“An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets” by Iturbide et al.

Letter to the Editor

Dear Editor,

We have revised the above mentioned document taking into account all comments received from the referees (also the two additional comments received in the interactive discussion). We have undertaken all major changes suggested (both related to scientific topics and also those related to potential changes of the regions). Below we provide point-by-point responses for the comments of the two referees and also the revised document including tracked changes.

We hope the paper is now suitable for publication in ESSD.

José Manuel Gutiérrez

On behalf of the authors

“An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets” by Iturbide et al.

Response to Referee 1

Dear referee. Thank you very much for the time devoted to the revision of our manuscript and the positive feedback received. Please find below a point-by point response (in blue) to your comments (in black).

Comment: General Comments The manuscript presents the updated climate reference regions for regional synthesis of observed and projected climate change information. The rationale behind the definition of the new regions is presented together with regional aggregated datasets generated from different observational temperature and precipitation datasets and from information of global climate models from the Coupled Model Intercomparison Project Phase 5 and 6 (CMIP5 and CMIP6) to assess observed climate and future climate projections (for different time horizons and emission scenarios). The manuscript provides the reference regions, datasets and code through a GitHub repository (https://github.com/SantanderMetGroup/ATLAS). The manuscript presents a valuable contribution for climate change assessments at sub-continental scales that rely on the efficient use of huge volumes of climate data and on the distillation and production of climate information for decision making. The topic of the manuscript is very interesting, the aims and results are clearly presented, and the code and data are easily accessible.

Response: We thank the referee for the time devoted to review our manuscript, and for the positive feedback provided.

Comment: Specific comment: I consider the updated and redefined regions make a significant improvement regarding the two premises established: climatic consistency and representativeness of model results. I would suggest adding a comment about that although the use of the aggregated climate information for each sub-continental region is very useful for a broad spectrum of users and they represent regions with climate- consistent regimes, detailed climate information at local or regional scales (in each sub-continental region) would require further analysis.

Response: We included a comment on the limitations of the aggregated data in the last paragraph of Section 4:

> “Note that although the aggregated data provides summary climate information for each sub-continental region which is useful for a broad spectrum of users, detailed climate information at local or regional scales (in each sub-continental region) would be required for further regional analysis.”

Comment: Technical comments: Page 3, line 29: Wouldn’t it be “from these datasets”?

Response: Yes. This has been changed in the revised manuscript.

Comment: Page 4, line 11: Reference period 1986-2005 for climate projections and WMO period (page 3, line 35) 1980-2010. These maybe confusing for readers who are not familiar with these periods. I suggest adding a brief explanation

Response: For the current WMO climatological normal period (1981–2010) we included a reference in the manuscript (WMO, 2017), which provides a clear description. For the period 1986-2005, in the revised manuscript we clarify that this was the baseline period used in AR5-WGI for modern climate; we refer to this period as the AR5 modern climate baseline in order to differentiate it from the WMO reference periods.

Comment: Caption Figure 1: What do the white regions? I think they are the regions that did not change from one AR to the other but it would be good to clarify it in the caption.

Response: The white areas indicate coastal regions within the land reference regions which should be excluded from the analysis (masked out using land-sea masks) to obtain land-only results. The blue color is reserved for ocean reference regions. This is clarified in Figure 1 caption and the use of these coastal regions in combination with ocean regions is discussed at the end of Sec 3.1:

> "In contrast to the AR5 regions, those defined in this paper also include 14 oceanic regions (note that the Caribbean and Mediterranean and considered both land and ocean regions, defined considering the land and sea masks, respectively). Since these largely exclude the coastal zones (which are often included in the "land" regions), they are generally more suitable for the analysis of large-scale atmospheric data. Figure 2d and e demonstrates that in this respect the ocean regions are a good addition to the AR5 definitions even though they were not developed with the intention of defining ocean basin masks for zonal means used by oceanographers. However, we note that since the coastal regions can be defined by applying a land-sea mask to the land boxes, it is possible to combine regions to enable the more traditional ocean basin definitions used by oceanographers to be produced to a large extent (albeit not exactly)."

“An update of IPCC climate reference regions for subcontinental analysis of climate model data: Definition and aggregated datasets” by Iturbide et al.

Response to Referee 2

Dear referee. Thank you very much for the time devoted to the revision of our manuscript and the positive feedback received. Please find below a point-by point response (in blue) to your comments (in black).

Comment: This dataset, and therefore manuscript, is clearly an important contribution to the field. I appreciate the openness of the process this time around to define the regions, and that this allows the community a chance to comment on the choice of them. Previously the regional definitions have been either mandated from the top-down or decided by individual researchers for their own purposes. Having said that I feel that the manuscript would benefit from some revisions before it can be published.

Response: We thank the referee for the time devoted to review our manuscript, and for the positive feedback provided.

Comment: This manuscript has multiple different aims. I interpret these as:

1. Justifying any changes in the pre-existing regions
2. Analysing the homogeneity of the regions (this is explicitly stated in the abstract)
3. Providing detailed information to allow researchers to apply the regions them- selves
4. Presenting 2 codes to permit regional analyses to be performed
5. Describing a dataset of precomputed time series from the CMIP5 (and CMIP6) simulations

This is an ambitious, but really useful, set of goals. Unfortunately, I find some of the presentation in the manuscript is sub-optimal for these aims. There are some questions that arose from my reading of the manuscript and I have some suggestions that would strengthen the manuscript. I’ve decided to separate my comments into ones relating to the regions themselves, and ones relating the manuscript. For the purpose of peer-review I feel that only the manuscript comments must be addressed. I do not really mind whether the authors alter the regions in light my comments – rather that they justify the choices they have made.

Response: Again we thank the referee by the positive comments and have included point by point responses to the comments below. We will take into account comments related to both the manuscript and the regions, as explained in the point by point responses below.

Comment: I would also like to mention that I have forked their repository and started to look at the python code. I work mainly in NCL myself, and have added an equivalent function I’ve written to compute the area-statistics for the AR5 regions into my version. When this manuscript is revised, I should be able to update the definitions in this function as a contribution to the effort.

Response: We are glad to see that the GitHub repository and the code are useful for the community. We would be happy to have your contributions in the package; you can just send a pull-request to the main Atlas repository.

Comments about the manuscript

Comment: I often found the justifications for the sub-divisions to be criticisms of the earlier regions, rather than providing an argument for the new choices. For example, in Africa (P5, L12-20) you convincingly demonstrate that the AR5 regions have failings. But there is no acknowledgment the new boundary is different in the Central/Northern compared to the Southern region, let alone justification for it.

Response: The new regions were defined to better accommodate the different sub-climates; the mentioned paragraph for Africa has been rewritten focusing on the reasons for the definition of the new regions. These maintain climatic homogeneity characterized in terms of mean temperature and precipitation considering Köppen-Geiger climatic regions but have provided additional discrimination motivated by differences in the annual precipitation cycle. For example, the new WAF and CAF region have similar Köppen-Geiger climates, but the annual cycle of precipitation is different. At the same time we recognize that these regions still encompass a variety of regional microclimate, but the number of subregions that can be discerned credibly in this assessment is limited.

