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Half a degree Additional warming, Projections, Prognosis and Impacts (HAPPI): Background and Experimental Design

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Abstract.

The Intergovernmental Panel on Climate Change (IPCC) has accepted the invitation from the UNFCCC to provide a special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. Many current experiments in, for example, the Coupled Model Inter-comparison Project (CMIP), are not specifically designed for informing this report. Here, we document the design of the Half a degree Additional warming, Projections, Prognosis and Impacts (HAPPI) experiment. HAPPI provides a framework for the generation of climate data describing how the climate, and in particular extreme weather, might differ from the present day in worlds that are 1.5°C and 2.0°C warmer than pre-industrial conditions. Output from participating climate models includes variables frequently used by a range of integrated assessment models. The key challenge is to separate the impact of an additional approximately half degree of

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warming from uncertainty in climate model responses and internal climate variability that dominate CMIP-style experiments.

Large ensembles of simulations (>50 members) of atmosphere-only models for three time slice experiments are proposed, each a decade in length; the first being the most recent observed 10-year period (2006-2015), the second two being estimates of the a similar decade but under 1.5 and 2°C conditions a century in the future. We use the Representative Concentration Pathways 2.6 (RCP2.6) to provide the model boundary conditions for the 1.5°C scenario, and a weighted combination of RCP2.6 and RCP4.5 for the 2°C scenario.

1 Introduction

In its Paris Agreement, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) has established a long-term temperature goal for climate protection by "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" UNFCCC (2015). Such an agreement has naturally received interest from the academic community, with numerous authors commenting on this outcome (e.g. Hulme, 2016; Peters, 2016; Rogelj and Knutti, 2016; Mitchell et al., 2016b; Anderson and Nevins, 2016; Boucher et al., 2016; Schleussner et al., 2016). However, the body of research assessing impacts under a 1.5°C world is small compared to higher emission scenarios studies (James et al., in revision), though there are notably exceptions (Fischer and Knutti, 2015; Schleussner et al., 2015). It has been argued that current coordinated international climate modeling experiments, such as the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012), may not be best suited to address this question, and so we need dedicated climate experiments (Mitchell et al., 2016b).

HAPPI is proposed to provide a framework to assess the impacts of a 1.5°C world, and the impacts avoided from higher degree worlds, such as 2°C. As argued in Mitchell et al. (2016b), assessment of the impacts of a 1.5°C world requires large sets of simulations in order to adequately sample the extreme weather that often is associated with the highest climate-related risks, and it also requires simulations under steady forcing conditions in order to address the 1.5°C target. Figure 1 shows a schematic of how HAPPI differs from scenario based approaches, such as CMIP. The more traditional scenario-based approach (top panel) starts with either an emission scenario, such as those used in CMIP3 (Special Report on Emissions Scenarios; SRES)(Nakicenovic and Swart, 2000), or a pathway to reach a certain radiative forcing by 2100, such as those used in CMIP5 (Representative Concentration Pathway; RCP)(Van Vuuren et al., 2011). As uncertainty increases with time, and is dominated by responses and variability in CMIP-style experiments, as illustrated in Figure 1 (upper panel), such experiments are not ideal to inform assessments of impacts at specific levels of warming

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such as 1.5°C or 2°C, yet alone the difference between two such warming levels. For example, the lowest CMIP5 scenario, the RCP2.6, shows a median GMT increase of 1°C above 1986-2005 levels, with a likely range between 0.3 and 1.7°C over the CMIP5 model ensemble (IPCC, 2013). This range comprises 1.5°C and 2°C warming above pre-industrial levels, which renders the assessment of differences in impacts of these warming levels based on such a model ensemble very difficult.

The parties to the UNFCCC have chosen to frame their goals for climate protection in terms of a global temperature response, rather than an emission scenario. As such, the UNFCCC is not asking for the risks associated with emission scenarios that is "likely" to maintain temperatures below 1.5°C (or some other criterion): it is asking about the risks associated with 1.5°C warming per se, irrespective of what emission path is followed to achieve it (emission paths being addressed in the second challenge). As such, the global response is where the HAPPI design starts, tracing through to regional extreme weather and potential impacts.

2 Experimental Design

The experiments under HAPPI are designed to be as similar as possible in experimental design as current (or proposed) climate experiments, notably the International CLIVAR Climate of the 20th Century Plus Detection and Attribution (C20C+ D&A) project (Gillett et al., 2016; Folland et al., 2014). Synergies between the experiments allows to minimize the additional computational time required from modeling centers. The core experiments will be driven with a spectrum of different leading atmosphere-only Global Circulation Models (GCMs), the initial participants of which are listed in Table 1. By using atmosphere-only models instead of fully coupled models, we are able to generate larger ensemble sizes (due to decreased computational cost) while providing more accurate regional climate projections (He and Soden, 2016). Boundary conditions for the models are taken from the CMIP5 experimental design and from models that participated in that initiative.

There are two tiers of experiments, intended to characterize various climate scenarios, as well as uncertainties in the specifications of the temperature-based scenarios.

2.1 Tier 1 Experiments

Three core experiments are proposed:

1. Current decade conditions (2006-2015 50- to 100-member ensembles).
2. 1.5°C warmer than preindustrial (1861-1880) conditions (50- to 100-member ensembles) relevant for the 2106-2115 period.
3. 2.0°C warmer than preindustrial (1861-1880) conditions (50- to 100-member ensembles) relevant for the 2106-2115 period.

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Table 1: Table of models that will likely contribute to HAPPI with specifications and expected number of simulated models years per experiment tier. Regional Climate Models (RCMs) are also listed. In addition to the simulations detailed here, modeling centres will run five ensemble members of 1959-2015 conditions for bias-correction purposes.

