https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Earth System Science Data
Open Access Discussions

An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets

Maialen Iturbide[a], José Manuel Gutiérrez[a], Lincoln Muniz Alves[b], Joaquín Bedia[c], Ezequiel Cimadevilla[c], Antonio S. Cofiño[c], Ruth Cerezo-Mota[d], Alejandro Di Luca[e], Sergio Henrique Faria[f], Irina Gorodetskaya[g], Mathias Hauser[h], Sixto Herrera[c], Helene T. Hewitt[i], Kevin J. Hennessy[j], Richard G. Jones[i,k], Svitlana Krakovska[l,m], Rodrigo Manzanas[n], Daniel Martínez-Castro[o,p], Gemma Teressa Narisma[q], Intan S. Nurhati[r], Izidine Pinto[s], Sonia I. Seneviratne[h], Bart van den Hurk[t], and Carolina S. Vera[u]

[a]Grupo de Meteorología. Instituto de Física de Cantabria (CSIC-UC). Santander, Spain
[b]National Institute for Space Research. São José dos Campos, Brazil
[c]Grupo de Meteorología. Dpto. Metemática Aplicada y C.C. University of Cantabria. Santander, Spain
[d]Universidad Nacional Autónoma de México (UNAM). Mexico city, Mexico
[e]Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, University of New South Wales. Sydney, Australia
[f]BC3 - Basque Centre for Climate Change. IKERBASQUE - Basque Foundation for Science. Bilbao, Spain
[g]Centre for Environmental and Marine Studies Department of Physics, University of Aveiro. Aveiro, Portugal
[h]Institute for Atmospheric and Climate Science, ETH Zurich. Zurich, Switzerland
[i]Met Office Hadley Centre. Exeter, United Kingdom
[j]CSIRO Oceans and Atmosphere. Canberra, Australia
[k]School of Geography and Environment, University of Oxford. UK
[l]Ukrainian Hydrometeorological Institute. Kyiv, Ukraine
[m]State Institution National Antarctic Scientific Center. Kyiv, Ukraine
[n]Intergovernmental Panel on Climate Change (IPCC), WGI-TSU, Université Paris-Saclay. Paris, France
[o]Instituto de Meteorología de Cuba. La Habana, Cuba
[p]Instituto Geofísico del Perú. Lima, Perú
[q]Manila Observatory, Ateneo de Manila University campus. Quezon City, Philippines
[r]Research Center for Oceanography. Indonesian Institute of Sciences. Jakarta, Indonesia
[s]Climate Systems Analysis Group (CSAG), University of Cape Town. South Africa
[t]DELTARES. Delft, The Netherlands
[u]Departamento de Ciencias de la Atmósfera y los Océanos, FCEyN-UBA. Centro de Investigaciones del Mar y la Atmósfera (CIMA), Instituto Franco Argentino sobre Estudios de Clima y sus Impactos (UMI IFAECI)/CNRS-CONICET. Buenos Aires, Argentina

Correspondence: José M. Gutiérrez (gutierjm@ifca.unican.es)

Abstract. Several sets of reference regions have been proposed in the literature for the regional synthesis of observed and model-projected climate change information. A popular example is the set of reference regions introduced in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Adaptation (SREX) based on a prior coarser selection and then slightly modified for the 5^{th} Assessment Report of the IPCC. This set was developed for reporting sub-continental observed and projected changes over a reduced number (33) of climatologically consistent regions encompassing a representative number of grid boxes (the typical resolution of the 5^{th} Climate Model Intercomparison Projection, CMIP5,

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

climate models was around 2°). These regions have been used as the basis for several popular spatially aggregated datasets, such as the seasonal mean temperature and precipitation in IPCC regions for CMIP5.

Here we present an updated version of the reference regions for the analysis of new observed and simulated datasets (including CMIP6) which offer an opportunity for refinement due to the higher model resolution (around 1° for CMIP6). As a result, the number of regions is increased to 43 land plus 12 open ocean, better representing consistent regional climate features. The paper describes the rationale followed for the definition of the new regions and analyses their homogeneity. The regions are defined as polygons and are provided as coordinates and shapefile together with companion R and Python notebooks to illustrate their use in practical problems (trimming data, etc.). We also describe the generation of a new dataset with monthly temperature and precipitation spatially aggregated in the new regions, currently for CMIP5 (for backwards consistency) and CMIP6, to be extended to other datasets in the future (including observations). The use of these reference regions, dataset and code is illustrated through a worked example using scatter diagrams to offer guidance on the likely range of future climate change at the scale of reference regions. The regions, datasets and code (R and Python notebooks) are freely available at the ATLAS GitHub repository; https://github.com/SantanderMetGroup/ATLAS, doi:10.5281/zenodo.3688072 (Iturbide et al., 2020).

KEY WORDS: *Regional climate change; Climatic regions; CMIP5; CMIP6; Climate change projections; Reproducibility*

1 Introduction

Different sets of climate reference regions have been proposed in the literature for the regional synthesis of observed and model-projected climate change information, and have been subsequently used in the different Assessment Reports of the IPCC. The Giorgi-type reference regions (originally 23 squared regions proposed in Giorgi and Francisco, 2000) were used in the third (AR3, Giorgi et al., 2001) and fourth (AR4, Christensen et al., 2007) IPCC Assessment reports. These regions were modified and expanded (including islands, Arctic and Antarctica) using more flexible polygons in the IPCC SREX special report (Seneviratne et al., 2012) and then slightly modified and extended to 33 regions for the fifth Assessment Report (AR5, van Oldenborgh et al., 2013), as shown in Figure 1a. The goal in these subsequent revisions was to improve the climatic consistency of the regions so they represented sub-continental areas of greater climatic coherency. This process typically resulted in a larger number of smaller regions, limited in size by the relatively coarse resolution of the global models (thought this is increasing in the successive CMIP datasets), since each region should encompass a sufficient number of gridboxes for the sake of representativeness. The IPCC AR5 reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html; last access: 30 December 2019) were developed for reporting sub-continental CMIP5 projections (with an average horizontal resolution greater than 2°) and were quickly adopted by the research community as a basis for regional analysis in a variety of applications (Wartenburger et al., 2017; Bärring and Strandberg, 2018; Madakumbura et al., 2019). Moreover, these regions have been used to generate popular spatially aggregated datasets, such as the *seasonal mean temperature and precipitation in IPCC regions for CMIP5* (McSweeney et al., 2015), which provides

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

ready-to-use information from the CMIP5 models, suitable for regional analysis of climate projections and their uncertainties. This dataset can be directly used for researchers and stakeholders for a variety of purposes, including assessing the internal variability, model and scenario uncertainty components (Hawkins and Sutton, 2009), or assisting in the comparison and selection of representative sub-ensembles for impact studies (see, e.g., Ruane and McDermid, 2017).