The presentation of the new regions (and the underlying reasons) have been extended and included in a new subsection (Section 3.1).

Comment (a): I was surprised by the fact the manuscript only uses the (somewhat arbitrary) interpolated grids for any discussion about whether there are sufficient grid boxes in the regions. This use was exemplified by Fig. 3, whose findings are strongly reliant on the presumed 1º or 2º grid resolution. This component of the manuscript would be much more convincing if you used actual GCM grids. [I believe that an easy way to compute this would be to apply the region masks to the areacella variable. You could then back out the number of grid boxes by dividing the sum of areacella by the mean of areacella.]

Response: The 2º (1º) resolution considered for CMIP5 (CMIP6) corresponds to the typical resolution of the models forming the ensemble, which have been used to interpolate model results to common reference grids with a single land/sea mask (conservative regridding is used for precipitation). However, we agree with the referee that it would be informative having the numbers of gridboxes falling in each of the reference regions considering the original model grids as well. We have included this information in the revised manuscript (see Figure 5 in the new manuscript). In particular, in the figure we calculate the number of land gridboxes which fall in each of the reference regions; for each of the individual models we calculate those numbers and then present the mean value. The results show that the 1º grid is a good reference for CMIP6 models, being representative of the multi-model mean.

Comment: It was unclear to me from either the manuscript, or the provided codes, whether interpolation onto a common grid is/was performed in the computation of the regional averages. Whilst I accept the necessity of using a common grid for any ensemble averaging - such as in Fig 2(d,e) – it would appear to introduce unnecessary computation in determining an area mean, and may even introduce errors in computing higher order statistics.

Response: The reference grid is used to compute the areal aggregated values. Only land (ocean) model gridboxes are used in the interpolation to the land (ocean) reference regions. For precipitation, conservative remapping is used. Therefore, the regional mean values computed from the reference grid are representative of the ensemble and do not include artifacts due to different model land/sea masks.

Comment: I did not notice any analysis of the homogeneity of the new regions in the manuscript. You discuss Fig. 2 as if it presents such analysis. But this figure solely presents some key spatial fields and requires the reader to make their own qualitative assessment about the homogeneity. I suspect the box and whiskers in Fig. 5 conventionally presents the spread with time of the monthly values. Therefore, it does not demonstrate that all the grid points within a region have a homogeneous climate. Rather Fig 5 shows that the area averages of the regions follow different structures, which does not allow a reader to identify where 3 different rainfall regimes exist, but are being shoehorned into 2 boxes. (I note that Fig. 5 may instead use the box and whiskers to measure the spatial variance in the climatological monthly rainfall over the region, but this not mentioned in the caption – nor would it be necessary if an alternate method of demonstrating the homogeneity is used).

Response: As the referee notes in the last sentence, the box-and-whiskers plots in Figures 4 and 5 represent the spatial (gridbox) spread of climatological monthly means over the region; therefore it provides a view of the spatial consistency of the seasonal cycle across the area. We apologize for the confusion and have clarified and extended the analysis on the (in)homogeneity of the new regions in combination with Figure 2.

Comment: Please be careful about using the term (inter)annual variability (e.g. P5, L15). This phrase relates to things like the North Atlantic Oscillation and El Niño. You are using it to discuss the climatological seasonal cycle.

Response: Thank you for pointing this out. We modified the terminology accordingly (now we use annual cycle, or seasonal cycle consistently).

Comment: In light of my own efforts to apply the AR5 regions in NCL, can you please explicitly mention that the regions are defined by straight lines on a projected plane – rather than great circles over a sphere.

Response: We clarified that in the revised version (last paragraph in Section 3).

Comment: Can you please be more explicit about your treatment of coastal ocean? P6, L1 and the caption in Fig. 1 suggest that the terrestrial regions are only defined over land (as was the case in AR5). This brings up 2 questions:

- Clearly the new terrestrial regions avoid the open ocean by definition, but this still means that the coastal grid boxes are not included in any region. How much of the Earth's surface is not included in any region at all?
- Some of the old regions were defined as both land and sea regions (for ex- ample the aptly named SEA), with the Caribbean region combining both. The manuscript needs to both explicitly state, and justify why, you eschewed such an option in these updated regions?

Response: The polygones of the terrestrial regions include both land (grey) and ocean regions (in white), but the ocean regions are not considered in the calculation of model values, by using the land/sea mask of the models (or the reference grids). We clarified this in the revised manuscript. The two specific questions are answered below:

- As mentioned by the referee, the coastal regions are not included in the land regions nor in open ocean (in blue) regions used to represent atmospheric variables. Coastal ocean regions for representing oceanic variables require specific reference regions focusing on e.g. upwelling key areas and should be treated differently. We included a description of this issue (last paragraph in Sec. 3.1.):

- Regarding the use of some regions as both land and ocean ones (e.g. the Caribbean), we agree with the referee and included those dual land/ocean regions or the Caribbean and the Mediterranean (see Figure 1).

Comment: Your discussion around Fig. 3 (P4, L20) suggests that 20 gridboxes is sufficient, but less than that should be treated with caution. What is the impact of the variations in resolution of the CMIP6 models on the fidelity the 4 small regions highlighted? I note that for example the GISS-E2-1-G model has a resolution of 2ºx2.5º - so clearly falls into the 'treat with caution' category. Perhaps you could advise readers on an approach to acknowledge this uncertainty.

Response: A comment on this will be included together with the new calculation of the number of gridboxes for individual models; see comment (a).

Comment: I was surprised by your choice of which regions to illustrate in Fig. 6. You may want to consider highlighting some of the new regions that you've defined in this manuscript – perhaps even in comparison to an old one.

Response: The code provided allows to automatically calculate the same figures for any other reference region (just by changing the region "code" in the script). We have used three regions where a clear gradient is shown in the precipitation's climate change signal (increasing/neutral/decreasing in the north/center/south).

Comment: I appreciate that you've provided scripts to use these regions in both python and R. Would you be able to comment on the scripts' performance? For example, does the region extraction take a long time? Is the R approach faster than the Python?

Response: The calculation of the regional aggregated values is time consuming (but computed offline and results are provided in the GitHub repository). Accessing the values and plotting the results is straightforward and the scripts provided run very fast. We included some comments on this in the revised manuscript.

Comments about the actual regions

Comment: I can see a lot merit in the criticisms from both Jason Evans and Michael Grose about the new Central Australian region. I have little preference as to which version you pick – but their comments highlight the issues inherent in writing a manuscript that argues against the old regions - rather than arguing for the new ones.

Response: We also see the need of the change requested (the reasons given are very convincing). Therefore we included a new region (Eastern Australia, EAU) following the comments of both reviewers.

