited set of indicators implies that differences in climate impacts between 1.5°C and 2°C are most pronounced for particularly vulnerable regions and ~~for groups in countries~~ societal groupings with limited adaptive capacity (Olsson et al., 2014). Under a 2°C warming, coastal tropical regions and islands may face the combined effects of a near-complete loss of tropical coral reefs, which provide coastal protection and are a main source of ecosystem services, on-going sea-level rise above present day rates over the 21st century and increased threats by coastal flooding and inundation. The risks posed by extreme heat and potential crop yield reductions in tropical regions in Africa and South East Asia under a 2°C warming are particularly critical given the projected trends in population growth and urbanization in these regions (O'Neill et al., 2013). In conjunction with other development challenges, the impacts of climate change represent a fundamental challenge for regional food security (Lobell and Tebaldi, 2014) and may trigger new poverty traps for several countries or populations within countries (Olsson et al., 2014).

Furthermore, the emergence of the Mediterranean region, including North Africa and the Levant, as a hot-spot for reductions in water availability and dry spell increases between 1.5°C and 2°C is of great relevance given the specific vulnerability of this region to water scarcity (Schellnhuber et al., 2014). The political instability in several countries in this region may further exacerbate the vulner-

		1.5°C	2°C	
Heat wave (warm spell) duration [month]				
	Global	1.1 [1,1.3]	1.5 [1.4,1.8]	Tropical regions up to 2 (3) month at 1.5°C (2°C) warming
Reduction in annual water availability [%]				
	Mediterranean	9 [5,16]	17 [8,28]	Other dry subtropical regions like Central Amerika and South Africa also at risk
Increase in heavy precipitation intensity [%]				
	Global	5 [4,6]	7 [5,7]	Global increase in intensity due to warming, high latitudes (>45°N) and monsoon regions affected most.
	South Asia	7 [4,8]	10 [7,14]	
Global sea-level rise				
	in 2100 [cm]	40 [30,55]	50 [35,65]	1.5°C end-of-century rate about 30% lower than for 2°C reducing long-term SLR commitment.
	2081-2100 rate [mm/yr]	4 [3,5.5]	5.5 [4,8]	
Fraction of global coral reefs at risk of annual bleaching [Constant case, %]				
	2050	90 [50,99]	98 [86,100]	Only limiting warming to 1.5°C may leave window open for some ecosystem adaptation.
	2100	70 [14,98]	99 [85,100]	
Changes in local crop yields over global and tropical agricultural area [%}				
Wheat	Global	2 [-6,17]	0 [-8,21]	Projected reduction risks are largest for tropical regions, while high-latitude regions may benefit. Projections not including highly uncertain positive effects of CO_2-fertilization project reductions for all crop types of about 10% already at 1.5°C and further reductions at 2°C.
	Tropics	-9 [-25,12]	-16 [-42,14]	
Maize	Global	-1 [-26,8]	-6 [-38,2]	
	Tropics	-3 [-16,2]	-6 [-19,2]	
Soy	Global	7 [-3,28]	1 [-12,34]	
	Tropics	6 [-3,23]	7 [-5,27]	
Rice	Global	7 [-17,24]	7 [-14,27]	
	Tropics	6 [0,20]	6 [0,24]	

Figure 15. Summary of key differences in climate impacts between a warming of 1.5°C and 2°C above pre-industrial and stylized 1.5°C and 2°C scenarios over the 21st century. Square brackets give the likely (66 %) range.

ability of societies to climatic stresses, potentially increasing the risk of violent conflict outbreak (Kelley et al., 2015).

~~In conjunction with a recent analysis of~~ Taken together, we provide a consistent and comprehensive assessment of existing projections and a solid foundation for future work on refining our understanding of the difference between impacts at 1.5 °C and 2 °C warming. In particular, we illustrate how limiting warming to 1.5°C would "significantly reduce the risks and impacts of climate change" as stated in the Paris Agreement. However, our analysis can only be a first step towards a more integrative post - Paris science agenda including the assessment of below 1.5°C impacts and requirements and costs of energy system transformation pathways in line with limiting warming to below 1.5°C in 2100 (Rogelj et al., 2015), we hope that our analysis can contribute to inform the discussion about the adequacy of different long-term climate targets. In the light of the upcoming UNFCCC negotiations in Paris in December 2015, where a global agreement on limit climate change is anticipated, a comprehensive overview of the consequences of different temperature-pathways is essential to reach informed decisions. (Rogelj et al., 2015).

Acknowledgements. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP, the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provided coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. We would like to thank the modelling groups that participated in the Inter-Sectoral Impact Model Intercomparison Project (ISI- MIP).

The ISI-MIP Fast Track project underlying this paper was funded by the German Federal Ministry of Education and Research with project funding reference number 01LS1201A. The work on this paper was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (11H093 Global A 11-II-093-Global-A SIDS and LDCs)., within the framework of the Leibniz Competition (SAW-2013-PIK-5), from EU FP7 project HELIX (grant no. FP7-603864-2), and by the German Federal Ministry of Education and Research (BMBF, grant no. 01LS1201A1)

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