Model	Hor. Resolution	Tier 1	Tier 2	RCM	References
CAM5.1-1degree	1.25×0.94°	3000	6000	N	Risser et al. (submitted)
CanAM4	T63	1500	0	N	von Salzen et al. (2013)
HadAM3P	1.88×1.25°	30,000	30,000	Africa (25 km)	Massey et al. (2014)
				S. Asia (50 km)	
seCAM5.1-0.25degree	25×25 km	90	0	N	Risser et al. (submitted)
MIROC5	150 × 150 km	3000	0	N	Shiogama et al. (2014)
NorESM1_Happi	0.90×1.25°	3000	2000	N	Bentsen et al. (2012)
					Iversen et al. (2013)

Each simulation within an experiment differs from the others in its initial weather state. The use of 50-100 10-year time slices provides 500-1000 years of data per experiment. Simulations are limited to 10 years in length because the observed ocean temperatures, upon which all HAPPI experiments are based, have been approximately constant during this period (at least within the context of the anthropogenic warming scales considered by HAPPI). However, 10-year should provide material for some analysis of multi-year events, such as droughts. The degree to which the output of the simulations can be used to estimate unbiased return values for a specific return period will depend on various aspects of the event, such as region and climate variable. In the extratropical winter, for instance, the 500-1000 years can be considered a full unbiased sample, whereas in the tropics it may be important to acknowledge the absence of a major La Niña event during the 2006-2015 period.

Current decade experiment: Modeling centers will use observed forcing conditions as in the DECK AMIP design, including Sea Surface Temperatures (SSTs) and sea ice (Taylor et al., 2012). The 2006-2015 decade is chosen because it is our most recently observed period, but also because it contains a range of different SST patterns over the decade, allowing for an assessment of how the ocean conditions vary on inter-annual timescales. From 2017 onward, modeling centers will also have the option of simulating observed 2016 climate, thereby capturing the large El Niño event in 2015-2016. Note that the C20C project will also perform these experiments.

The 1.5°C experiment: It is difficult (without lots of climate-model-specific iterations) to explicitly design an emissions scenario that would lead to a world exactly 1.5°C warmer than preindustrial conditions. This is because the CMIP community are set up to use particular emission scenarios or RCP scenarios, rather than a scenario that leads to some chosen amount of warming. Here, we take

1.5°C to mean '1.5°C as measured as the near-surface air temperature', as is the formal definition of the transient climate response, rather than some mix of measuring systems (for instance surface ocean) that may have implications for the energy-budget (Richardson et al., 2016).

By chance, the average across climate model simulations submitted to CMIP5 under the RCP2.6 forcing scenario results in a global average temperature response at 1.55°C relative to preindustrial (2091-2100 relative to 1861-1880). Figure 2 shows the average and 5-95% spread in global mean temperature anomaly for all available CMIP5 models for the RCP2.6 scenario (dark blue). Within HAPPI, we assume that this amount of warming is sufficiently close to inform the call of the UNFCCC on a special report on the "impacts of global warming of 1.5°C above pre-industrial levels" (UNFCCC, 2015), and thus HAPPI adopts the end-of-century anthropogenic radiative forcing conditions from the RCP2.6 emissions scenario. Natural radiative forcings, however, are set to the same values as in the current-decade experiment.

SST temperatures are calculated by adding to the observed 2006-2015 SSTs a change in SST (ΔSST) between the decadal-average of the 2006-2015 period and the decadal-averaged of the projected 1.5°C world over the 2091-2100. The decadal average of the 2091-2100 SSTs is estimated from previous CMIP5 RCP2.6 simulations shown in Figure 2, of which 23 models have the required data (see Section 2.2 for more details on the individual patterns). The resulting multi-model average ΔSST, used in the 1.5°C experiment, is shown in Figure 3. The global mean SST response is 1.02°C relative to the preindustrial period, with larger warming over land providing the global 1.55°C total.

Estimated sea ice is more problematic than estimated SSTs, because the CMIP-predicted Arctic and Antarctic sea ice extents vary dramatically between models (Collins et al., 2013). In the Arctic, most climate models show a decrease at all longitudes in sea ice. In the Antarctic, the overall model responses show a similar decrease with equally variable projections. The CMIP5 climate models are also unable to capture the observed increases in Antarctic sea ice over the satellite era (Turner et al., 2013), leading to low confidence in their ability to predict future changes. As such, we use a different method to estimate sea ice under 1.5°C and higher scenarios, which is an adaptation of Massey (in prep). In short, we calculate an anomaly (from 1996-2015) for every month from 1996-2015 in both SSTs and sea ice from the OSTIA data set (Stark et al., 2007) and find a linear relationship between SSTs and sea ice as a function of month and grid box. We use as the regressor the meridional average of SST grid boxes, within a hemisphere, at grid points where there is ice present at some point in time between 1996 and 2015 (i.e. the climatological monthly mean ice concentration for the grid box is non-zero). This represents temperature at that longitude under and near the ice edge, thereby minimizing poorly observed values in ice-covered regions. We use ice cover in an index gridbox as the regressand, and smooth the resultant field with a 500 km smoother. We then apply the sea ice-SST relationship to the 1.5°C experiment SST anomalies, to give a projected sea ice concentration anomaly. These anomalies are added on to the observed OSTIA data spanning the most recent decade. The absolute sea ice concentration fields, and anomalies from observations are given in Figure 4. This methodology has the added benefit that the SSTs and sea ice are consistent with each other in the HAPPI experiments.