Comment: I found your new sub-divisions for South America puzzling.

Comment: (a) You provide little justification for division between NSA and SAM. The only differences visible in the variables shown in figure 2 occur in the Koppen- Geiger classification. Yet other regions, most notably CAF, happily combine these classes.

Response: We appreciate the reviewer's comment. Although several studies on South America have analyzed regional climate variability at the scale of the entire Amazon basin, most of them have documented that Amazon has a heterogeneous climate, particularly a strong temporal and spatial rainfall variability (e.g., Espinoza et al., 2019). In our study, the NSA and SAM regions were proposed because they present different climate regimes. They exhibit a well-identified seasonal cycle of precipitation (Figure 4) and represent sub-continental areas of greater climatic coherency (Figure 2c). For instance, the precipitation for SAM shows the rainy season from October to March, while for NSA, there are no clear wet and dry seasons. These new areas then provide further insight into sub-continental observed climate variability and projected changes in South America.

Using it as an opportunity, we have now edited the text to improve clarity and added literature references. The newly added text states,

> "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 (NWS) –which includes the northern Andes Mountains range–, and the South America Monsoon (SAM) region. These regions represent sub-continental areas of greater climatic coherency (both in terms of climate and climate change signals; see Figures 2c-e; Espinoza et al 2019) and exhibit characteristic seasonal precipitation cycles (Figure 3), with a rainy season from October to March in SAM and no clear wet and dry seasons for NSA and NWS. The Northeastern region is maintained, but the name is changed to Northeastern South America (NES). The old southern South America region is divided in two, separating the northern (southeastern South America, SES) and southern (SAS) parts, the later encompassing the mostly cold desert climates exhibited in this region (see Figure 2c)."

References:

Espinoza, J.C., Ronchail, J., Marengo, J.A. et al. Contrasting North–South changes in Amazon wet-day and dry-day frequency and related atmospheric features (1981–2017). Clim Dyn 52, 5413–5430 (2019). https://doi.org/10.1007/s00382-018-4462-2

Comment: (b) I was unsure that the subdivision of Southern South America provides an improvement. The new SWS region mashes together both the Atacama desert and the Mediterranean climate – a distinction which is made in N. Africa & Europe, Australia and North America.

Response: The reviewer is right in pointing out that SWS combines areas with desert and Mediterranean climates and even cool rain forest in the south tip. We have now included the southern part of the region into the modified SSA region (see response to your next comment). However further separating this region would lead to regions that are way too small (e.g., the Atacama Desert occupies a relatively small area). It should be noted that the new SSW constitutes a clear improvement compared to the AR5 WSA version that, in addition to desert and Mediterranean climates, also included tropical rainforest and monsoonal areas (see Figures 1-2 in the main text).

Comment: (c) The creation of SSA – a region focussed on Patagonia – seems reason- able. But it was unclear why 47◦S was taken as a dividing boundary. Given the small size of the region (as you warn readers about in Fig. 3), why did you pick that latitude as its boundary?

Politically, the Argentinian Province of Chubut provides two convenient alternate latitudes, given that it strad- dles 42-46ºS. I would leave it to the authors to assess whether Chubut is sufficiently Patagonian for inclusion into the region or not.

Response: The reviewer makes a good point. Based on the Koppen-Geiger classification and the CMIP5 projected future changes in precipitation, it would be reasonable to include the Argentinian province of Chubut as part of the novel SSA. Consequently, we have moved the northern boundary of SSA region from -47 to -40 degrees. This change has the additional benefit of substantially increasing the size of the currently relatively small SSA region.

Comment: What about Madagascar? Inspecting the variables shown in Fig 2a-c and the fact that it's not contiguous, I wonder if it should really be considered as part of the South East Africa. It is certainly a larger landmass that New Zealand.

Response: We agree with the referee and will split Madagascar from South East Africa, including a new region.

Comment: Will ensemble-wide relationships between the North Atlantic Ocean warming and the AMOC be confounded because both the Labrador and Norwegian Seas are not incorporated into the region?

Response: The open ocean regions are used for representing atmospheric variables (see a comment above). We moved the northern boundary of the North Atlantic region as much as possible.

Comment: Is the New Zealand region adequately resolved as a land-only region across all CMIP6 model resolutions?

Response: New Zealand and the Caribbean are the smallest regions (with 26 and 20 land gridboxes for the 1º reference grid, respectively). This is considered adequate for representing the region. We discuss this in more detail in the revised manuscript taking into account the results for the individual models.

Comment: Why do the Russian Arctic and Far East regions stop at 180º? Why does NWA exclude the Alaskan Peninsula (defining a latitude lower that 60◦N may not be unsuitable)? The peninsula and Russian area around the Bering Strait are the only examples of continental land masses that is incorporated into ocean regions.

Response: The referee is right. There is no reason for stopping at 180º (apart from convenience for representing the region) and therefore, the RAR region has been extended accordingly in the revised version. Similarly, NWN has been extended to include the Alaskan peninsula and other land regions excluded from the original definition.

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], Ruth Cerezo-Mota d, Ezequiel Cimadevilla [c], Antonio S. Cofiño [c], Alejandro Di Luca [e], Sergio Henrique Faria [f,f2], Irina Gorodetskaya [g], Mathias Hauser [h], Sixto Herrera [c], Kevin Hennessy i, Helene T. Hewitt j, Richard G. Jones j,[k], Svitlana Krakovska [l,m], Rodrigo Manzanas [n,c], 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. Matemática Aplicada y Ciencias de la Computación. 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 Basque Centre for Climate Change (BC3), Leioa, Spain

f2 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 CSIRO Oceans and Atmosphere. Canberra, Australia

j Met Office Hadley Centre. Exeter, United Kingdom

[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 System Analysis Group (CSAG), University of Cape Town. South Africa

Eliminado: Ruth Cerezo-Mota [d],

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Eliminado: [j] CSIRO Oceans and Atmosphere. Canberra, Australia…

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[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

Abstract. Several sets of reference regions have been used in the literature for the regional synthesis of observed and modelled climate and climate change information. A popular example is the set of reference regions introduced in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Adaptation (SREX). The SREX regions were slightly modified for the 5th Assessment Report of the IPCC and used for reporting sub-continental observed and projected changes over a reduced number (33) of climatologically consistent regions encompassing a representative number of grid boxes. These regions are intended to allow analysis of atmospheric data over broad land or ocean regions and 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.

e 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 atmospheric model resolution. As a result, the number of land and ocean regions is increased to 46 and 14 respectively, better representing consistent regional climate features. The paper describes the rationale 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 (e.g. calculating regional averages). We also describe the generation of a new dataset with monthly temperature and precipitation, spatially aggregated in the new regions, currently for CMIP5 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 plots to offer guidance on the likely range of future climate change at the scale of the 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.3968318 (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 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 using more flexible polygons in the IPCC SREX special report (Seneviratne et al., 2012) and then slightly modified and extended to 33 regions (by including island states, the Arctic and Antarctica) for the fifth Assessment Report (AR5, van Oldenborgh et al., 2013), as shown in Figure 1a. The goal in these revisions was to improve the climatic consistency of the regions so they represent sub-continental areas of greater climatic coherency. This process typically resulted in a larger number of smaller regions, constrained by the relatively coarse resolution of the global models, since each region should encompass a sufficient number of gridboxes. 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

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horizontal resolution greater than 2°) and were quickly adopted by the research community as a basis for regional analysis in a variety of applications (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 by 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 (e.g., Ruane and McDermid, 2017).