The recent initial provision (and the increasing availability) of CMIP6 multi-model projections (O'Neill et al., 2016; NCC editorial, 2019) offers an opportunity for the refinement of the AR5 reference regions —due to the higher model resolution, typically around 1°— and also for producing ready-to-use aggregated regional information for the resulting reference regions. This is a timely task due to the great interest the research community is showing in the higher sensitivity of some CMIP6 models and the potential implications for climate change studies (Forster et al., 2020). Here we present the results of an initiative carried out during the last year to achieve this task. First, we present the updated regions (referred to as updated AR5 reference regions) and describe the rationale followed for the revision, which was guided by two basic principles: 1) climatic consistency and better representation of regional climate features and 2) representativeness of model results (sufficient number of model gridboxes). Climatic homogeneity was characterized in terms of mean temperature and precipitation considering Köppen-Geiger climatic regions (Rubel and Kottek, 2010) and the annual cycle (and projected changes) of the reference regions. The resulting 43 land plus 12 open ocean regions (see Figure 1b) are provided as text-csv (coordinates) and shapefile GIS formats with companion notebooks to illustrate their use in R and Python. Second, we describe the monthly regional temperature and precipitation dataset obtained by spatially aggregating the model data over the reference regions (currently for CMIP5 for backwards consistency and CMIP6, to be later extended to observations and additional datasets). Finally, the use of these reference regions, datasets and code is illustrated through a reproducible example which analyses the likely range of future temperature and precipitation changes for different European regions using scatter diagrams.

Section 2 presents the data and methods used in this work. Sec. 3 describes the reference regions and their rationale. The regionally aggregated CMIP5 dataset is presented in Section 4 and links are provided for additional aggregated datasets (e.g. CMIP6, which are periodically updated); a reproducible illustrative example is described in Sec. 5. Finally, conclusions and discussion are presented in Sec. 6.

2 Data and Methods

We use global gridded observations to characterize the regional climatological conditions at a sub-continental scale. In particular, we use CRU TS (version 4.03; Harris et al., 2014; Harris and Jones, 2020) providing monthly precipitation and temperature values over a 0.5° resolution grid for land only regions for the period 1901-2017. Figure 2a-b shows the annual mean temperature and precipitation climatological values for the period 1981-2010 (note that this dataset does not cover the Antarctic, which is filled here with an alternative dataset, in particular the EWEMBI gridded observations; Lange, 2019). Figure 2c shows the Köppen-Geiger climatic regions (Rubel and Kottek, 2010) computed from this dataset. There are, however, a large number of alternative products which allow quantifying observational uncertainty (see e.g. Sun et al., 2018, for a review), which is an increasing concern in climate studies, particularly for precipitation (Kotlarski et al., 2019). Therefore, in some parts of this study we use two additional observational datasets for precipitation: 1) Global Precipitation Climatology Centre (GPCC, v2018 used here; Schneider et al., 2011) providing monthly land precipitation values over a 0.5° resolution grid covering the period from 1891 to 2016, and 2) Global Precipitation Climatology Project (GPCP; Monthly Version 2.3 gridded, merged satellite/gauge precipitation; Huffman et al., 2009), providing monthly land and ocean precipitation values at 2.5° resolution for the period 1979-2018. We use the current WMO climatological standard normal period 1981–2010 (WMO, 2017).

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Global model scenario data was dowloaded for CMIP5 (Taylor et al., 2012)/CMIP6 (O'Neill et al., 2016) models for the historical (1850-2005/1850-2014) and RCP2.6/SSP1, RCP4.5/SSP2 and RCP8.5/SSP5 future scenarios (2006-2100/2015-2100). Data for CMIP5 (curated version used for IPCC-AR5) was downloaded from the IPCC Data Distribution Center (https://www.ipcc-data.org/sim/gcm_monthly/AR5/index.html; last accessed, 31 Dec 2019) and for CMIP6 was downloaded from the Earth System Grid Federation (ESGF, Balaji et al., 2018); an up-to-date inventory (updated periodically) is available at the ATLAS GitHub repository (*AtlasHub-inventory* folder). All model data has been interpolated to common 2° (for CMIP5) and 1° (CMIP6) resolution grids —separately for land and ocean gridboxes using conservative remapping (using CDO with the models and target land/sea masks; CDO, 2019),— which are the typical model resolutions for CMIP5 and CMIP6, respectively. The common grids and land/sea masks are available in the ATLAS GitHub repository (*reference-grids* folder).

In this paper we illustrate the results using the curated CMIP5 dataset and refer to the ATLAS GitHub repository for similar results (updated periodically) for CMIP6. Figure 2d-e shows the CMIP5 multi-model climate change annual signal (relative in % for precipitation and absolute in °C for temperatures, respectively) for RCP8.5 2081-2100 (w.r.t. the modern climate reference 1986-2005); hatching indicates weak model agreement (less than 80%) in the sign of the multi-model mean. This figure shows the typical spatial patterns of the climate change signal and is used to illustrate the consistency of the regional signals in the climate reference regions.

The higher resolution of CMIP6 yields better model representation on the reference regions (more gridboxes per region) allowing a revision for better climatic consistency (e.g. dividing heterogeneous regions) while preserving model representativeness. Figure 3 illustrates this issue displaying the number of gridboxes (only land gridboxes for land regions) in each of the original (last column) and revised (first column) reference regions —shown in Figures 1a and 1b, respectively,— for the two reference 1° (first row) and 2° (last row) grids, representing the typical resolution of CMIP6 and CMIP5, respectively. Shade colors indicate regions with less than 250 gridboxes (the dark colors correspond to less than 20 gridboxes). Figures 3a and 3d correspond to the cases of CMIP6 data on the updated reference regions, and to CMIP5 data in the original IPCC-AR5 regions, respectively, showing that the new reference regions are more representative than the original ones due to the increment of model resolution, with minimum model coverage in New Zealand (NZ), the Caribbean (CAR), and Southern South America (SSA), where the number of land gridboxes is in the range 20-60. Note that the updated regions are also suitable for the analysis of CMIP5 data (at 2° resolution, Fig. 3c) since all regions encompass over twenty land gridboxes, with the exception of the three above mentioned and Southern Central America, where results should be taken with caution.