The 2°C experiment: For the 2°C experiment, no analogous CMIP5 simulations are available. The RCP scenario resulting in the second coolest temperatures by the end of the 21st century is RCP4.5, which reaches ∼2.5°C relative to preindustrial by the end of the 21st century (Fig. 2). Both RCP2.6 and RCP4.5 have 5-95% ranges that overlap a GMT of 2°C, and the mean of both scenarios are a similar distance from this threshold.

To calculate the future SST and sea ice conditions of a 2°C world we therefore take a weighted sum of the two RCP scenarios, W1 × RCP2.5 + W2 × RCP4.6. The weights are calculated such that the global mean temperature response is 2.05°C (i.e. exactly half a degree above the 1.55°C response from the 1.5°C experiment), and equates to W1 = 0.41 and W2 = 0.59. These weights are used to calculate the SSTs and sea ice coverage using the same methodology as with the 1.5°C experiment.

The same weightings are applied to the logarithms of the two CO_2 concentrations (as warming is proportional to the logarithm of concentrations). Natural forcings should remain at 1.5°C experiment (and current-decade experiment) values. Land cover/use is represented in a discretised form in the climate models, and so cannot be interpolated. Meanwhile, the climate responses to anthropogenic aerosols aerosol and ozone concentrations (or, for some models, emissions of their precursors) do not follow a simple functional form, and in the case of aerosols this is further complicated by major differences in the spatial distributions of concentrations between the two RCPs. Considering that the parties to the UNFCCC are most concerned about a CO_2-dominated warming, and this is the dominant contributor to changes in the radiative budget by 2100 (e.g. see figure 12.3 of Collins et al., 2013), we chose to set the remaining (i.e. other than CO_2, SST, sea ice, and natural forcings) 2°C experiment forcings to their 1.5°C experiment values.

In addition to the three core experiments, modeling centers will also run five ensemble members spanning the period 1959-2015, thereby allowing for a range of biases in the climate models to be assessed (see Section 4).

2.2 Tier 2 Experiments

The Tier 2 experiments will replicate the Tier 1 1.5 and 2°C experiments, but also take into account SST and sea ice uncertainty at the expense of ensemble size. Individual estimates of SST response patterns from the 23 different CMIP5 models will be used, the annual means of which are presented in Appendix 1 for both scenarios. Each individual model pattern will be scaled to have the same SST mean response as the multi-model mean (MMM) response (1.02°C for the 1.5°C experiment), this would give a measure of the impact of uncertainty in the pattern of large-scale warming, conditioned on a specific global temperature change, consistent with research demanded by the UNFCCC call.

3 Toward understanding impacts

Assessing potential impacts of 1.5 and 2°C of warming goes beyond climate scenarios and requires integrated impact model projections. HAPPI therefore cooperates with the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP, Warszawski et al., 2013a) range of sectors including agriculture and agro-economic modeling (Rosenzweig et al., 2013; Elliott et al., 2013), water (Schewe et al., 2014), biomes and forestry (Warszawski et al., 2013b), permafrost and human health (Mitchell et al., 2016a). To allow for the HAPPI modeling effort to be most useful for the impact community, the HAPPI diagnostics provided resemble the climate model input required for the ISI-MIP modeling protocol.

Specifically, a priority subset of HAPPI AGCM output will be provided in bias-corrected format following the ISI-MIP trend-preserving bias correction approach (Hempel et al., 2013). A sector specific modeling protocol will be provided following the ISI-MIP2 simulation protocol including socio-economic and management options. All impact model output will be included on the server used for HAPPI data storage (see Section 4).

The large-ensemble approach pursued in HAPPI in principle also allows for fully physical consistent bias correction approaches that have been found to be particularly relevant for the representation of climate extremes (Sippel et al., 2015). It is planned to also provide alternative bias correction approaches in a low priority set to study the effect of these methods on the impact projections.

4 Data usage and availability

Data published on the portal will be compliant with a modified version of the C20C+ D&A conventions. All raw data will be available, as well as a bias corrected ISI-MIP subset using the Hempel et al. (2013) methodology.

Output from all HAPPI and associated experiments are to be published through the joint C20C+ D&A project-HAPPI portal, hosted by the National Energy Research Scientific Computing center (NERSC) at $http://portal.nersc.gov/c20c/data.html$. The HAPPI data policy uses the same principals as the Coupled Chemistry Model Validation (CCMVal) policy. The HAPPI data are therefore made available to all researchers outside the HAPPI community, provided that they become official HAPPI collaborators. All collaborators are asked to respect the interests of the HAPPI community, and therefore encouraged to keep lines of communication throughout any analysis. Publications of HAPPI data and corresponding scientific analysis are encouraged, and the data policy involves two phases in line with CCMVal. Phase 1 runs up to the cut-off date for publications to be included in the IPCC Special Report (in spring 2018). During this phase users are obligated to offer co-authorship to the HAPPI core-team, and to acknowledge NERSC for data storage. Phase 2 follows publication of the IPCC Special Report, and requires acknowledgment of the HAPPI core-

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team and NERSC. During the latter phase is it intended that HAPPI data will be used to inform AR6 among other initiatives, and may well include high temperature scenarios, such as 3°C.

5 Summary

HAPPI has been developed to explicitly inform one of the primary aims in the Paris Agreement, which seeks to understand impacts of a world limiting global averaged warming to 1.5°C. It provides climate data for analysis of a range of impacts under current, 1.5 and 2°C climate scenarios. The high number of ensemble members (>50) allow for information on policy-relevant timescales to be assessed, while the 10-year length of the simulation also allows for long-lived extremes, such as droughts, to be characterized. The two tiers of experiments provide an assessment of not only the desired climate change scenario, but also the uncertainties in how we developed the scenario, most notably through sensitivity tests in the SSTs and sea ice conditions. The data are available in bias corrected or raw formats, and ready for direct input to a range of common climate impact models.