The increasing availability of CMIP6 multi-model simulations (O'Neill et al., 2016; NCC editorial, 2019) offers an opportunity to refine the AR5 reference regions — due to the higher atmospheric model resolution, typically around 1° — and also to produce ready-to-use aggregated regional information for the updated reference regions. This is a timely task due to the great interest of the research community 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 goal. First, we present the updated regions (referred to as updated IPCC WGI reference regions) and describe the rationale 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 per region). Climatic homogeneity is characterized in terms of mean temperature and precipitation considering Köppen-Geiger climatic regions (Rubel and Kottek, 2010), the annual cycle and projected changes of the reference regions.

The resulting 46 land plus 14 ocean regions (see Figure 1b) are provided as coordinates (in csv format and as shapefile) 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 and CMIP6, to be extended later 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 that are expected for different European regions using scatter plots.

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 with a resolution of 0.5° over land for the period 1901-2017. Figure 2a-b shows the annual mean temperature and precipitation climatology for the period 1981-2010. CRU TS does not cover Antarctica, which is therefore infilled with an alternative dataset, namely the EWEMBI gridded observations (Lange, 2019). Figure 2c shows the Köppen-Geiger climatic regions (Rubel and Kottek, 2010) computed from these datasets. Quantifying the observational uncertainty is an increasing concern in climate studies, particularly for precipitation (Kotlarski et al., 2019). Therefore, we use two additional observational datasets for precipitation in some parts of this study: 1) Global Precipitation Climatology Centre (GPCC, v2018 used here; Schneider et al., 2011) providing monthly land precipitation values with 0.5° resolution for 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 with a resolution of 2.5° for the period 1979-2018. We show results for 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/SSP1-2.6, RCP4.5/SSP2-4.5 and RCP8.5/SSP5-8.5 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); a periodically updated inventory is available at the ATLAS GitHub repository (in the *AtlasHub-inventory* folder). All model data has been interpolated to common 2° (for CMIP5) and 1° (CMIP6) grids — separately for land and ocean gridboxes using conservative remapping (using CDO with the models and target land/sea masks; CDO, 2019), — which are typical model resolutions for CMIP5 and CMIP6 models, respectively. The common grids and land/sea masks are available in the ATLAS GitHub repository (in the *reference-grids* folder).

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In this paper we illustrate the results using the curated CMIP5 dataset and refer to the ATLAS GitHub repository for similar results for CMIP6. Figure 2d-e shows the CMIP5 multi-model climate change signal for annual mean temperature (in absolute terms) and precipitation (relative, in %) for RCP8.5 2081-2100 (w.r.t. the modern climate baseline 1986-2005 used in AR5). 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.

3 Reference Regions: Rationale and Definition

The Giorgi reference regions were originally defined with the goal 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 3 and 4); in the later case, observational uncertainty is analysed using the three alternative datasets described in Sec. 2. Representativity of model results (sufficient number of gridboxes per region) is analysed at the end of this section in Figure 4.

3.1 Definition of new regions

In North America, the Polar Greenland-Iceland (GIC) region was divided in two, Northeastern North America (NEN) and Greenland/Iceland (GIC), to better accommodate the subarctic and Polar climates, respectively (Figure 2c). The eastern and central Northern America regions (ENA and CNA) are maintained mostly unaltered while the western part was reorganized to increase climate consistency. The new Northwestern region (NWN) includes mostly the subarctic regions, the modified western region (WNA) encompasses a variety of regional intermixed climates (semiarid, Mediterranean, and continental) which are difficult to further separate due to the complex orography, and the new North Central America (NCA) region includes the semiarid and arid climates of Northern Mexico, separating them from the tropical climates in southern Central America which constitute a new region (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 (NWS) –which includes the northern Andes Mountains range– and the South America Monsoon (SAM) region. These regions represent sub-continental areas of greater climatic coherency (both in terms of climate and climate change signals; see Figures 2c-e; Espinoza et al 2019) and exhibit characteristic seasonal precipitation cycles (Figure 3), with a rainy season from October to March in SAM and no clear wet and dry seasons for NSA and NWS. The Northeastern region is maintained, but the name is changed to Northeastern South America (NES). The old southern South America region is divided in two, separating the northern (southeastern South America, SES) and southern (SAS) parts, the later encompassing the mostly cold desert climates exhibited in this region (see Figure 2c).

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

For Africa, the old WAF region has been divided in divided in two (WAF and CAF, see Figure 2b); although these regions have similar Köppen-Geiger climates (see Figure 2c), they have very different annual cyles (Figure 4) and therefore should be analysed independently (Diedhiou et al., 2018). A similar situation was found in the original EAF (Osima et al., 2018), which was also divided in two, Northern subregion (NEAF) which includes the arid region of the Horn of Africa and a Southern subregion (SEAF). These two regions also exhibit different precipitation seasonal cycles, with different timing of the annual maximum (see Figure 4). Moreover, the South Africa region SAF was also divided in two subregions with different rainfall regimes (Maúre et al., 2018), the western subregion (WSAF) including the arid regional climates, and the Eastern region (ESAF).

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 region (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 seasonal cycle (see Figure 4). The old Tibetan plateau (TIB) region is divided in two subregions, separating the highland climate of the Tibetan plateau in the South (TIB) from the northern arid subregion (Eastern Central Asia, ECA) The South Asia (SAS), East Asia (EAS) and Southeast Asia (SEA) are maintained unaltered (with the exception of adjustments caused by changes in neighboring regions).

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Regarding Australasia, the Southern region (SAU) is now further south (better differentiating the rainfall climatology, Fig. 2c) and separated from the oceanic New Zealand (NZ). The Northern region is divided in three subregions to increase climatic consistency (CSIRO, 2015; see Figure 1b) separating the northern tropical region (NAU), the central arid region (CAU) and the subtropical east coast (EAU). In contrast to the AR5 regions, those defined in this paper also include 14 oceanic regions (note that the Caribbean and Mediterranean and considered both land and ocean regions, defined considering the land and sea masks, respectively). Since these largely exclude the coastal zones (which are often included in the "land" regions), they are generally more suitable for the analysis of large-scale atmospheric data. Figure 2d and e demonstrates that in this respect the ocean regions are a good addition to the AR5 definitions even though they were not developed with the intention of defining ocean basin masks for zonal means used by oceanographers. However, we note that since the coastal regions can be defined by applying a land-sea mask to the land boxes, it is possible to combine regions to enable the more traditional ocean basin definitions used by oceanographers to be produced to a large extent (albeit not exactly).

