Global freshwater shortage at low runoff conditions based on HAPPI experiments

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Pre-submitted to: Environmental Research Letters

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August 2017

Abstract Whilst climate change is expected to accelerate the hydrological cycle, it is not clear how the renewable freshwater availability below normal (a form of extremes or drought, e.g., low runoff) conditions and societal impact would change globally and regionally. Recent call for reporting naturally occurring drought with anthropogenic water shortage and the need for new scientific knowledge around the warming targets (1.5˚C, 2˚C) prompts us to tackle this challenge. Based on the large ensembles of the HAPPI experiments (historical, +1.5˚C, +2˚C experiments), we evaluate how the magnitude of freshwater availability at low runoff (i.e., Q_{20}, Q_{10}, Q_5) would change in the future period. We found that, relative to the historical period, the multi-model ensemble mean of low runoff would decline in the mid-latitudes and the tropics. Whilst the geographic pattern of changes in low runoff for the +2˚C experiment (changes are more intense but not always) is quite close to that of +1.5˚C experiment, a 1.5˚C warming target is more likely to reduce drought risk triggered by low runoff conditions at both global and regional scales. Relative to the historical period, an additional ~12 million people would be adversely affected by water shortages if we stabilised climate at 2˚C over 1.5˚C. Regionally, more people in East Asia, South Asia, Southern Europe and Mediterranean, Central Europe and Southeast Asia would be exposed to water shortage; less in West Africa, West Coast of South America, Alaska/Northwest Canada. Stabilising warming at 1.5˚C instead of 2˚C would constrain adverse impact on people suffering water shortages in most of the regions but less effective in Southeast Asia, Alaska/Northwest Canada, few Latin America regions (Amazon, West Coast South America).

Keywords: global scale, freshwater shortage, low runoff, 1.5˚C warming, population

1. Introduction

Securing adequate renewable freshwater supply (i.e., net of precipitation minus evapotranspiration) is vital for sustaining human activities (e.g., agricultural production, industrial, domestic water consumptions) and environmental requirement (Falkenmark 1989, Rijsberman 2006). Whilst the global-mean hydrological cycle is anticipated to intensify with global warming (Oki and Kanae 2006, Lim and Roderick 2009, Roderick *et al* 2012), changing distribution of renewable freshwater across space and time albeit with large uncertainty (Jimenez Cisneros *et al* 2014, Prudhomme *et al* 2014) adds to the concern on freshwater supply (World Economic Forum 2015, Liu *et al* 2017, Vorosmarty *et al* 2010) and its risk on national food security, economic prosperity and societal well-being (Rijsberman 2006, Mekonnen and Hoekstra 2016). To minimise these uncertainty along with climate extremes in an interfered climate system (Tschakert 2015), official agreement has been reached to hold global warming at less than 2˚C above pre-industrial levels with possible adoption of the 1.5˚C target (UNFCCC Conference of the Parties 2015).

The lack of scientific literature to inform climate policy about differences between these specified warming targets (i.e., 1.5˚C and 2˚C) has called for new form of analyses to support an IPCC special report on “Global warming of 1.5˚C” in 2018 (Mitchell *et al* 2016, Hulme 2016, Schleussner *et al* 2016, Peters 2016, Seneviratne *et al* 2016). In response to this call and the recent proposal for broadening the definition of drought to include shortage cause and modified by human process in the anthropocene (Van Loon 2015; Van Loon *et al* 2016), we put forward some relevant questions including: How would global renewable freshwater below normal conditions (as a form of extremes) change at these global warming targets? How would they affect the water shortage of society? Could we avoid/reduce the impact and risk at 1.5˚C relative to 2˚C? The 'attribution-style' (Allen 2003) climate experiments -- half a degree additional warming, prognosis and projected impacts (HAPPI, link: http://www.happimip.org/), explicitly designed to differentiate impacts between these global warming targets (i.e., 1.5˚C and 2˚C worlds) using large ensembles and the fact that they are not transient (Mitchell *et al* 2017) allow to gain new insights on these questions relative to the earlier climate experiments, e.g., the Couple Model Intercomparison Project Phase 3 (CMIP3) (e.g., Arnell 2004, Fung *et al* 2011, Murray *et al* 2012), CMIP5 (e.g., Hanasaki *et al* 2013, Arnell and Lloyd-Hughes 2014) and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Prudhomme *et al* 2014, Schewe *et al* 2014, Veldkamp *et al* 2016).