HAPPI website: The project is kept up-to-date with news, collaborations, publications and experiments at www.happimip.org.

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References

Anderson, K. and Nevins, J.: Planting Seeds So Something Bigger Might Emerge: The Paris Agreement and the Fight Against Climate Change, Socialism and Democracy, 30, 209–218, 2016.

Bentsen, M., Bethke, I., Debernard, J., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I., Hoose, C., et al.: The Norwegian earth system model, NorESM1-M-Part 1: Description and basic evaluation, Geoscientific Model Development Discussions, 5, 2843–2931, 2012.

Boucher, O., Bellassen, V., Benveniste, H., Ciais, P., Criqui, P., Guivarch, C., Le Treut, H., Mathy, S., and Séférian, R.: Opinion: In the wake of Paris Agreement, scientists must embrace new directions for climate change research, Proceedings of the National Academy of Sciences, 113, 7287–7290, 2016.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W., Johns, T., Krinner, G., et al.: Long-term Climate Change: Projections, Commitments and Irreversibility, 2013.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B. M., Folberth, C., Foster, I., Gosling, S. N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A. C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., and Wisser, D.: Constraints and potentials of future irrigation water availability on agricultural production under climate change., Proceedings of the National Academy of Sciences of the United States of America, 111, 3239–3244, doi:10.1073/pnas.1222474110, http://www.ncbi.nlm.nih.gov/pubmed/24344283, 2013.

Fischer, E. and Knutti, R.: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes, Nature Climate Change, 2015.

Folland, C., Stone, D., Frederiksen, C., Karoly, D., and Kinter, J.: The international CLIVAR Climate of the 20th Century Plus (C20C+) Project: Report of the sixth workshop, CLIVAR Exchange, 19, 57–59, 2014.

Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., and Tebaldi, C.: Detection and Attribution Model Intercomparison Project (DAMIP), Geoscientific Model Development Discussions, pp. 1–19, 2016.

He, J. and Soden, B. J.: The Impact of SST Biases on Projections of Anthropogenic Climate Change: A Greater Role for Atmosphere-only Models?, Geophysical Research Letters, 2016.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., and Piontek, F.: A trend-preserving bias correction–the ISI-MIP approach, Earth System Dynamics, 4, 219–236, 2013.

Hulme, M.: 1.5 [deg] C and climate research after the Paris Agreement, Nature Climate Change, 6, 222–224, 2016.

Iversen, T., Bentsen, M., Bethke, I., Debernard, J., Kirkevåg, A., Seland, Ø., Drange, H., Kristjansson, J., Medhaug, I., Sand, M., et al.: The Norwegian earth system model, NorESM1-M—Part 2: climate response and scenario projections, Geosci. Model Dev, 6, 389–415, 2013.

James, R., Washington, R., Schleussner, C.-F., Rogelj, J., and Declan, C.: What difference does half a degree make? Progress in modelling regional climate responses to global warming targets, WIRES, in revision.

Massey, N.: Generating sea ice patterns and uncertainity from coupled climate models, JGR, in prep.

Massey, N., Jones, R., Otto, F., Aina, T., Wilson, S., Murphy, J., Hassell, D., Yamazaki, Y., and Allen, M.: weather@ home—development and validation of a very large ensemble modelling system for probabilistic event attribution, Quarterly Journal of the Royal Meteorological Society, 2014.

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Manuscript under review for journal Geosci. Model Dev.
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Geoscientific Model Development Discussions
Open Access

Mitchell, D., Heaviside, C., Vardoulakis, S., Huntingford, C., Masato, G., Guillod, B. P., Frumhoff, P., Bowery, A., Wallom, D., and Allen, M.: Attributing human mortality during extreme heat waves to anthropogenic climate change, Environmental Research Letters, 11, 074 006, http://stacks.iop.org/1748-9326/11/i=7/a=074006, 2016a.

Mitchell, D., James, R., Forster, P., Betts, R., Shiogama, H., and Allen, M.: Realizing the impacts of a 1.5C warmer world., Nature Climate Change, doi:10.1038/nclimate3055, 2016b.

Nakicenovic, N. and Swart, R.: Special report on emissions scenarios, Special Report on Emissions Scenarios, Edited by Nebojsa Nakicenovic and Robert Swart, pp. 612. ISBN 0521804930. Cambridge, UK: Cambridge University Press, July 2000., 1, 2000.

Peters, G. P.: The'best available science'to inform 1.5 [deg] C policy choices, Nature Climate Change, 2016.

Richardson, M., Cowtan, K., Hawkins, E., and Stolpe, M. B.: Reconciled climate response estimates from climate models and the energy budget of Earth, Nature Climate Change, 2016.

Risser, M., Stone, D., Paciorek, M., Wehner, M., and Angélil, O.: Quantifying the effect of interannual ocean variability on the attribution of extreme climate events to human influence, Climate Dynamics, submitted.

Rogelj, J. and Knutti, R.: Geosciences after Paris, Nature Geoscience, 9, 187–189, 2016.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. a. M., Schmid, E., Stehfest, E., Yang, H., and Jones, J. W.: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison., Proceedings of the National Academy of Sciences of the United States of America, 111, 3268–3273, doi:10.1073/pnas.1222463110, http://www.ncbi.nlm.nih.gov/pubmed/24344314, 2013.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colon-Gonzalez, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., and Kabat, P.: Multimodel assessment of water scarcity under climate change, Proceedings of the National Academy of Sciences of the United States of America, 111, 3245–3250, doi:10.1073/pnas.1222460110, http://www.pnas.org/cgi/doi/10.1073/pnas.1222460110, 2014.