3.2 Representativeness of model results

The higher atmospheric 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 5 illustrates this, displaying the number of gridboxes (only land gridboxes for land regions) in each of the AR5 (last column) and revised (first column) reference regions for the two reference grids (1° and 2°), as well as for the CMIP6 model grids (representing the multi-model mean of gribox numbers). This figure shows that the 1° grid provides a good reference for CMIP6. Moreover, it shows that the new reference regions are more representative than the original ones due to the increase of model resolution (see Figures 5a and 5d, corresponding to the cases of CMIP6 data on the updated reference regions, and to CMIP5 data in the original IPCC-AR5 regions, respectively). The regions with the smallest number of gridboxes correspond to three island regions: The Caribbean (CAR), New Zealand (NZ), and Madagascar (MDG), with around 20-60 gridboxes per region. Note that the updated regions are also suitable for the analysis of CMIP5 data (at 2° resolution, Fig. 5c) since all regions encompass over ten land gridboxes, with the exception of the three above-mentioned regions, where results should be interpreted with caution.

These updated regions are defined as polygons (the lines in Figure 1 are straight lines on a projected plane) and are provided as coordinates and shapefile at the ATLAS GitHub (*reference-regions* folder); the reference grids and land-sea masks can be found at the reference-grids folder. Moreover, companion R and Python notebooks are also available (*reference-regions/notebooks*) to illustrate their use in practical problems (e.g. calculating regional averages).

4 Regionally Aggregated CMIP Datasets

The seasonal mean temperature and precipitation in IPCC regions for CMIP5 McSweeney et al. (2015) is a popular dataset based 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. Note that although the aggregated data provides summary climate information for each sub-continental region which is useful for a broad spectrum of users, detailed climate information at local or regional scales (in each sub-continental region) would be required for further regional analysis.

5 Illustrative Case Study

To demonstrate a potential application of the reference regions and the associated regionally-averaged CMIP data (for temperature and precipitation), we show a simple case study illustrating the projected range of future temperature/precipitation change. This can provide useful context information for a variety of impact and adaptation studies. In particular, we use scatter plots to show the median, 10th, and 90th percentiles of the CMIP5 ensemble

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change. We focus on three illustrative European regions (NEU, WCE and MED) with opposite climate change signals for precipitation (see Figure 2e). The code and data needed to run this example (which can be 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 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*. In particular, 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 subregions are displayed. This figure evidences 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 WCE (uncertainty range crossing the zero line), and reduced precipitation over MED. The same scripts can be applied to the currently available CMIP6 dataset by changing two parameters to check the consistency of these results for the updated models and scenarios.

Note that this illustrative example can be 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 (e.g. Ruane and McDermid, 2017). The calculation of the regional aggregated values is time consuming (computed offline and results are provided in the GitHub repository), but accessing the values and plotting the results is straightforward and the scripts provided run in a few seconds.

6 Conclusions and Discussion

A new set of 46 land plus 14 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 island regions: the Caribbean, New Zealand and Madagascar). 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 plots.

7 Code and data availability

The present work is part of the climate change ATLAS initiative (which is aligned with IPCC AR6 activities). The definition of the regions, the code and the associated spatially-aggregated datasets are available at the GitHub ATLAS repository: https://github.com/SantanderMetGroup/ATLAS, doi:10.5281/zenodo.3968318 (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 python notebook is based on the open source projects regionmask (Hauser, 2019) and xarray (Hoyer and Hamman, 2017), among others. 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 of them 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).

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Author contributions. Gutiérrez J.M. and Iturbide M. conceived the study and wrote the code and the manuscript; vandenHurk 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 is not any competing interest.

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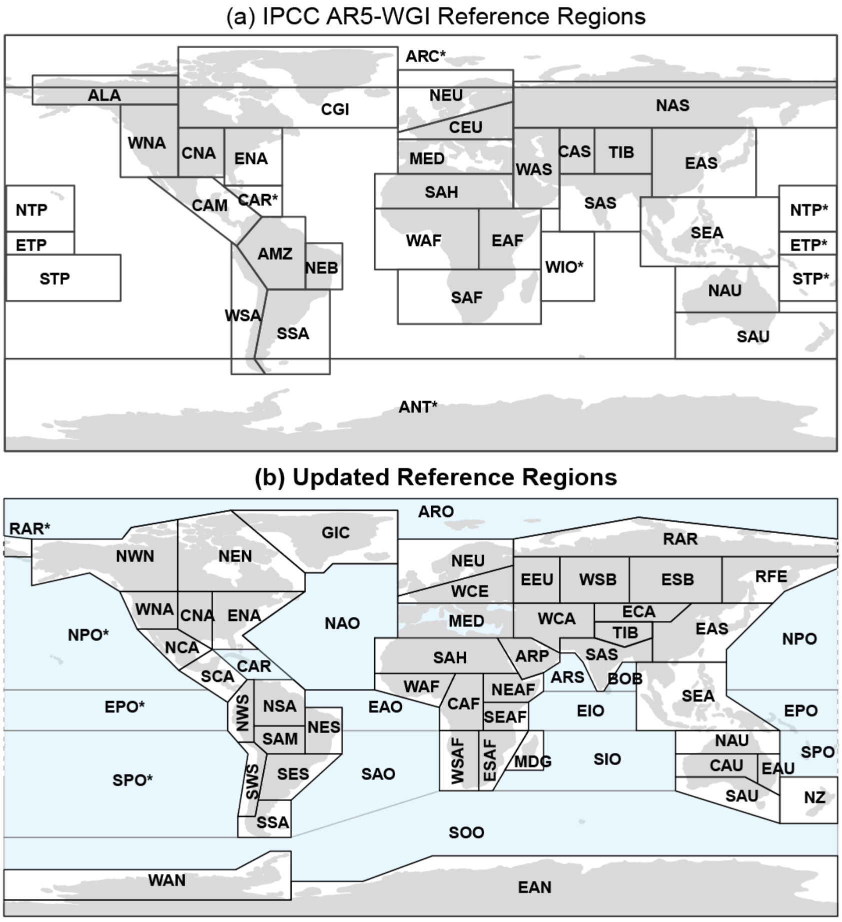
FIGURES