3 Reference Regions: Rationale and Definition

The Giorgi-type reference regions were originally defined trying to represent consistent climatic regimes and physiographic settings, while maintaining an appropriate size for model representation (thousands of kilometers, to contain several model gridboxes), using some subjectivity in the final selection (Giorgi and Francisco, 2000). Here we are guided by the same basic principles to define the revised reference regions (see Figure 1b). Climatic homogeneity is characterized in terms of mean temperature and precipitation considering Köppen-Geiger climatic regions (see Figure 2) and also the annual precipitation cycle (Figures 4 and 5); in the later case, observational uncertainty is analyzed using the three alternative datasets described in Sec. 2. Representativity of model results (sufficient number of gridboxes per region) is analyzed in Figure 3.

In North America, the Polar CGI region was divided in two, Northeastern Canada (NEC) and Greenland/Iceland (GIC), in order to better accommodate the subarctic and Polar climates, respectively (see Figure 2c). The eastern and central ENA and CNA regions are maintained mostly unaltered and the western part was reorganized to increase climate consistency, with the new Northwestern region (NWN) including mostly the subarctic regions, a modified western region (WNA) encompassing a variety of regional intermixed climates (semiarid,

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Mediterranean, and continental) which is difficult to further separate due to the complex orography, and a new North Central America (NCA) region including the semiarid and arid climates of Northern Mexico, separating them from the tropical climates in southern Central America which constitute a new region alone (SCA). The Caribbean (CAR) region has been modified to fully include the Greater Antilles.

In South America, the old northwestern Amazonia region is divided into three subregions to separate the Northern South America (NSA) region from the western region including the northern Andes Mountains range (NWS), and the South America Monsoon (SAM) region, exhibiting a characteristic annual cycle (see Figure 4). The Northeastern region is maintained, but the name is changed to Northeastern South America (NES). A new region has been also defined in the South (SSA) to encompass the subpolar climates exhibited in this region (see Figure 2c).

The three European reference regions NEU, CEU and MED have been maintained unaltered since they encompass the main regional climates in Europe, from subarctic, to oceanic/continental and to Mediterranean, respectively. However, the additional region of Eastern Europe (EEU) has been introduced, including the continental region at the western side of the Ural mountain range.

In the case of Africa, recent papers have shown that the AR5 regions were suboptimal; for instance, Diedhiou et al. (2018) shows that the AR5 WAF region was inhomogeneous, with different sub-climates and responses to climate change for western and central parts. Therefore, in order to increase climatic consistency, we divided the original region in two (WAF and CAF, see Figure 2b). Although these regions have similar Köppen-Geiger climates (see Figure 2c), they have very different annual variability, as shown in Figure 5, and therefore should be analyzed independently. A similar behavior was found in EAF (Osima et al., 2018), which was also divided in two new Northern and Southern regions (NEAF, which includes the arid region of the Horn of Africa, and CEAF). These two regions also exhibit different interannual variability, with different timing of the annual maximum (see Figure 5). Moreover, the South Africa region SAF was also divided in two subregions with different rainfall regimes (Maúre et al., 2018), the western subregion (SWAF) including the arid regional climates, and the Eastern region (SEAF).

In the case of Asia, Northern Asia is subdivided in a Northern subarctic region (RAR), two regions for Western (WSB) and Eastern (ESB) Siberia and a region for the Russian far East (RFE). The original Western Asia (WAS) is divided in two regions, Western central Asia (WCA) and the Arabian peninsula (ARP), the later with an arid climate; these two sub-regions exhibit a distinct annual cycle (see Figure 5). The Tibetan plateau (TIB), South Asia (SAS), East Asia (EAS) and Southeast Asia (SEA) are maintained unaltered.

Regarding Australasia, the original Northern region is divided in two (NAU and CAU, see Figure 1b) in order to increase consistency separating the central arid region from the northern tropical one with associated high rainfall climatology (Figure 2b). Moreover, the Southern region (SAU) is now further south (better differentiating the rainfall climatology) and separated from the oceanic New Zealand (NZ). The possibility to include a new region for eastern Australia to treat separately this wetter region was also considered, but was not implemented due to the limited size of the resulting region.

These updated regions are defined as polygons and are provided as coordinates and shapefile at the ATLAS GitHub (*reference-regions* folder). Moreover, companion R and Python notebooks are also available (*reference-regions/notebooks*) to illustrate their use in practical problems (trimming data, etc.).

4 Regionally Aggregated CMIP Datasets

The seasonal mean temperature and precipitation in IPCC regions for CMIP5 McSweeney et al. (2015) is a popular dataset developed building on the IPCC AR5 reference regions, suitable for the regional analysis of climate projections and their uncertainties. Here we extended this idea to the new regions and model data and computed aggregated monthly results over the different reference regions (see Figure 1b) for all

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

the CMIP5 model runs (and also the available CMIP6 ones), considering land only, sea only, and land-sea gridboxes (the land/sea masks are available in the ATLAS GitHub repository, *reference-grids*). Results are calculated for each model run and stored individually as a text-csv file, with regions in columns (including the global results in the last column) and dates (months) in rows; results for a single run are included directly in the ATLAS Github repository (*aggregated-datasets* folder), and links are provided to the general dataset (full ensemble with all runs) which allows for internal variability studies.

Whereas the aggregated CMIP5 dataset is final, results for CMIP6 will be regularly updated when new data becomes available at ESGF; these two datasets constitute alternative lines of evidence for climate change studies and the ATLAS initiative presented here allows facilitates intercomparison of results and consistency checks for the reference climatic regions.

5 Illustrative Case Study

In order to illustrate the potential applications of the reference regions and the associated regionally averaged CMIP datasets (for temperature and precipitation), in this section we describe a simple case study aimed at providing guidance on the projected range of future temperature/precipitation change in a particular reference region, which provides useful context information for a variety of impact and adaptation studies. In particular we use scatter diagrams to represent the median and 10^{th} and 90^{th} percentiles of the CMIP5 ensemble change signals for temperature and precipitation. We focus on three illustrative European regions (NEU, CEU and MED) with opposite climate change signals (see Figure 2e). The code and data needed to run this example (which can be easily extended to other regions, or combination of regions, and datasets, e.g. CMIP6) are all available at the ATLAS GitHub repository (*aggregated-datasets/scripts* folder) and can be run in a local R session accessing remotely the GitHub data with no further requirements.

Figure 6 shows the projected changes in annual mean temperature and precipitation resulting from the script *scatterplots_TvsP.R*, which accesses the CMIP5 regionally aggregated dataset available in the GitHub repository. Shown are averaged results from RCP2.6, RCP4.5 and RCP8.5 scenarios for early (2021-2040), mid (2041-2060 and 2061-2080) and late (2081-2100) 21st century relative to the 1986-2005 baseline period for each of the three European sub-regions. The results show an increase of temperature in all European domains —with similar warming in all regions for the different scenarios and future periods— and a consistent meridional gradient of changes in precipitation, with a clear precipitation increase in NEU, non-changing conditions in CEU (uncertainty range crossing the zero line), and reduced precipitation over MED. The same scripts can be applied to the currently available CMIP6 dataset by simply changing two parameters to check the consistency of these results for the updated models and scenarios.