Here we aim to address these freshwater availability questions (above) as part of contribution towards the upcoming IPCC special report. To do that, we use atmosphere-only global circulation models (AGCMs) output from HAPPI experiments, global hydrological product from a climate data record and global population data that is consistent with World Bank (constant 2005) (CIESIN 2005, Lim *et al* in review) (we do not account for future population growth in this study). We evaluate how the magnitude of freshwater availability below normal (e.g., low runoff) conditions in the future period (1.5˚C and 2˚C) would change relative to the historic period. From there, we estimate the number of people affected by freshwater shortage on population in the historic and future periods. We present these results on global and sub-continental scales consistent with IPCC (2012) and make inference to previous studies.

2. Data and Methods

2.1 Data

The overall approach of current study is illustrated in Figure 1. Firstly, we obtain AGCMs output from the Tier 1 experiments of the HAPPI archive. Briefly, the Tier 1 experiments consist of multiple runs (50-100 ensembles) for three 10-year period experiments: (i) a historical period (2006-2015; hereafter referred to as 'historical experiment'), (ii) a future period at 1.5˚C above the pre-industrial levels (2106-2115; hereafter referred to as '+1.5˚C experiment') and (iii) a future period at 2˚C above the pre-industrial levels (2106-2115; hereafter referred to as '+2˚C experiment'). Within each experiment, each run distinguishes itself from others in terms of its initial weather state, thus provides large samples per experiment to support multi-year event analysis (see details in Mitchell *et al* 2017). We select the AGCM that fulfills these criteria: (i) monthly precipitation flux (*pr*, kg m^{-2} s^{-1}), (ii) monthly latent heat flux (*hfls*, W m^{-2}), (iii) monthly surface air temperature (*tas*, K) and (iv) the first 50 ensembles are available for all the Tier 1 experiments. Following this, we get five AGCMs (CanAM4, ECHAM6-3-LR, ETH-CAM4-2degree, MIROC5, NorESM1-HAPPI) with sufficient samples (50 ensembles x 10 years x 12 months = 6000 monthly samples per AGCM) per experiment (see Table S1). To enable consistent analysis across all AGCMs and the baseline period (see next paragraph), we rescale them to a spatial resolution of 0.5˚ x 0.5˚ using bilinear interpolation.

We use the runoff of the climate data record (CDR) (Zhang *et al* 2017) for the global terrestrial water budget (spatial resolution: 0.5˚ × 0.5˚, temporal resolution: monthly, time period: 1984-2010) to represent that of the baseline (27 years x 12 months = 324 monthly samples). The CDR is an optimised estimation of terrestrial water budget through merging in-situ observations, satellite remote sensing, reanalysis and land surface model outputs using data assimilation techniques. It has been validated against in-situ discharge measurements obtained from the Global Runoff Data Centre (GRDC) and the United States Geological Survey (USGS) (Zhang *et al* 2017).

We apply a recently prepared World Bank adjusted global population map (constant 2005) (Lim *et al* in review). Shortly, a population distribution map (year: 2005, spatial resolution: 2.5'x2.5') was obtained from the Gridded Population of the World version 3 (GPWv3) (CIESIN 2005). The ratio of country population from the World Bank (2005) to the sum of distributed population of each country from the GPWv3 was calculated, and then multiplied with the population distribution of each country in GPWv3 in order to produce the final product (data not available for French Guiana, Taiwan, Western Sahara). Here we rescale this final product to a spatial resolution of 0.5˚ x 0.5˚.