1	GIC	Greenland/Iceland	21	SAH	Sahara	40	NAU	N.Australia
2	NWN	N.W.North-America	22	WAF	Western-Africa	41	CAU	C.Australia
3	NEN	N.E.North-America	23	CAF	Central-Africa	42	EAU	E.Australia
4	WNA	W.North-America	24	NEAF	N.Eastern-Africa	43	SAU	S.Australia
5	CNA	C.North-America	25	SEAF	S.Eastern-Africa	44	NZ	New-Zealand
6	ENA	E.North-America	26	WSAF	W.Southern-Africa	45	EAN	E.Antarctica
7	NCA	N.Central-America	27	ESAF	E.Southern-Africa	46	WAN	W.Antarctica
8	SCA	S.Central-America	28	MDG	Madagascar	47	ARO	Arctic-Ocean
9	CAR	Caribbean	29	RAR	Russian-Arctic	48	NPO	N.Pacific-Ocean
10	NWS	N.W.South-America	30	WSB	W.Siberia	49	EPO	Equatorial.Pacific-Ocean
11	NSA	N.South-America	31	ESB	E.Siberia	50	SPO	S.Pacific-Ocean
12	NES	N.E.South-America	32	RFE	Russian-Far-East	51	NAO	N.Atlantic-Ocean
13	SAM	South-American-Monsoon	33	WCA	W.C.Asia	52	EAO	Equatorial.Atlantic-Ocean
14	SWS	S.W.South-America	34	ECA	E.C.Asia	53	SAO	S.Atlantic-Ocean
15	SES	S.E.South-America	35	TIB	Tibetan-Plateau	54	ARS	Arabian-Sea
16	SSA	S.South-America	36	EAS	E.Asia	55	BOB	Bay-of-Bengal
17	NEU	N.Europe	37	ARP	Arabian-Peninsula	56	EIO	Equatorial.Indic-Ocean
18	WCE	Western&Central-Europe	38	SAS	S.Asia	57	SIO	S.Indic-Ocean
19	EEU	E.Europe	39	SEA	S.E.Asia	58	SOO	Southern-Ocean
20	MED	Mediterranean						

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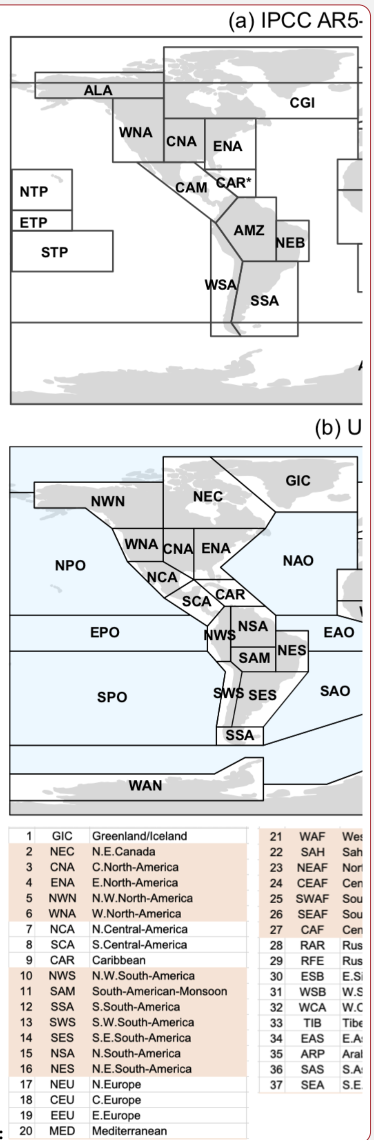


Figure 1. Updated IPCC reference land (gray shading) and ocean (blue shading) regions; note that the Caribbean and the Mediterrean are considered both land and ocean regions (defined using the land and sea masks, respectively). Land masks are used to obtain land-only information for land regions (excluding the coastal white regions).

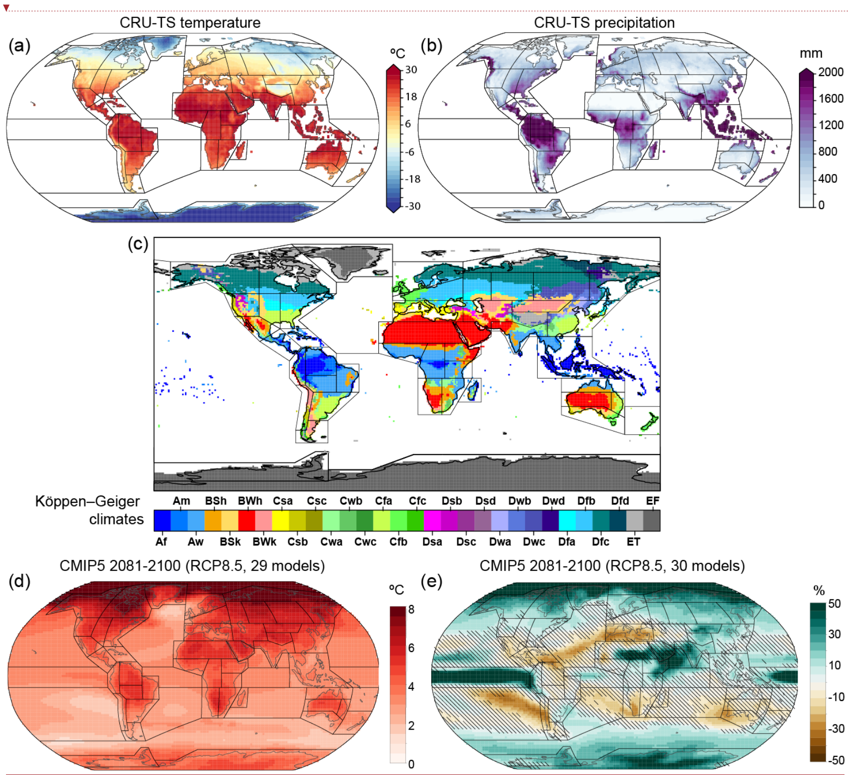
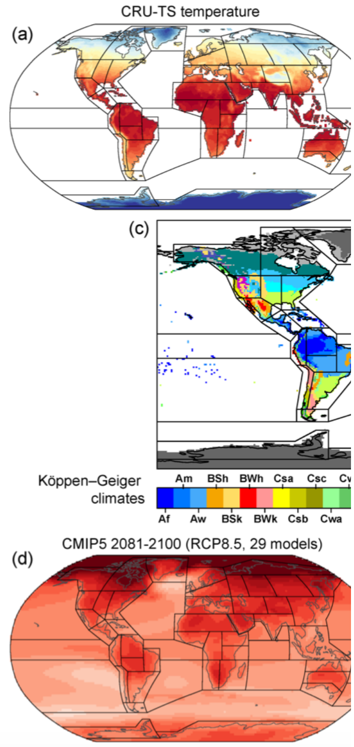


Figure 2. (a) Global mean temperature, (b) accumulated precipitation and (c) Köppen-Geiger climate classification from the CRU-TS dataset for the period 1981-2010 (data for Antarctica is filled with the EWEMBI dataset). This information is used to characterize the regional climate consistency of the reference regions (solid lines). (d,e) Climate change projections for temperature and precipitation, respectively, from the CMIP5 curated dataset for RCP8.5 2081-2100 w.r.t. the AR5 modern climate baseline 1986-2005. Hatching indicates weak (less than 80%) model agreement on the sign of the change.