Note that this illustrative example can be easily modified to serve different purposes. For instance, the same diagram can be adapted to display the individual model values (or to select the subset of models spanning the uncertainty range) in order to assist in the comparison and the selection of representative sub-ensembles for impact studies (see, e.g. Ruane and McDermid, 2017).

6 Conclusions and Discussion

A new set of 43 land plus 12 open ocean regions is introduced in this work updating the previous set of IPCC AR5 WGI reference regions for the regional synthesis of model-projected climate change information (in particular for the new CMIP6 simulations). The new regions increase the climatic consistency of the previous ones —by rearranging and dividing regions exhibiting mixed regional climates— and have a suitable model representation (the minimum is in the range 20-60 model gridboxes for three particular land regions: the Caribbean, New

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Zealand and Suthern South America). This revision was guided by the basic principles of climatic consistency and model representativeness, but there is of course some subjectivity in the final selection.

We also present a new dataset of monthly CMIP5/6 spatially aggregated information using the new reference regions and the available CMIP5 (from the IPCC-DDC) and CMIP6 data (from ESGF, as of 30 September 2019), and describe a worked-out example on how to use this dataset to inform regional climate change studies, in particular about the likely range of future temperature/precipitation changes for the different European reference regions using scatter diagrams.

7 Code and data availability

The present work is part of the ATLAS initiative (which is aligned with the IPCC AR6 activities) and the definition of the regions and the associated spatially aggregated datasets and auxiliary code are available at the GitHub ATLAS repository; https://github.com/SantanderMetGroup/ATLAS, doi:10.5281/zenodo.3688072 (Iturbide et al., 2020). The ATLAS project builds in the publicly available climate4R R framework (Iturbide et al., 2019) (available under the GNU General Public License v3.0) and provides additional functions which may be relevant for the users of the reference regions and aggregated datasets, such as the calculation of global warming levels, thus enhancing the functionalities presented in this work. The results for CMIP5 are based on the final curated dataset used for IPCC-AR5, but other datasets will be updated periodically when new data becomes available (e.g. CMIP6, still in progress).

Regarding the original datasets used in this work, all are publicly available from the local providers —CRU TS4.03 is distributed under the Open Database License, and EWEMBI and GPCCv2018 are distributed under the Creative Commons Attribution 4.0 International License— and/or the Earth System Grid Federation (ESGF, Balaji et al., 2018) —CMIP5 and CMIP6.— Moreover, for the sake of reproducibility some datasets have been also replicated at the Santander Climate Data Service which is transparently accesible from climate4R via the User Data Gateway (registration is required to accept the terms of use of the original datasets; more information at http://meteo.unican.es/udg-wiki, last access: 31 December 2019).

Author contributions. Gutiérrez J.M. and Iturbide M. conceived the study and wrote the code and the manuscript; van den Hurk B. conceived the case study; Iturbide M. and Hauser M. implemented the R and Python companion notebooks; all authors contributed to the definition of the regions, to the discussion and revised the text and the results.

Competing interests. The authors declare that there are not any competing interest.

Acknowledgement. We acknowledge all data providers and, in particular, 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. We also thank the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP and ESGF.

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Open Access Earth System Science Data Discussions

References

Balaji, V., Taylor, K. E., Juckes, M., Lawrence, B. N., Durack, P. J., Lautenschlager, M., Blanton, C., Cinquini, L., Denvil, S., Elkington, M., Guglielmo, F., Guilyardi, E., Hassell, D., Kharin, S., Kindermann, S., Nikonov, S., Radhakrishnan, A., Stockhause, M., Weigel, T., and Williams, D.: Requirements for a global data infrastructure in support of CMIP6, Geoscientific Model Development, 11, 3659–3680, https://doi.org/https://doi.org/10.5194/gmd-11-3659-2018, 2018.

Bärring, L. and Strandberg, G.: Does the projected pathway to global warming targets matter?, Environmental Research Letters, 13, 024 029, https://doi.org/10.1088/1748-9326/aa9f72, publisher: IOP Publishing, 2018.

CDO: Climate Data Operator Version 1.9.8. Max-Planck-Institute for Meteorology, https://code.mpimet.mpg.de/projects/cdo, 2019.

Christensen, J., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R., Kwon, W.-T., Laprise, R., Rueda, V. M., Mearns, L., Menez, C., Rn, J., Rinke, A., Sarr, A., and Whetton, P.: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)], book section Regional Climate Projections, pp. 847–940, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Diedhiou, A., Bichet, A., Wartenburger, R., Seneviratne, S. I., Rowell, D. P., Sylla, M. B., Diallo, I., Todzo, S., Touré, N. E., Camara, M., Ngatchah, B. N., Kane, N. A., Tall, L., and Affholder, F.: Changes in climate extremes over West and Central Africa at 1.5°C and 2°C global warming, Environmental Research Letters, 13, 065 020, https://doi.org/10.1088/1748-9326/aac3e5, 2018.

Forster, P. M., Maycock, A. C., McKenna, C. M., and Smith, C. J.: Latest climate models confirm need for urgent mitigation, Nature Climate Change, 10, 7–10, https://doi.org/10.1038/s41558-019-0660-0, 2020.

Giorgi, F. and Francisco, R.: Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM, Climate Dynamics, 16, 169–182, https://doi.org/10.1007/PL00013733, 2000.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., Storch, H. V., Whetton, P., Jones, R., Mearns, L., and Fu, C.: Climate Change 2001: The Scientific Basis [J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. vad der Linden, X. Dai, K. Maskell, C. A. Johnson (eds.)], book section Regional Climate Information?Evaluation and Projections, pp. 583–638, Cambridge University Press, 2001.

Harris, I. and Jones, P.: CRU TS4.03: Climatic Research Unit (CRU) Time-Series (TS) version 4.03 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2018), Centre for Environmental Data Analysis, https://doi.org/http://dx.doi.org/10.5285/10d3e3640f004c578403419aac167d82, 2020.

Harris, I., Jones, P. D., Osborn, T. J., and Lister, D. H.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, International Journal of Climatology, 34, 623–642, https://doi.org/10.1002/joc.3711, 2014.

Hawkins, E. and Sutton, R.: The Potential to Narrow Uncertainty in Regional Climate Predictions, Bulletin of the American Meteorological Society, 90, 1095–1108, https://doi.org/10.1175/2009BAMS2607.1, 2009.