<Figure 1, here, thanks>

2.2 Methods

From the AGCMs output (Table S1), we calculate the monthly runoff (Q, mm d^{-1}) at each grid-cell as,

$$Q = \frac{86400000}{\rho_W}\left(pr - \frac{hfls}{\lambda_W}\right) \quad (1)$$

where ρ_W (kg m^{-3}) is the density of liquid water (≈1000 kg m^{-3}) and λ_W (J kg^{-1}) is the latent heat of vapourisation. Following Allen et al. (1998), we calculate λ_W as,

$$\lambda_W = 2.501 \times 10^6 - 2361(tas - 273.15) \qquad (2)$$

From these equations, we prepare the monthly runoff for the historical and future periods (Q_{his} and Q_{fut}, respectively).

Without subscribing to any specific statistical distribution, we use percentile (e.g., x^{th} percentile) as one way to set the low runoff conditions for both historical and future periods (i.e., $Q_{his,x}$ and $Q_{fut,x}$, respectively). To compare them, we compute the percentile in the historical period for monthly runoff $Q_{his,(fut,x)}$ corresponding to the future period $Q_{fut,x}$. If the computed percentile of $Q_{his,(fut,x)}$ is lower (higher) than $Q_{fut,x}$, then $Q_{fut,x}$ is drier (wetter) than $Q_{his,x}$. If the computed percentile of $Q_{his,(fut,x)}$ equates $Q_{fut,x}$, then $Q_{fut,x}$ is identical to $Q_{his,x}$ (refer to Figure 1 for better illustration).

From literature, we confirmed that the 20th percentile (Q_{20}; a value being equaled or exceeded 80% of the time) is a commonly used threshold in large scale hydrologic investigations (i.e., hydrological drought, water scarcity) (Andreadis *et al*, 2005, Sheffield *et al* 2009, van Huijgevoort *et al* 2013). Hence we set x = 20 (in the previous paragraph) for our analysis throughout the main text. For each AGCM, we calculate the Q_{20} at each grid-cell (50 ensembles x 10 years x 12 months = 6000 samples) across all experiments (i.e., historical, +1.5˚C and +2˚C experiments). To generalise them, we calculate the ensemble mean of all AGCMs and model consistency. To test the robustness of our findings, we repeat the analysis using lower thresholds (e.g., Q_{10}, Q_5) in Supplementary Information.

For each AGCM per experiment, we quantify the people affected by water shortage per grid-cell as (water supply – water demand threshold x population per grid-cell)/(water demand per capita). To calculate the water supply at low runoff conditions, we first remove the bias of the runoff through matching the percentile of the AGCM runoff (by setting x=20 in $Q_{his,(fut,x)}$ and $Q_{fut,x}$) with that of the baseline (see second paragraph in Section 2.1) in order to get the CDR runoff. We compute the water supply as (runoff x grid-cell area, m^3 day^{-1}). Following the Falkenmark water stress indicator (e.g., Falkenmark *et al* 1989, 2013), we set the water demand threshold at 1700 m^3 $capita^{-1}$ $year^{-1}$ (results in main text) and 1000 m^3 $capita^{-1}$ $year^{-1}$ (results in Supplementary Information), respectively. We aggregate them to sub-continental and global scales and calculate the change in affected population from the historical period to the future period (i.e., $\Delta(fut_{+1.5}\text{-his})$, $\Delta(fut_{+2.0}\text{-his})$) (Note: Negative (positive) number means that people adversely affected by water shortage would increase (decrease)).