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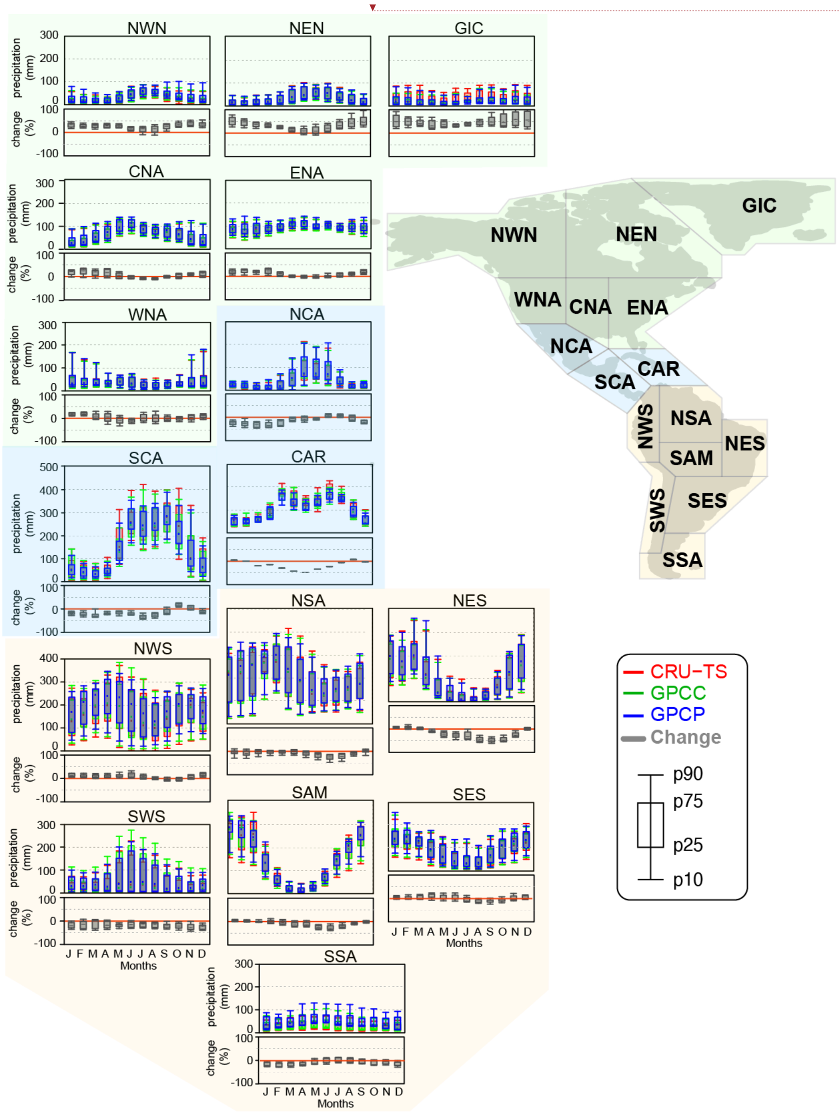
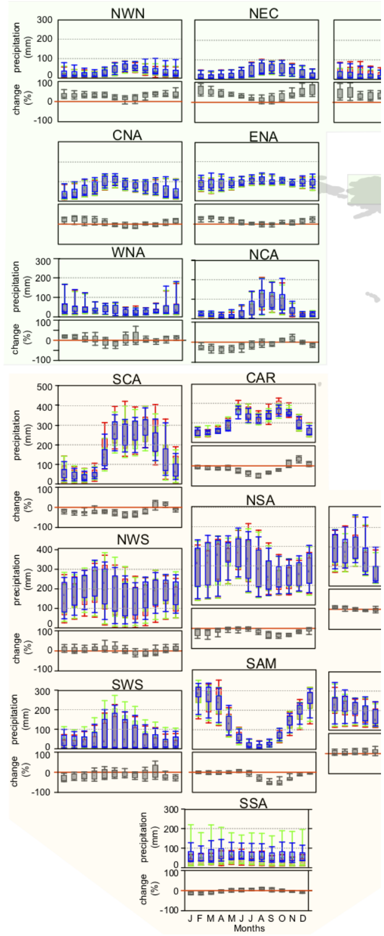


Figure 3. Observed annual cycle (1981-2010) for precipitation for the American reference regions from three different observational datasets (CRU-TS, GPCC, GPCP) and climate change signal (RCP8.5, 2081-2100 w.r.t. the AR5 modern climate baseline 1986-2005). The panel for each reference region shows the observed annual cycle (top, in monthly accumulated mm) and the monthly projected changes (bottom, in gray, as %); box and whiskers plots represent the spatial (gridbox) spread of monthly values over the region.



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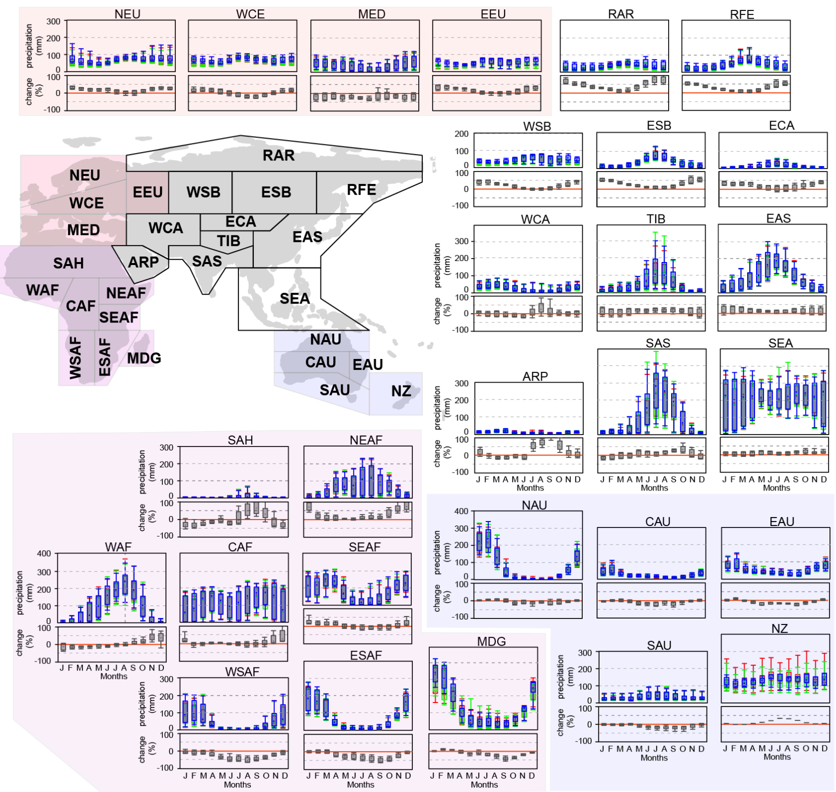
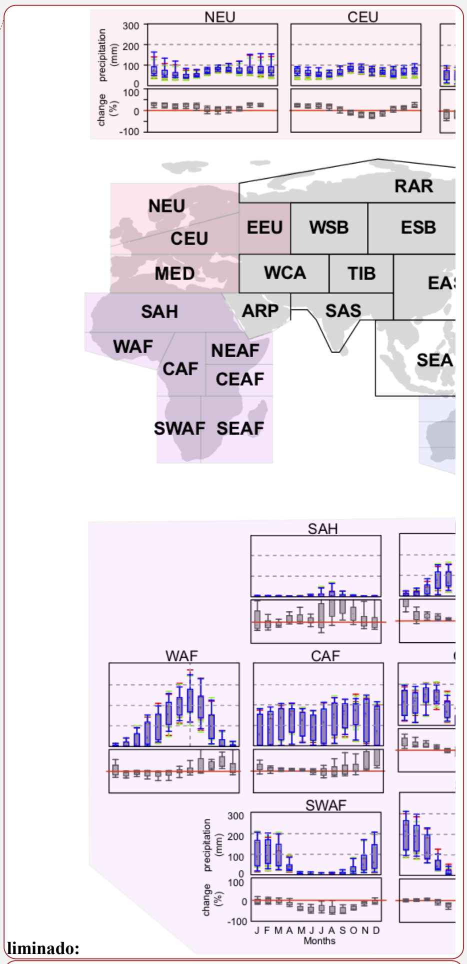


