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Changes in the world rivers' discharge projected from an updated high resolution dataset of current and future climate zones

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SUMMARY

In this paper, an updated global map of the current climate zoning and of its projections, according to the Köppen–Geiger classification, is first provided. The map at high horizontal resolution (0.5° × 0.5°), representative of the current (i.e. 1961–2005) conditions, is based on the Climate Research Unit dataset holding gridded series of historical observed temperature and precipitation, while projected conditions rely on the simulated series, for the same variables, by the General Circulation Model CMCC-CM. Modeled variables were corrected for their bias and then projections of climate zoning were generated for the medium term (2006–2050) and long term (2056–2100) future periods, under RCP 4.5 and RCP 8.5 emission scenarios. Results show that Equatorial and Arid climates will spread at the expenses of Snow and Polar climates, with the Warm Temperate experiencing more moderate increase. Maps of climate zones are valuable for a wide range of studies on climate change and its impacts, especially those regarding the water cycle that is strongly regulated by the combined conditions of precipitation and temperature.

As example of large scale hydrological applications, in this work we tested and implemented a spatial statistical procedure, the geographically weighted regression among climate zones' surface and mean annual discharge (MAD) at hydrographic basin level, to quantify likely changes in MAD for the main world rivers monitored through the Global Runoff Data Center database. The selected river basins are representative of more than half of both global superficial freshwater resources and world's land area. Globally, a decrease in MAD is projected both in the medium term and long term, while spatial differences highlight how some areas require efforts to avoid consequences of amplified water scarcity, while other areas call for strategies to take the opportunity from the expected increase in water availability. Also the fluctuations of trends between the medium to long term time frames is viewed in order to pay attention to the lifespan of investments and decisions. Despite preliminary and illustrative, this study suggests how large scale valuable information can be extracted even through indicators derived from statistical spatial modeling procedures, without the pretention to replace more sophisticated studies that allow process based reproduction of inter-annual and intra-annual discharge variability, and on which a robust and comprehensive assessment of future water resource reliability should be however also based.

1. Introduction

Nowadays, many global scale studies on ecology, biology, botany, zoology, hydrology, dynamic vegetation, human health, patterns of natural biomes and agricultural systems are based on empirical relationships between ecosystems and climate characteristics (Kottek et al., 2006; Rubel and Kottek, 2011). In this context, the Köppen–Geiger climate classification (Geiger, 1961; Köppen, 1900) is considered highly valuable even after more than 100 years since its formulation as having the advantage of overcoming the limit of evaluations based on separated variables, considering instead the combination of temperature and precipitation in terms of their monthly and seasonal cycle along the year, which is a better representative of both geographical (e.g. latitude, coastal vs. inland territory), topographic (e.g. altitude, aspect) and ecosystems' (e.g. vegetation, hydrology) settings.

Despite the original dataset on which the Köppen–Geiger classification has been determined was not very dense and homogeneous across the world, another advantage and reason of evergreenness is that it can be applied more and more easily at spatialized level, since georeferenced datasets on precipitation and temperature are now widely available for several decades, in

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computer compatible formats, and are often based on spatial interpolation of meteorological station data into regular grids (e.g. the WordClim and Climate Research Unit products for both precipitation and temperature; the Global Precipitation Climatology Centre and the Global Historical Climatology Network-Monthly datasets for precipitation and temperature, respectively). Such datasets allow producing digital maps, like the updated world map of the Köppen–Geiger climate classification provided by Kottek et al. (2006) and Peel et al. (2007).

The usefulness of the Köppen–Geiger (or similar) classification system to represent climate shifts was tested by Triantafyllou and Tsonis (1994): although they concluded that, on a very short term, shift performances can be region-specific, the potential for the decadal shift detection was recently reconsidered and demonstrated in Chen and Chen (2013). Due to the increasing availability of temperature and precipitation datasets over long time series, the Köppen–Geiger classification scheme became useful to assess historical shifts in climate zones at a global scale (Belda et al., 2014; Chen and Chen, 2013; Fraedrich et al., 2001) and with focus in Europe, China and United States by Gerstengarbe and Werner (2009), Kim et al. (2008), and Diaz and Eischeid (2007), respectively.

Concerning climatology and climate studies via modeling approaches, first of all, Köppen–Geiger climate classification was largely used as a means to validate General Circulation Models (GCMs) (Guetter and Kutzbach, 1990; Hanf et al., 2012; Kalvova et al., 2003; Kleidon et al., 2000; Lohmann et al., 1993; Manabe and Holloway, 1975; Wang and Overland, 2004; Zhou et al., 2010), and still appears one of the most powerful tools for this purpose (Gnandesikan and Stouffer, 2006). In addition, climate simulations coming from multi-model or multi-scenario intercomparison datasets are often used to project the distribution of future Köppen–Geiger zones or the modifications of the climate conditions into the current zones. Such evaluations range from global (Feng et al., 2014; Kalvova et al., 2003; Mahlstein et al., 2013; Rubel and Kottek, 2010) to regional scales using multiple GCMs (Alessandri et al., 2014; Crosbie et al., 2012; Jylhä et al., 2010) or GCM–RCM (Regional Climate Model) chains (De Castro et al., 2007; Teichmann et al., 2013), and also including the ensemble mean methods where the average of temperature and precipitation distributions is used to identify with higher likelihood the potential future climate zones (De Castro et al., 2007; Hanf et al., 2012).