3. Projections of low runoff

The multi-model ensemble mean percentile in the historical period for monthly runoff corresponding to the future period Q_{20} (+1.5˚C, +2˚C experiments) show some robust large-scale features (Figure 2). For the +1.5˚C experiment, the low runoff would increase at high latitudes in the Northern Hemisphere and Sahara (in relative sense); decrease in the mid-latitudes (e.g., Central Asia, West Asia and East Asia, middle and south of North America) and the tropics (e.g., parts of Amazon basin, north of Chile, southeastern Brazil, Malaysia, Indonesia, Thailand, Cambodia, Vietnam, Laos, New Guinea, Kenya, Tanzania, Gabon, Congo and Democratic Republic of Congo). Whilst the geographic pattern of changes in low runoff for the +2˚C experiment is quite close to that of +1.5˚C experiment, we notice that the magnitude of change would intensify (in both directions) except for Sahara, Malaysia and Indonesia. We repeat similar process at lower thresholds (Q_{10}, Q_5) and find that the spatial pattern of the changes (drier/wetter) are not sensitive to the threshold (whilst the magnitude would vary) (Figures S1-S2 in Supplementary Information), confirming the robustness of these projections. More generally, they imply that the magnitude of droughts arising from low runoff conditions would be less severe in most parts of the world (except for the Malaysia and Indonesia) should we pursue climate change mitigation efforts to hold temperature increase at 1.5˚C instead of 2˚C above the pre-industrial levels.

<Figure 2, here, thanks>

Most of these spatial patterns are consistent with the previous studies despite different climate experiments and/or methods (Alcamo *et al* 2007, Hagemann *et al* 2013, Schleussner *et al* 2016, Lehner *et al* 2017). Specifically, our results are also in general agreement with an analysis using CMIP5 experiments and river-routing process performed by Koirala and colleagues (Koirala *et al* 2014) in terms of spatial extent of decreasing future low flows in Europe, Middle East, southwestern United States and Central America relative to the historical period.

The high model consistency on the sign of change (3-5 models in totally 5 AGCMs) in most of the regions for the future periods (+1.5˚C, +2˚C experiments and their difference) gives us some confidence on these projections. Specifically, MIROC5 projects a more intense drying pattern relative to CanAM4 in most of the fragmented regions (Figure S3 in Supplementary Information). All models indicated that the drought risk at low runoff conditions would intensify when global warming approaches the 2˚C (instead of 1.5˚C) above pre-industrial levels.

Following the definition of regions in IPCC (2012), we sort our projections and estimate the global and regional mean of changes in mean percentile in the historical period (2106-2115) for monthly runoff corresponding to the Q_{20} of the future periods (Figure 3). Globally, the multi-model ensemble mean of low runoff is projected to increase slightly (Q_{20} -> $Q_{20.14}$) under +1.5˚C experiment whilst barely change (Q_{20} -> $Q_{20.07}$) under +2˚C experiment relative to the historical experiment, indicating that differences between +1.5˚C and +2˚C experiments are not statistically robust or nonlinear effect plays an important role. Regionally, the multi-model ensemble means of low runoff would decrease except for West Africa (Q_{20} -> $Q_{20.31}$), Sahara (Q_{20} -> $Q_{22.06}$), Northern Europe (Q_{20} -> $Q_{20.24}$), North Australia (Q_{20} -> $Q_{20.60}$), North Asia (Q_{20} -> $Q_{20.46}$), South Australia/New Zealand (Q_{20} -> $Q_{20.09}$), East Canada, Greenland, Iceland (Q_{20} -> $Q_{22.03}$) and Alaska/Northwest Canada (Q_{20} -> $Q_{21.08}$) under the +1.5˚C experiment. The direction of changes in multi-model mean of low runoff is quite similar under the +2˚C experiment except for South Australia/New Zealand (Q_{20} -> $Q_{19.48}$) and West Africa (Q_{20} -> $Q_{19.97}$). Relative to the 2˚C warming target, a 1.5˚C warming target is more likely to reduce drought risk triggered by low runoff conditions at both global and regional scales (except for the Southeast Asia, North Asia, Southern Europe and Mediterranean, East Canada, Greenland, Iceland and Alaska/Northwest Canada).