Huffman, G. J., Adler, R. F., Bolvin, D. T., and Gu, G.: Improving the global precipitation record: GPCP Version 2.1, Geophysical Research Letters, 36, https://doi.org/10.1029/2009GL040000, 2009.

Iturbide, M., Bedia, J., Herrera, S., Baño-Medina, J., Fernández, J., Frías, M. D., Manzanas, R., San-Martín, D., Cimadevilla, E., Cofiño, A. S., and Gutiérrez, J. M.: The R-based climate4R open framework for reproducible climate data access and post-processing, Environmental Modelling & Software, 111, 42–54, https://doi.org/10.1016/j.envsoft.2018.09.009, 2019.

Iturbide, M., Gutiérrez, J. M., Bedia, J., Cimadevilla, E., and Manzanas, R.: SantanderMetGroup/ATLAS GitHub (Version v1.4), http://doi.org/10.5281/zenodo.3688072, 2020.

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Kotlarski, S., Szabó, P., Herrera, S., Räty, O., Keuler, K., Soares, P. M., Cardoso, R. M., Bosshard, T., Pagé, C., Boberg, F., Gutiérrez, J. M., Isotta, F. A., Jaczewski, A., Kreienkamp, F., Liniger, M. A., Lussana, C., and Pianko-Kluczyńska, K.: Observational uncertainty and regional climate model evaluation: A pan-European perspective, International Journal of Climatology, 39, 3730–3749, https://doi.org/10.1002/joc.5249, 2019.

Lange, S.: EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI). V. 1.1. GFZ Data Services., http://doi.org/10.5880/pik.2019.004, 2019.

Madakumbura, G. D., Kim, H., Utsumi, N., Shiogama, H., Fischer, E. M., Seland, A., Scinocca, J. F., Mitchell, D. M., Hirabayashi, Y., and Oki, T.: Event-to-event intensification of the hydrologic cycle from 1.5°C to a 2°C warmer world, Scientific Reports, 9, 1–7, https://doi.org/10.1038/s41598-019-39936-2, 2019.

Maúre, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., Dosio, A., and Meque, A.: The southern African climate under 1.5°C and 2°C of global warming as simulated by CORDEX regional climate models, Environmental Research Letters, 13, 065 002, https://doi.org/10.1088/1748-9326/aab190, 2018.

McSweeney, C. F., Jones, R. G., Lee, R. W., and Rowell, D. P.: Selecting CMIP5 GCMs for downscaling over multiple regions, Climate Dynamics, 44, 3237–3260, https://doi.org/10.1007/s00382-014-2418-8, 2015.

NCC editorial: The CMIP6 landscape, Nature Climate Change, 9, 727–727, https://doi.org/10.1038/s41558-019-0599-1, 2019.

O'Neill, B. C., Tebaldi, C., Vuuren, D. P. v., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geoscientific Model Development, 9, 3461–3482, https://doi.org/https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Osima, S., Indasi, V. S., Zaroug, M., Endris, H. S., Gudoshava, M., Misiani, H. O., Nimusiima, A., Anyah, R. O., Otieno, G., Ogwang, B. A., Jain, S., Kondowe, A. L., Mwangi, E., Lennard, C., Nikulin, G., and Dosio, A.: Projected climate over the Greater Horn of Africa under 1.5°C and 2°C global warming, Environmental Research Letters, 13, 065 004, https://doi.org/10.1088/1748-9326/aaba1b, 2018.

Ruane, A. C. and McDermid, S. P.: Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment, Earth Perspectives, 4, 1, https://doi.org/10.1186/s40322-017-0036-4, 2017.

Rubel, F. and Kottek, M.: Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification, Meteorologische Zeitschrift, pp. 135–141, https://doi.org/10.1127/0941-2948/2010/0430, 2010.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC Full Data Reanalysis Version 6.0 at 0.5: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data., https://doi.org/10.5676/DWD_GPCC/FD_M_V7_050, 2011.

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., and Zhang, X.: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, Barros, Stocker et al. (eds.)], book section Changes in climate extremes and their impacts on the natural physical environment, pp. 109–230, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2012.

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., and Hsu, K.-L.: A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons, Reviews of Geophysics, 56, 79–107, https://doi.org/10.1002/2017RG000574, 2018.

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, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

van Oldenborgh, G.J., M. C., Arblaster, J., Christensen, J., Marotzke, J., Power, S., Rummukainen, M., and Zhou, T.: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

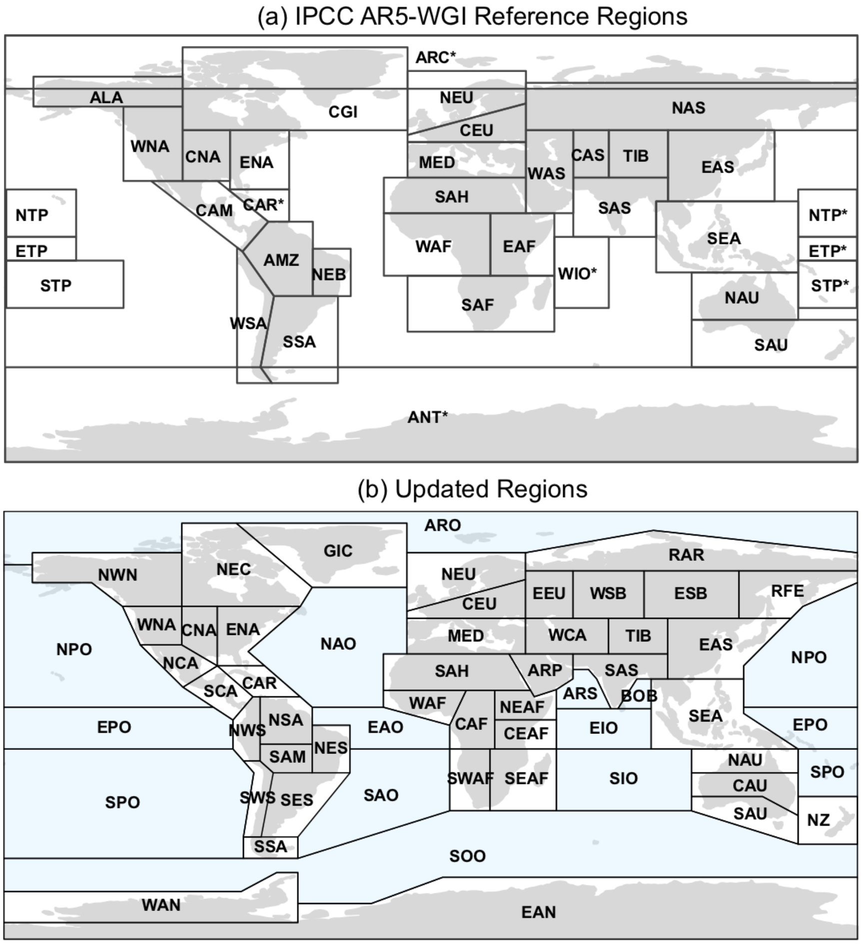
Climate Change[Stocker, T.F. and Qin, D. and Plattner, G.-K. and Tignor, M. and Allen, S.K. and Boschung, J. and Nauels, A. and Xia, Y. and Bex, V. and Midgley, P.M. (eds.)], book section Annex I: Atlas of Global and Regional Climate Projections, pp. 1311–1394, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/CBO9781107415324.029, www.climatechange2013.org, 2013.