Schleussner, C., Lissner, T. K., and Fischer, E. M.: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5-° C and 2-° C, Earth System Dynamics, 7, 327, 2015.

Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., Knutti, R., Levermann, A., Frieler, K., and Hare, W.: Science and policy characteristics of the Paris Agreement temperature goal, doi:10.1038/NCLIMATE3096, 2016.

Shiogama, H., Watanabe, M., Imada, Y., Mori, M., Kamae, Y., Ishii, M., and Kimoto, M.: Attribution of the June-July 2013 heat wave in the southwestern United States, SOLA, 10, 122–126, 2014.

Sippel, S., Otto, F. E. L., Forkel, M., Allen, M. R., Guillod, B. P., Heimann, M., Reichstein, M., Seneviratne, S. I., Thonicke, K., and Mahecha, M. D.: A novel bias correction methodology for climate impact simulations, Earth System Dynamics Discussions, 6, 1999–2042, doi:10.5194/esdd-6-1999-2015, http://www.earth-syst-dynam-discuss.net/6/1999/2015/, 2015.

Stark, J. D., Donlon, C. J., Martin, M. J., and McCulloch, M. E.: OSTIA: An operational, high resolution, real time, global sea surface temperature analysis system, in: Oceans 2007-Europe, pp. 1–4, IEEE, 2007.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-203, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 24 August 2016

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bulletin of the American Meteorological Society, 93, 485, 2012.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., and Hosking, J. S.: An initial assessment of Antarctic sea ice extent in the CMIP5 models, Journal of Climate, 26, 1473–1484, 2013.

UNFCCC: Adoption of the Paris Agreement, 2015.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., et al.: The representative concentration pathways: an overview, Climatic change, 109, 5–31, 2011.

von Salzen, K., Scinocca, J. F., McFarlane, N. A., Li, J., Cole, J. N., Plummer, D., Verseghy, D., Reader, M. C., Ma, X., Lazare, M., et al.: The Canadian fourth generation atmospheric global climate model (CanAM4). Part I: representation of physical processes, Atmosphere-Ocean, 51, 104–125, 2013.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., and Schewe, J.: The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework., Proceedings of the National Academy of Sciences of the United States of America, pp. 1–5, doi:10.1073/pnas.1312330110, http://www.ncbi.nlm.nih.gov/pubmed/24344316, 2013a.

Warszawski, L., Friend, A., Ostberg, S., Frieler, K., Lucht, W., Schaphoff, S., Beerling, D., Cadule, P., Ciais, P., Clark, D. B., Kahana, R., Ito, A., Keribin, R., Kleidon, A., Lomas, M., Nishina, K., Pavlick, R., Rademacher, T. T., Buechner, M., Piontek, F., Schewe, J., Serdeczny, O., and Schellnhuber, H. J.: A multi-model analysis of risk of ecosystem shifts under climate change, Environmental Research Letters, 8, 044 018, doi:10.1088/1748-9326/8/4/044018, http://stacks.iop.org/1748-9326/8/i=4/a=044018?key=crossref.2d722efbaf6d3e455e38f2c68888d873, 2013b.

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-203, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 24 August 2016

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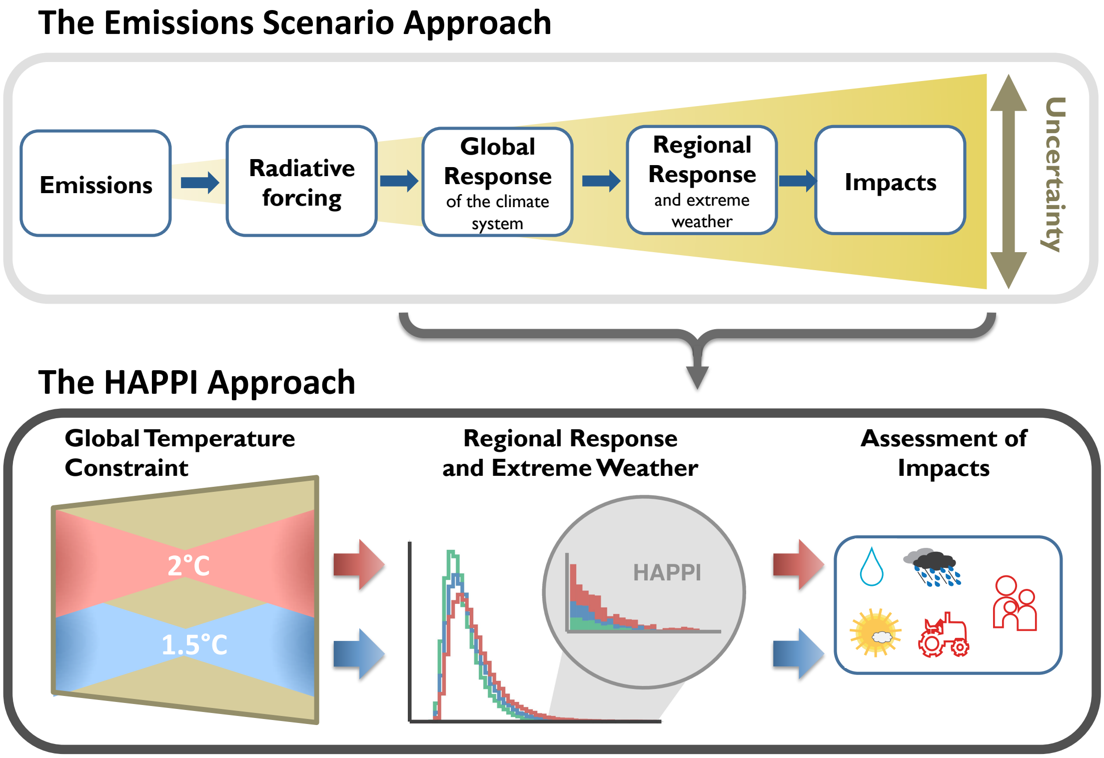