<Figure 3, here, thanks>

In some regions, the projections are subject to a large spread across the ensemble, e.g., East Asia, Central Asia, Central North America and Sahara. The spread owing to differences between AGCMs is evident in South Australia/New Zealand, the Northern Europe, Southern Africa and the West Africa, where AGCMs project low runoff changes are of opposite sign. However, the changes in multi-model ensemble mean of low runoff in Southern Africa (slightly decrease) under different warming periods (+1.5˚C and +2˚C experiments) also coincide with hydrological drought projected by Prudhomme *et al* (2014) using ISI-MIP experiments.

4. Projections of water shortage at low runoff conditions

To understand the societal impact of low runoff conditions, we reconcile the projections (Q_{20}) with population distribution information (see Section 2.2) in order to estimate the people affected by water shortage in the historical and future periods (Figure 4). At the water demand threshold level of 1700 m^3 $capita^{-1}$ $year^{-1}$ (Falkenmark *et al* 1989, 2013), we find that about 65% (~4.2 billion) of the global population (~6.5 billion) experience water shortage. This is close to the estimates of Mekonnen and Hoekstra (2016), which concluded that totally 4.3 billion people (4.0 billion people is facing severe water scarcity) lives under conditions of moderate to severe water scarcity at least one month per year (environmental flow requirements considered). Most of them live in the East Asia (~1.0 billion) and the South Asia (~1.1 billion); others live in the Southeast Asia (~0.2 billion), Southern Europe and Mediterranean (~0.2 billion), Central Europe (~0.2 billion), Western Africa (~0.2 billion), East Africa (~0.2 billion) and Central Asia (~0.2 billion) (Table 1).

<Figure 4, here, thanks>

Relative to the historical period, the people adversely affected by water shortage in +1.5˚C and +2˚C experiments would increase by ~0.5% (~35 millions) and ~0.7% (~48 millions) of global population, respectively. These are consistent with the expectation of elevating water stress/scarcity in a warmer climate (Liu *et al* 2017, Veldkamp *et al* 2016). The benefit of holding global warming at 1.5˚C instead of 2˚C above the pre-industrial levels is apparent in most of the regions (e.g., East Asia, South Asia, Central Europe, Western Africa and East Africa).

<Table 1, here, thanks>

From regional aggregation (Table 1), we find that more people in East Asia, South Asia, Southern Europe and Mediterranean, Central Europe and Southeast Asia would expose to the risk of water shortage under the future periods. Conversely, such risk would reduce in several regions, e.g., West Africa, West Coast South America, Alaska/Northwest Canada. Our projections suggest that stabilising temperature increase at 1.5˚C instead of 2˚C would constrain adverse impact on people suffering water shortages in most of the regions (particularly East Asia, South Asia, East Africa, Central Europe) but less effective in Southeast Asia, Alaska/Northwest Canada, few Latin America regions (Amazon, West Coast South America). Globally, we estimate this reduced risk (when limiting the warming to 1.5˚C rather than 2˚C) to be ~13 million people.

Repeating this analysis using the water demand threshold 1000 m^3 $capita^{-1}$ $year^{-1}$, we confirm that the spatial distribution (Figure S4 in Supplementary Information) of water shortage appears similar to that using 1700 m^3 $capita^{-1}$ $year^{-1}$. Whilst people affected by water shortage would reduce in the baseline as we would expect (i.e., about 3.6 billion people or 56% of global population)(Table S2 in Supplementary Information), its impact is more significant for the +1.5˚C (~44 million people above the baseline) and +2˚C experiments (~60 million people above the baseline) compared to the former case. Interestingly, at this relatively severe threshold, holding global warming at 1.5˚C instead of 2˚C would reduce the exposure to water shortage by ~16 million people (higher than but still close to that of the former case). In a sense, both thresholds confirm that there is a clear advantage of holding global warming at 1.5˚C relative to 2˚C.