Figure 4. As figure 3 but for Europe, Asia and Australasia.



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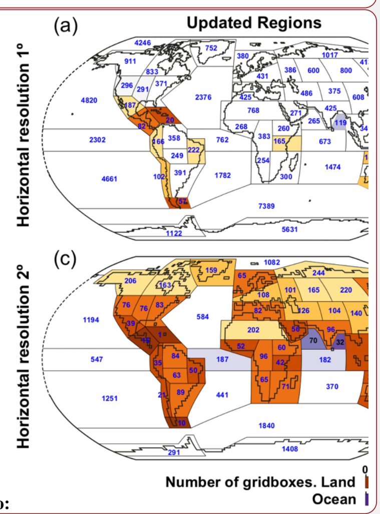

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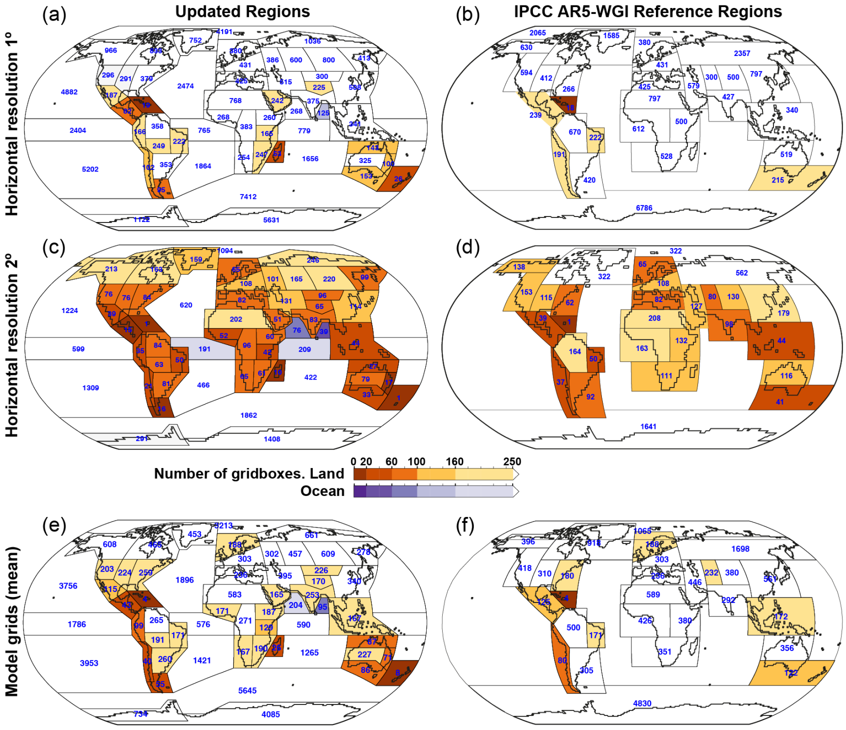


Figure 5. Number of gridboxes encompassed by the different reference regions for 1º (a,b) and 2º (c,d) resolution and for the CMIP6 model grids (e,f) –the multi-model mean is represented–, considering the updated (a,c,e) and the original AR5 (b,d,f) reference regions. Colors indicate regions with less than 250 gridboxes. The blue numbers in each of the regions show the number of gridboxes (only land gridboxes for land regions).

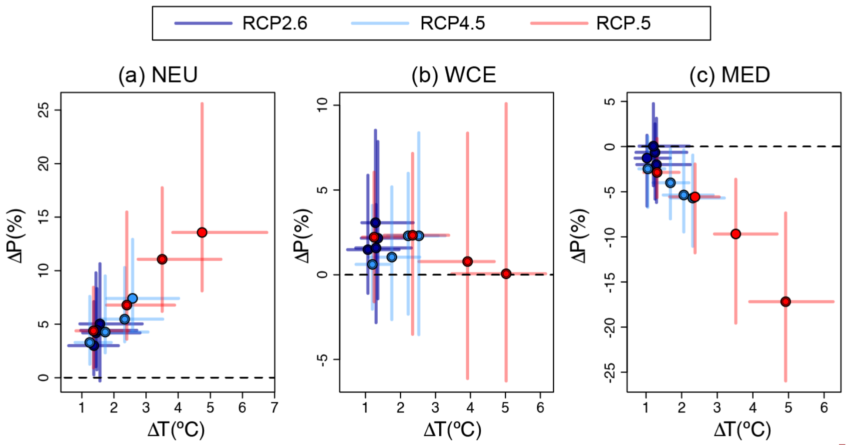
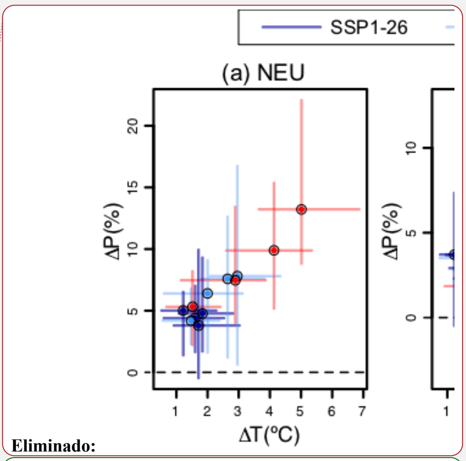


Figure 6. Illustrative example of the use of reference regions and aggregated CMIP5 datasets: Regional mean changes in annual mean temperature and precipitation for three European regions (NEU, WCE and MED) for four future periods (2021-2040, 2041-2060, 2061- 2080, 2081-2100), as obtained from CMIP5 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 adapted to produce similar results for alternative datasets (e.g. CMIP6).



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