While the zones' shift is a direct effect of climate change, it also supports the evaluations of the impacts in natural and anthropic systems (Feng et al., 2014), like implications for vegetation or hydrology (Crosbie et al., 2012; Kim et al., 2008; Roderfeld et al., 2008). As representatives of the usefulness in hydrological studies, McMahon et al. (1992, 2007) and Peel et al. (2001, 2004a) identified and explained the continental-scale variability in runoff by applying the Köppen's climate classification to regionalize the world's lands.

Under the purposes of climate change studies, despite continuous efforts to improve the GCM's capability of simulating historical climates, the use of bias-correction methods is essential and challenging for the assessment of climate change impacts, as also described in the special report of the Intergovernmental Panel on Climate Change (IPCC, 2012). Jacob et al. (2007) concluded that a multi-model ensemble mean might offer more reliable projections of climate change than any individual uncorrected member, and often the ensemble mean is indeed used for reducing errors (as in De Castro et al., 2007). Moreover, Alessandri et al. (2014) stated that, when adopting ensemble evaluations, correcting the ensemble members before averaging them prevents from retaining all the probabilistic information coming from the single-models, and any evidence about the actual reliability of the multi-model experiment. However, when analyzing the average impacts from a single climate model simulation, chosen due to the specific preference criteria (e.g. spatial resolution, forcing emission scenario), the best option (although more time consuming) is the use of bias-corrected data via available and well-assessed methods, and appropriate to the chosen time scale of analysis (e.g. Härter et al., 2011). For long-term climatological studies as those usually served by climate zoning, and mostly based on intra-annual (monthly) average for at least 30-years of data, low computational demanding procedures like delta methods (see e.g. Watanabe et al., 2012) are available and promising (Feng et al., 2014; Jylhä et al., 2010; Mahlstein et al., 2013).

In this work, we first produced a climate zoning for the recent historical period by using an updated dataset (Climate Research Unit; CRU hereafter) on precipitation and temperature with high spatial resolution at a global scale (0.5° latitude × 0.5° longitude), and for two future periods relying on the results of the GCM CMCC-CM (Scoccimarro et al., 2011) at ca. 0.75° latitude × 0.75° longitude horizontal resolution. Such a resolution was preferred as the most comparable, among those of GCMs participating in the Climate Model Intercomparison Project 5 experiment (CMIP5; Taylor et al., 2012), to that of the CRU dataset, thus limiting the additional bias generated by larger reduction of the pixel size during remapping procedures. We bias-corrected the simulated data by adopting the method of Sperna Weiland et al. (2010) that also provides a strategy to address the issue of a significant underestimation of precipitation by the model in some areas of the world. The results of this climate zones' mapping are also intended to complement the work of Rubel and Kottek (2010) with additional projections that use a different GCM and the new emission scenarios considered by IPCC (2013), and to sustain a preliminary and illustrative global scale hydrological analysis on future water availability.

While the majority of global hydrological studies based on climate zoning consider the location of river gauging stations (Peel et al., 2001, 2004a,b, 2005; McMahon et al., 1992, 2007; Van Vliet et al., 2013), i.e. they analyzed the discharge data aggregately into climate zones, we considered instead the arrangement of climate zones into world hydrographic basins as extracted from the Global Runoff Data Center (GRDC, 2007) database. First, we tested and parameterized a geographically weighted regression model, which represents a more local form of the regression analysis, for the baseline period. Successively, we adopted the calibrated model to quantify the hazard (assumed as a physical climate change impact, according to IPCC, 2014) in terms of changes in the mean annual discharge attributable to the changes in the extent of each climate zone within the hydrographic basins of the main world rivers selected. With this work, we explore an innovative and straightforward procedure to study the climate-hydrology interactions at the macro-scale, and we provide a first perception of the clearest trends in water resource availability, function of the combination of the annual cycle of temperature and precipitation. We are aware that the use of a single GCM, although under two emission scenarios, limits the results of this analysis in terms of robustness that is usually guaranteed by ensemble evaluations. Nevertheless, this work has to be seen as a proof of concept to demonstrate how the useful information can be also derived from such a statistical spatial modeling, without the pretention to replace more sophisticated studies, such as those based on mechanistic reproduction of inter-annual and intra-annual discharge variability by hydrological models or by the runoff outputs directly from GCMs, and which serve as the basis for a comprehensive assessment of water resource reliability.