5. Discussions

This study is performed using five AGCMs of HAPPI archive fulfilling our selection criteria (Section 2.1). Its experimental design enables generation of large ensembles (Mitchell *et al* 2016), making it particularly suitable for identification of changing pattern of extreme hydrological events such as droughts driven by low runoff conditions (e.g., Q_{20}, Q_{10}, Q_5). These new findings generated from HAPPI experiments supplement the drought/low flow studies prepared using earlier climate modeling archives (CMIP5, ISI-MIP) (e.g., Koirala *et al* 2014, Prudhomme *et al* 2014, Schewe *et al* 2014, Schleussner *et al* 2016). The coverage of future period here (+1.5˚C, +2˚C experiments) matches the global temperature targets of Paris Agreement (UNFCCC 2015), making it possible for international policymakers to comprehend societal impact of water shortages triggered by renewable freshwater availability below normal (e.g., low runoff) conditions on global and regional scales.

The estimates presented here are based on raw AGCMs runoffs, avoiding uncertainties due to structural weakness of low flow simulation within many existing hydrological models (see comprehensive review on pg. 375-376, Van Loon 2015). Furthermore, the need of removing warm-up period from the relatively short duration of HAPPI experiments (2006-2015, 2106-2115) makes it less preferable to apply hydrological modelling tools. The matching of percentile of AGCMs runoffs (i.e., historical period Q_{20}; percentile in the historical period for monthly runoff corresponding to the future period Q_{20}) with that of the baseline (e.g., CDR runoff) (Section 2.2) adopted here is also a form of 'distribution mapping' approach, which enables streamlining all AGCMs projections with little concern about the numerical bias of AGCMs output. Whilst this approach applies similar correction algorithm to both historical and future periods like all bias-correction approaches, comprehensive evaluation has confirmed its merit over other existing approaches (Teutschbein and Seibert 2012, Liu *et al* 2015, Liu and Sun 2017). The calculation of renewable freshwater supply at low runoff conditions here (top right panel of Figure 1) prioritised societal water requirements over the environmental water requirements below normal conditions. The calculation is conservative because it excludes the existing renewable freshwater storages (e.g., freshwater lakes, dams, reservoirs) which regulate the freshwater supply (mostly replenished during normal and above normal conditions, e.g., wet season). In a broad sense, the quantitative results here should be informative for policymakers and water managers to examine whether the current capacity and operation rules of these renewable freshwater storages would sustainably regulate the freshwater supplies to support both human and natural systems in the future period (1.5˚C, +2˚C experiments).

Estimates of water demand here made use of thresholds (e.g., 1700 m^3 $capita^{-1}$ $year^{-1}$, 1000 m^3 $capita^{-1}$ $year^{-1}$) of the Falkenmark water stress indicator. The shortcomings of this kind of water stress indicator lies in its inability to reflect local water scarcities, availability of infrastructure which modifies water supplies (e.g., dams, reservoirs, river diversion) or how representative it is for countries with differences in lifestyle and climate conditions (Rijsbermann 2006). Despite these limitations, it is commonly applied on large scale investigations (e.g., Schewe *et al* 2014, Veldkamp *et al* 2016), mainly because of its simplicity and broad account for water requirement covering household, agricultural, industrial, energy sector and the environment (Falkenmark 1989, Rijsbermann 2006). This is probably because it serves as a good proxy to gauge adequacy of water supply to meet the demand of the society on macro scales.