Wartenburger, R., Hirschi, M., Donat, M. G., Greve, P., Pitman, A. J., and Seneviratne, S. I.: Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework, Geoscientific Model Development, 10, 3609–3634, https://doi.org/https://doi.org/10.5194/gmd-10-3609-2017, 2017.

WMO: WMO Guidelines on the Calculation of Climate Normals. WMO - No. 1203, https://library.wmo.int/doc_num.php?explnum_id=4166, 2017.

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Open Access Earth System Science Data Discussions



1	GIC	Greenland/Iceland
2	NEC	N.E.Canada
3	CNA	C.North-America
4	ENA	E.North-America
5	NWN	N.W.North-America
6	WNA	W.North-America
7	NCA	N.Central-America
8	SCA	S.Central-America
9	CAR	Caribbean
10	NWS	N.W.South-America
11	SAM	South-American-Monsoon
12	SSA	S.South-America
13	SWS	S.W.South-America
14	SES	S.E.South-America
15	NSA	N.South-America
16	NES	N.E.South-America
17	NEU	N.Europe
18	CEU	C.Europe
19	EEU	E.Europe
20	MED	Mediterranean
21	WAF	West-Africa
22	SAH	Sahara
23	NEAF	North-East-Africa
24	CEAF	Central-East-Africa
25	SWAF	South-West-Africa
26	SEAF	South-Eeast-Africa
27	CAF	Central-Africa
28	RAR	Russian-Arctic
29	RFE	Russian-Far-East
30	ESB	E.Siberia
31	WSB	W.Siberia
32	WCA	W.C.Asia
33	TIB	Tibetan-Plateau
34	EAS	E.Asia
35	ARP	Arabian-Peninsula
36	SAS	S.Asia
37	SEA	S.E.Asia
38	NAU	N.Australia
39	CAU	C.Australia
40	SAU	S.Australia
41	NZ	New-Zealand
42	EAN	E.Antarctica
43	WAN	W.Antarctica
44	ARO	Arctic-Ocean
45	NPO	N.Pacific-Ocean
46	EPO	Equatorial.Pacific-Ocean
47	SPO	S.Pacific-Ocean
48	NAO	N.Atlantic-Ocean
49	EAO	Equatorial.Atlantic-Ocean
50	SAO	S.Atlantic-Ocean
51	ARS	Arabian-Sea
52	BOB	Bengal-Gulf
53	EIO	Equatorial.Indic-Ocean
54	SIO	S.Indic-Ocean
55	SOO	Southern-Ocean

Figure 1. Updated IPCC reference land (gray shading) and open ocean (blue shading) regions. Assessments and analyses are provided for land areas only. Exact coordinates of the regions are provided in the ATLAS GitHub (https://github.com/SantanderMetGroup/ATLAS; doi:10.5281/zenodo.3688072; Iturbide et al., 2020).

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Open Access Earth System Science Data Discussions

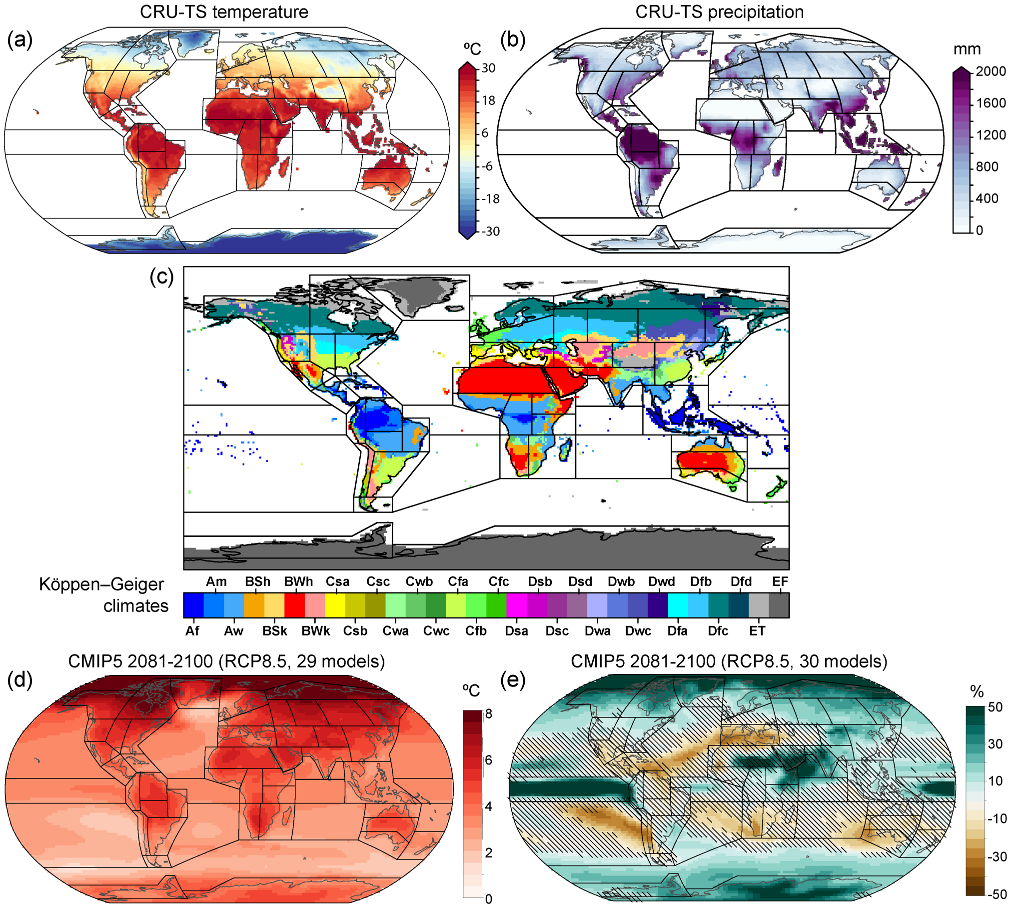


Figure 2. (a) Global mean temperature, (b) accumulated precipitation and (c) Köppen-Geiger climate classification from the CRU-TS dataset for the period 1981-2010 (data for Antarctica is filled with the EWEMBI dataset). This information is used to characterize the regional climate consistency of the reference regions (displayed as solid lines; see Figure 1b). (d,e) Climate change projections for temperature and precipitation, respectively, from the CMIP5 curated dataset for RCP8.5 2081-2100 w.r.t. 1986-2005; hatching indicates weak model agreement on the sign of the change (less than 80%).