Figure 1: A schematic comparing the emissions scenario based approaches (top), such as CMIP, with the HAPPI approach (bottom). The HAPPI approach flows from the constraint on global temperatures to the comparison of extremes using the large ensemble approach to impact models. The histogram depicts an illustrative example of distributions for extreme event indicators (such as e.g. maximum daily temperature) for the present day (green), 1.5°C (blue) and 2°C (red) above pre-industrial levels

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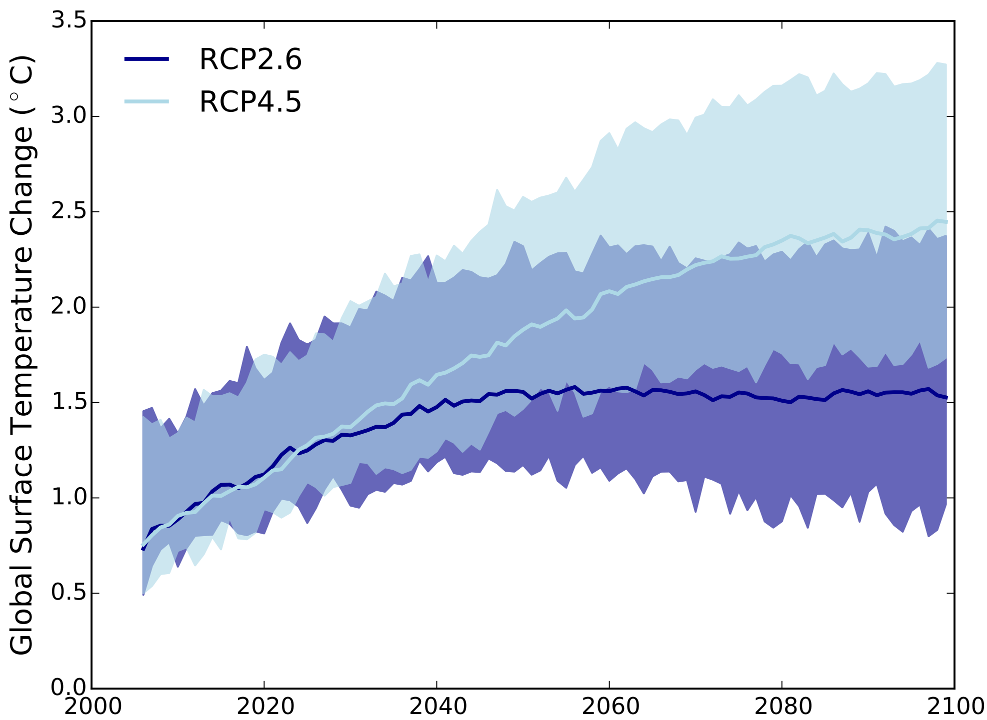

Figure 2: Time series of global annual mean surface air temperature anomalies (relative to 1861-1880) from CMIP5 RCP2.6 and RCP4.5 experiments. Solid lines show the multi-model mean and shaded regions show the 5-95% range across all 26 models. Only one simulation is used for each model. All models where the data were available for both scenarios were used, leading to 26 models in total.

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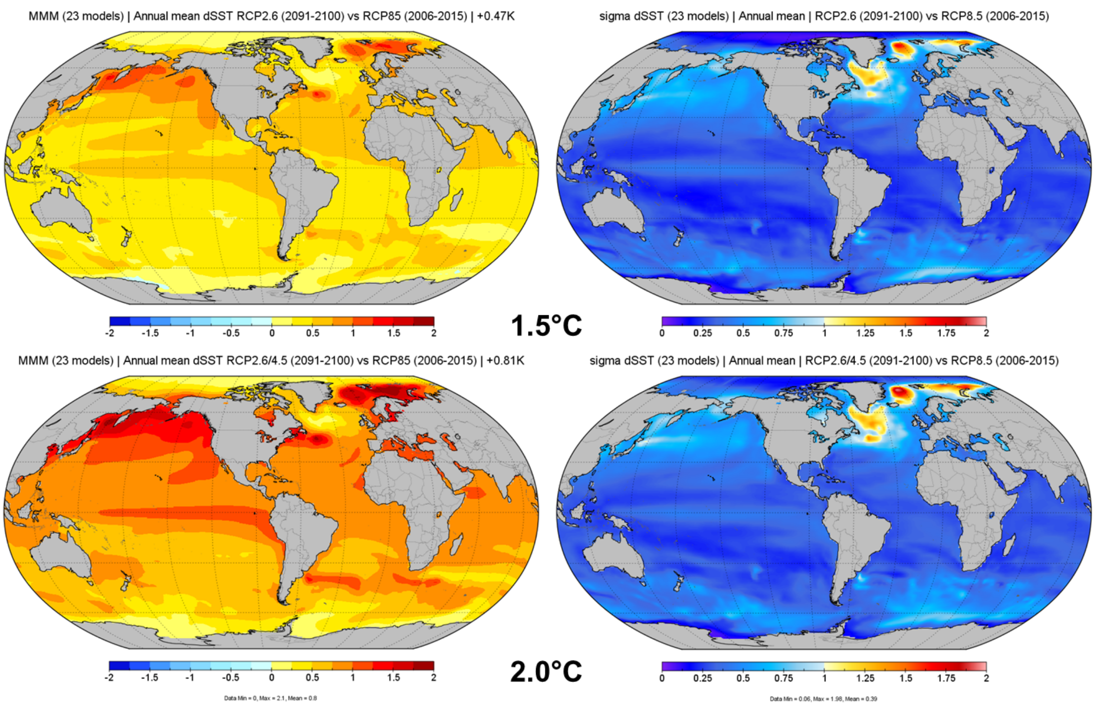