6. Summary

We began this manuscript by raising several questions around renewable freshwater availability below normal (e.g., low runoff) conditions with respect to the new climate change targets, its implication on the society and benefits of global warming at 1.5˚C over 2˚C (see Section 1). The newly released HAPPI experiments enable us, for the first time, to present a global assessment of changes for range of low runoff conditions (i.e., Q_{20} , Q_{10} , Q_5) and such impacts on people affected by water shortage under 1.5°C and 2°C warming scenarios. We found that the multi-model ensemble mean of low runoff would decrease in most global regions except for Northern Europe, North Australia, Northern Asia, Sahara, Eastern Canada, Greenland, Iceland and the Alaska/Northwest Canada under both 1.5˚C and 2˚C warming scenarios relative to the historical period. We confirmed the benefit of holding global warming at 1.5˚C instead of 2˚C above the pre-industrial levels, with less severe reduction in low runoff across most regions (except for Southeast Asia, Amazon, West Coast South America and the Alaska/Northwest Canada) and the globe. These results are insensitive to the selected thresholds of low runoff. At the low runoff conditions Q_{20}, our estimation suggested that approximately 65% of the global population suffered from water shortage (at water demand threshold of 1700 m^3 $capita^{-1}$ $year^{-1}$) in the baseline period (1984-2010), who mainly lived in East Asia and South Asia. The situations were projected to be more severe in 1.5˚C and 2˚C warming worlds. By stabilising warming to below 1.5˚C instead of 2˚C, the number of people affected by water shortage at low runoff conditions would be lesser in many regions, i.e., East Asia, South Asia and the Central Europe. We found our projections insensitive to alternative water demand threshold (e.g., 1000 m^3 $capita^{-1}$ $year^{-1}$). These findings addressed the questions raised earlier and should provide science-based evaluation on the benefit of holding 1.5˚C warming (in water sector) and inform climate policy in the upcoming IPCC special report on "Global warming of 1.5˚C" in 2018. Future efforts involving population growth (e.g., Shared Socioeconomic Pathways), hydrologic simulation (when low flow simulation technique advances) and water infrastructure (e.g., dams, reservoirs, river diversion canals) at finer scales would help addressing the local climate adaptation and water management strategies.

Acknowledgements

The research was supported by the National Key Research and Development Program of China (2016YFA0602402 and 2016YFC0401401), the Key Research Program of the

Chinese Academy of Sciences (ZDRW-ZS-2017-3-1), the National Science Foundation of China (41401037 and 41330529), the Open Research Fund of State Key Laboratory of Desert and Oasis Ecology in Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences and the CAS Pioneer Hundred Talents Program (Fubao Sun). WHL acknowledge funding support from the CAS President's International Fellowship Initiative (2017PC0068). HS was supported by Integrated Research Program for Advancing Climate Models. We thank all our colleagues involving in HAPPI experiments.

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Table and Figure captions:

Table 1: Impact of low runoff conditions Q_{20} induced water shortage (water demand threshold: 1000 m^3 $capita^{-1}$ yr^{-1}) on population (constant 2005): the baseline (1984-2010), +1.5˚C minus historical experiments $\Delta(fut_{+1.5}\text{-}his)$, +2˚C minus historical experiments $\Delta(fut_{+2.0}\text{-}his)$ and +1.5˚C minus +2˚C experiments $\Delta(fut_{+1.5}\text{-}fut_{+2.0})$. The estimates of affected population (absolute number and percentage of population) are presented on regional and the global scales. The +/- sign represents favorably/adversely affected population.

Figure 1: A schematic overview of overall methodology and workflow of this study (details in Section 2).

Figure 2: Multi-model ensemble mean percentile in the historical period for monthly runoff corresponding to the future period Q_{20} (i) and model consistency (ii) on a spatial resolution of 0.5˚ x 0.5˚ for: (a) +1.5˚C experiment, (b) +2˚C experiment and (c), (a) minus (b). The percentile <Q20 (>Q20) indicates that magnitude of the future period Q_{20} would become drier (wetter). Robustness of projections increases with higher model consistency and vice-versa. Legend in (a)(i) applies to (b)(i); legend in (a)(ii) applies to (b)(ii) and (c)(ii).

Figure 3: Multi-model percentile in the historical period for monthly runoff corresponding to the future period Q_{20} in different regions (a) for: (b) +1.5˚C experiment, (b) +2˚C experiment and (c), (a) minus (b). The color bar in (b)-(d) shows the multi-model maximum (blue), multi-model minimum (red) and multi-model ensemble mean (the dividing line between blue and red colors). The percentile <Q20 (>Q20) indicates that magnitude of the future period Q_{20} would become drier (wetter). Legend in (b) applies to (c) and (d).