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Open Access Earth System Science Data Discussions

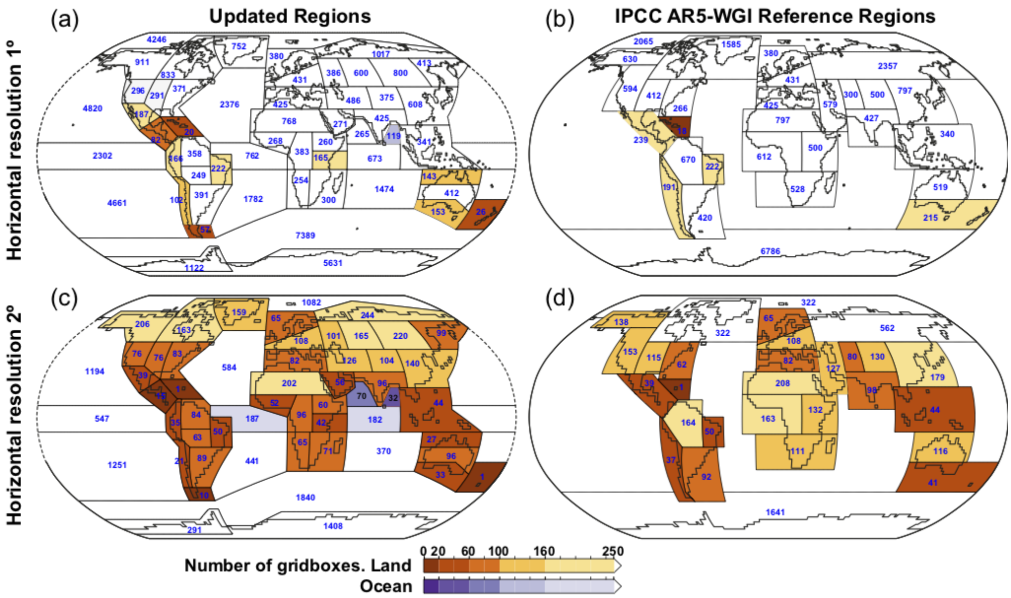


Figure 3. Number of land gridboxes encompassed by the different reference regions for CMIP6 1° (a,b) and CMIP5 2° (c,d) resolution, considering the AR5 (b,d) and the updated (a,c) reference regions. Shade colors indicate regions with less than 250 gridboxes (the dark colors correspond to less than 20 gridboxes). The polygons in the figures show the climate reference regions shown in Figure 1. The blue numbers in each of the regions show the corresponding number gridboxes (only land gridboxes for land regions).

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

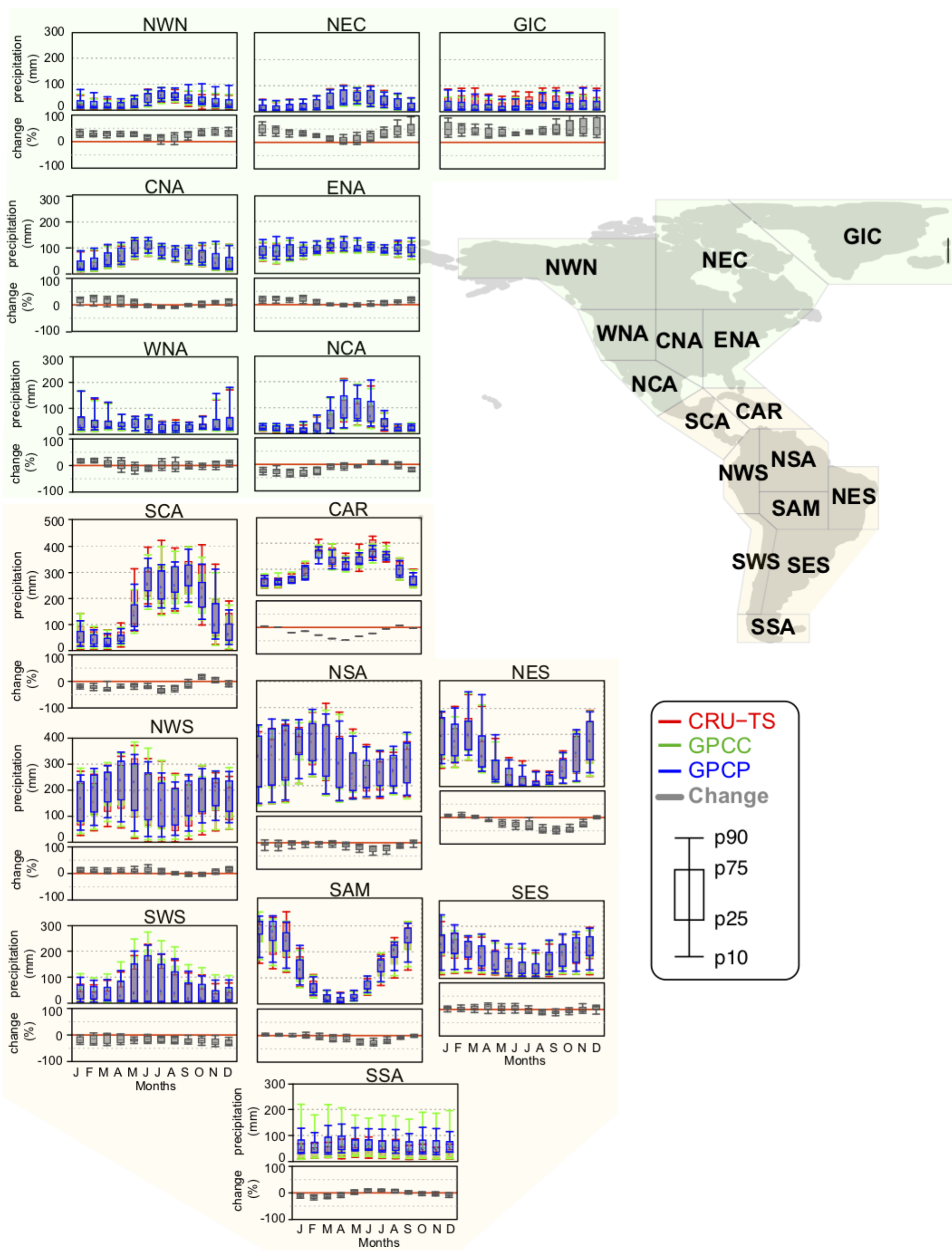


Figure 4. Observed annual cycle (1981-2010) for precipitation for the American reference regions from three different observational datasets (CRU-TS, GPCC, GPCP) and climate change signal (RCP8.5, 2081-2100 w.r.t. 1986-2005). The panel for each reference region shows the observed annual cycle (top, in monthly accumulated mm) and the monthly projected changes (bottom, in gray, as %).