Figure 3: (left) SST warming pattern added to the current decade to produce the (top) 1.5 and (bottom) 2 degree scenarios. (right) The standard deviation of annual mean delta SSTs across the 23 models. Units are in °

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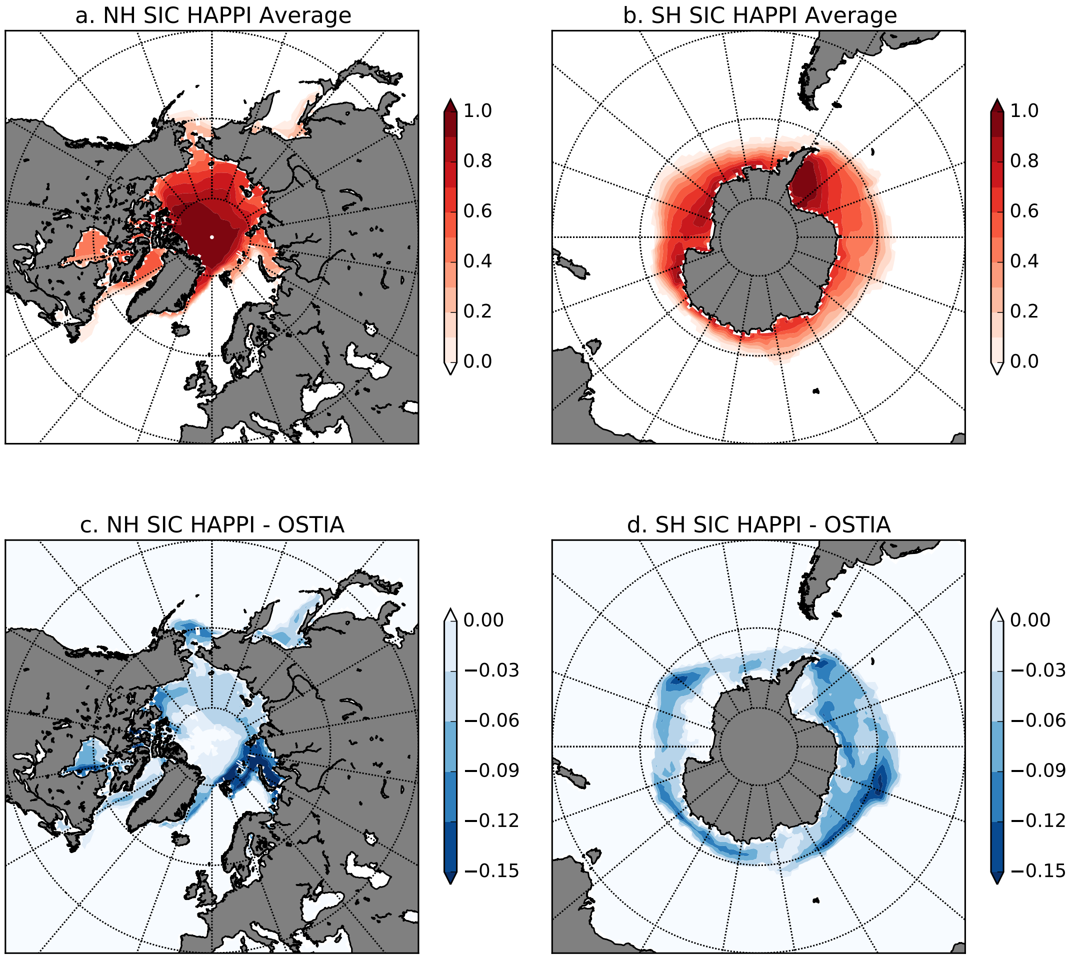

Figure 4: Polar stereographic projections of decadal-mean (top) sea ice concentration from the 1.5 degree experiment and (bottom) the difference in sea ice concentration between the 1.5 degree experiment and OSTIA. The OSTIA data cover the decade 2006-2015. Left panels show the NH, right panels show the SH.

