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


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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 5th 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 5th Climate Model Intercomparison Projection, CMIP5,
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

Copyright statement. The reference regions and the aggregated datasets derived from CMIP5 described in this paper are made available in the ATLAS GitHub repository (https://github.com/SantanderMetGroup/ATLAS) under the Creative Commons Attribution (CC-BY) 4.0 license, whereas the scripts and code are made available under the GNU General Public License (GPL) v3.0. Additional products included in the ATLAS GitHub comply with the licenses of the original datasets and are periodically updated (e.g. CMIP6 aggregated dataset).

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
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 CRUTS (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).
Global model scenario data was downloaded 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 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,
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 (Maure 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
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 10th and 90th 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...
Zealand and Southern 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 accessible 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.

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References


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