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Open Access Earth System Science Data Discussions

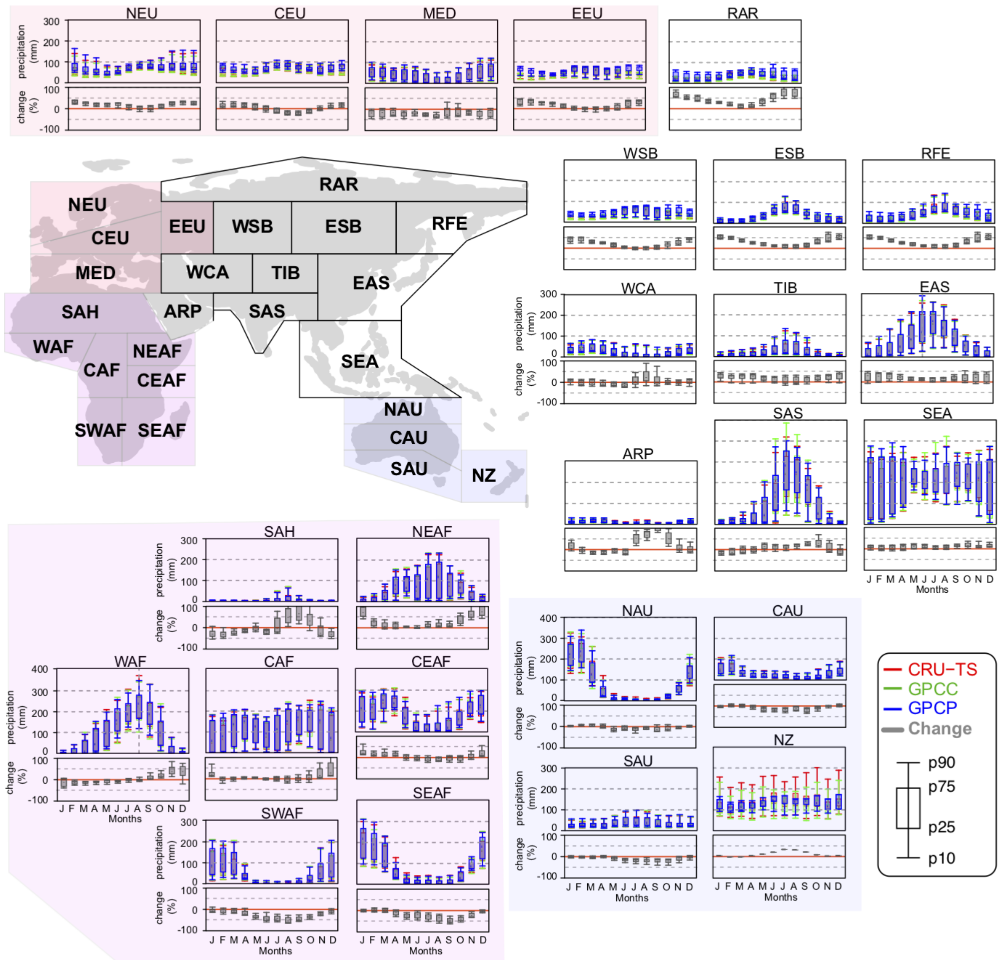


Figure 5. As figure 4 but for Europe, Asia and Austral Asia.

https://doi.org/10.5194/essd-2019-258
Preprint. Discussion started: 2 April 2020

Open Access Earth System Science Data Discussions

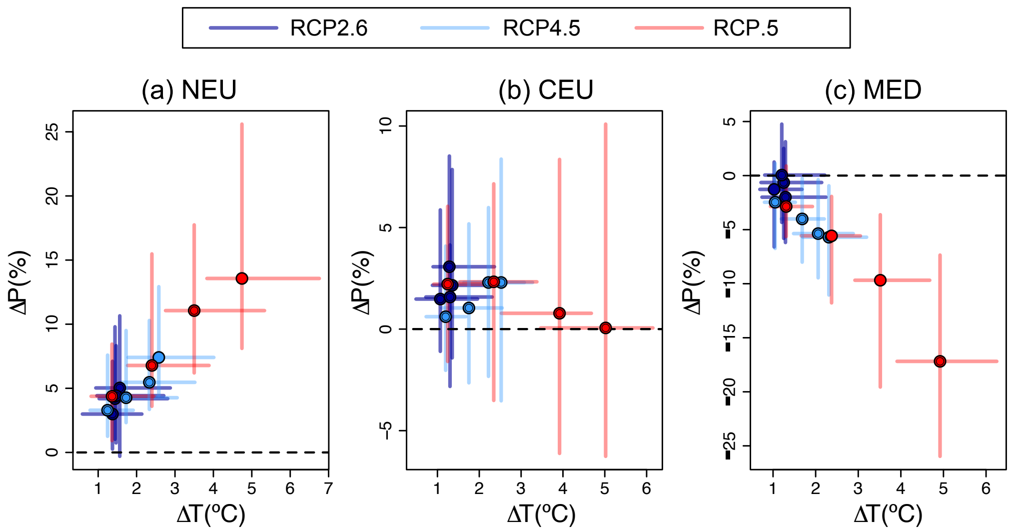


Figure 6. Illustrative worked out example of the use of reference regions and aggregated CMIP5 datasets: Regional mean changes in annual mean temperature and precipitation for three European regions (NEU, CEU and MED) for four future periods (2021-2040, 2041-2060, 2061-2080, 2081-2100), as obtained from CMIP5 projections. Changes are absolute for temperature and relative for precipitation. Horizontal and vertical error bars represent ±1 standard deviation from the mean calculated across the ensemble of included models. The script to generate this figure for all the 55 land and ocean regions (including the global region) from the ready-to-use aggregated CMIP5 datasets is available at the ATLAS GitHub, and can be easily adapted to produce similar results for alternative datasets (e.g. CMIP6).