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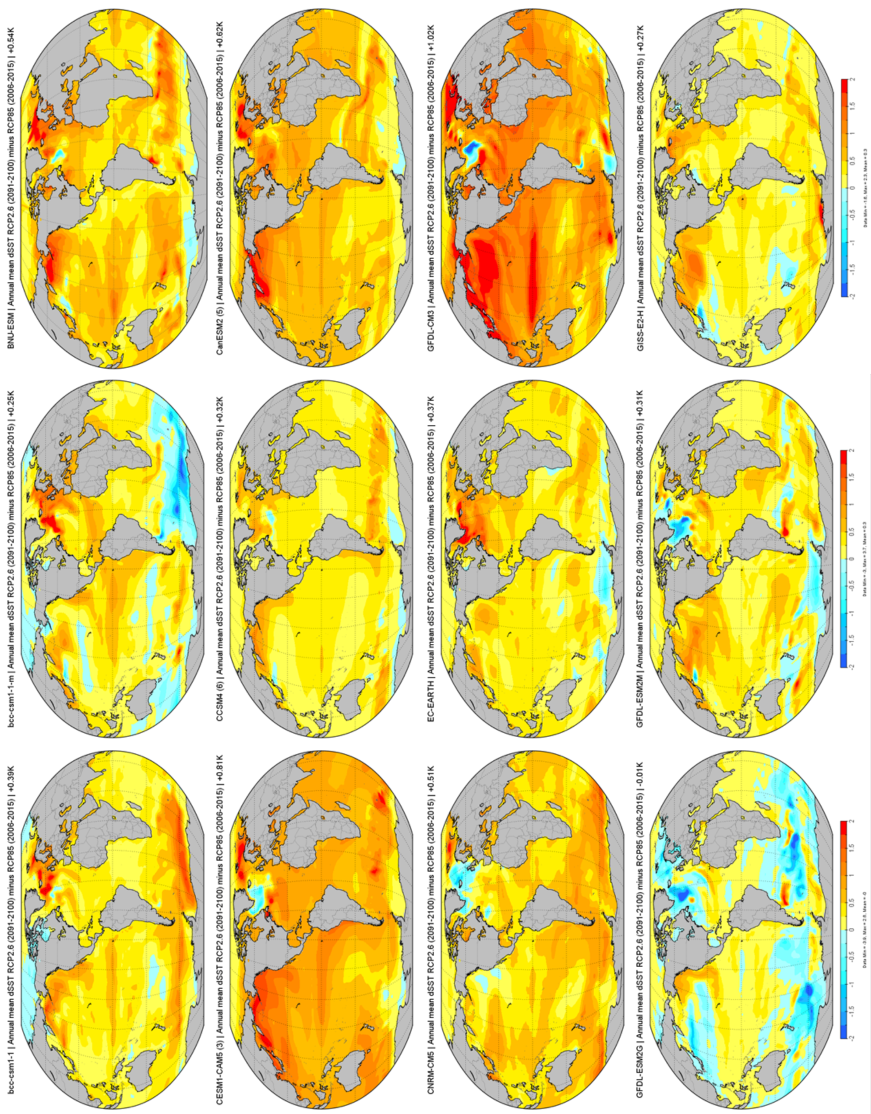

Figure A1: As in the 1.5 degree experiment delta SST pattern in Fig. 3 but for the first set of 12 individual models.

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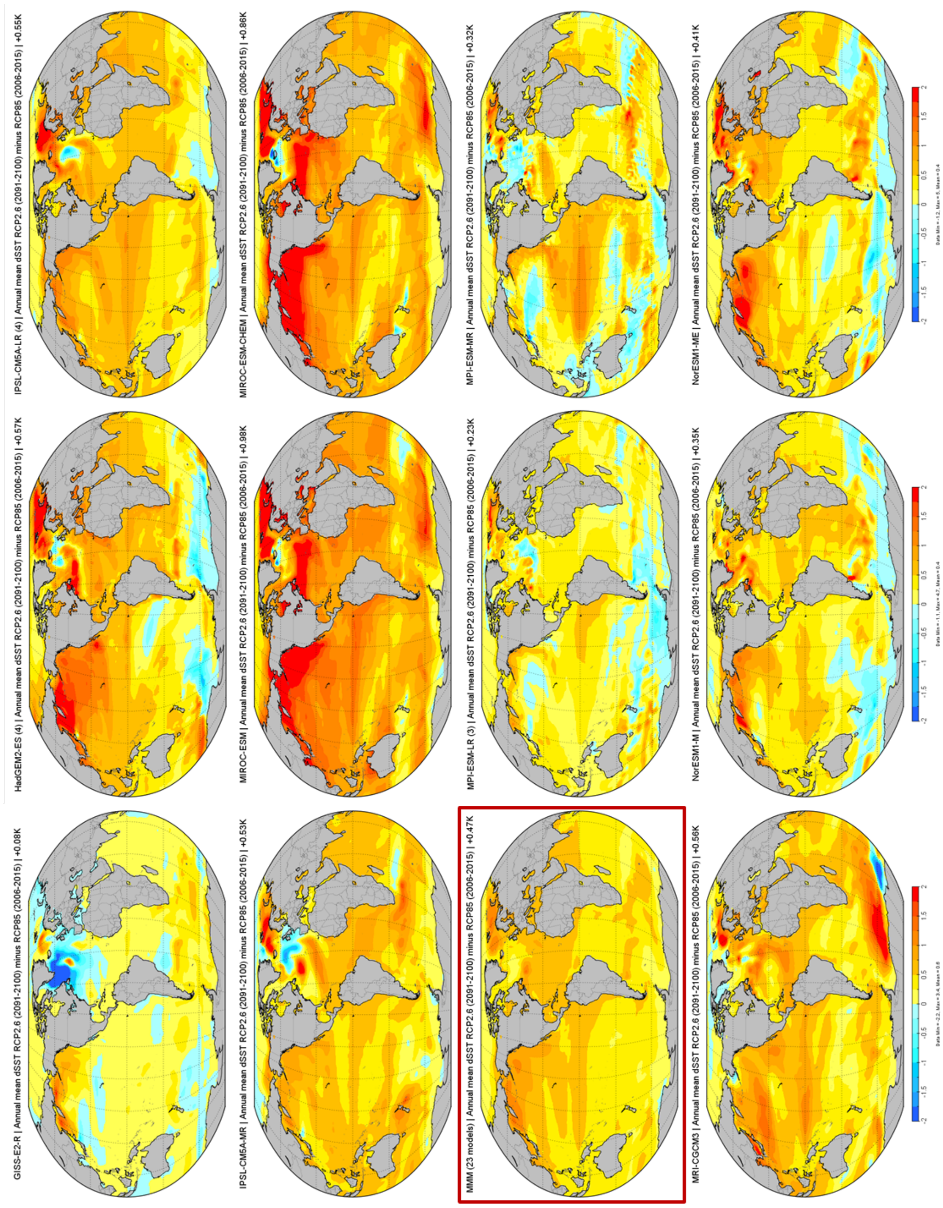

Figure A2: As previous but for the second set of 12 individual models.