Figure 4: Spatial-distribution of people affected by low runoff conditions Q_{20} induced water shortage (water demand threshold: 1700 m^3 $capita^{-1}$ yr^{-1}): (a) the baseline (1984-2010), (b) +1.5˚C experiment minus the historical period, (c) +2˚C experiment minus the historical period and (d), (b) minus (c). Estimated based on population data that is consistent with the World Bank (constant 2005). Legend in (a) applies to all panels.

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Label*	Population (constant 2005) [million]	Affected population (water demand threshold: 1700 m^3 $capita^{-1}$ yr^{-1})							
		Baseline		$\Delta(fut_{+1.5}\text{-}his)$		$\Delta(fut_{+2.0}\text{-}his)$		$\Delta(fut_{+1.5}\text{-} fut_{+2.0})$	
		[million]	%	[million]	%	[million]	%	[million]	%
ALA	0.6	-0.40	-66.67	+0.02 ± 0.01	+3.60 ± 1.66	+0.04 ± 0.01	+6.55 ± 2.16	-0.02 ± 0.01	-2.95 ± 1.18
AMZ	67.4	-21.00	-31.16	-0.45 ± 0.22	-0.66 ± 0.81	-0.35 ± 0.79	-0.52 ± 1.17	-0.10 ± 0.48	-0.14 ± 0.71
CAM	180.9	-100.20	-55.39	-0.53 ± 0.41	-0.29 ± 0.23	-1.06 ± 0.89	-0.59 ± 0.49	+0.53 ± 0.58	+0.29 ± 0.32
CAS	183.9	-153.10	-83.25	-1.02 ± 0.79	-0.56 ± 0.43	-1.25 ± 0.82	-0.68 ± 0.45	+0.23 ± 0.09	+0.13 ± 0.05
CEU	366.6	-237.30	-64.73	-1.71 ± 2.67	-0.47 ± 0.73	-3.63 ± 2.72	-0.99 ± 0.74	+1.92 ± 0.65	+0.52 ± 0.18
CGI	0.8	-0.20	-25.00	+0.00(2) ± 0.01	+0.20 ± 0.81	+0.00(0) ± 0.01	-0.05 ± 0.89	+0.00(2) ± 0.00	+0.25 ± 0.45
CNA	103.0	-41.70	-40.49	-0.43 ± 0.28	-0.42 ± 0.27	-0.53 ± 0.24	-0.52 ± 0.24	+0.10 ± 0.25	+0.10 ± 0.25
EAF	261.7	-178.10	-68.06	+0.01 ± 1.47	+0.00(3) ± 0.56	-1.00 ± 1.79	-0.38 ± 0.68	+1.00 ± 0.50	+0.38 ± 0.19
EAS	1498.8	-1010.50	-67.42	-12.44 ± 3.11	+0.83 ± 0.21	-15.68 ± 5.49	-1.05 ± 0.37	+3.23 ± 3.01	+0.22 ± 0.20
ENA	148.4	-58.00	-39.08	-0.64 ± 0.58	-0.43 ± 0.39	-1.04 ± 0.60	-0.70 ± 0.40	+0.40 ± 0.28	+0.27 ± 0.19
MED	366.2	-235.20	-64.23	-2.06 ± 1.57	-0.56 ± 0.43	-2.18 ± 2.16	-0.59 ± 0.59	+0.11 ± 0.92	+0.03 ± 0.25
NAS	82.4	-50.40	-61.10	-0.12 ± 0.43	-0.15 ± 0.52	-0.36 ± 0.63	-0.44 ± 0.77	+0.24 ± 0.25	+0.29 ± 0.30
NAU	5.2	-1.60	-30.77	-0.04 ± 0.04	-0.73 ± 0.73	-0.04 ± 0.04	-0.82 ± 0.70	+0.00(5) ± 0.01	+0.09 ± 0.27
NEB	75.9	-40.50	-53.36	-0.53 ± 0.73	-0.70 ± 0.96	-0.77 ± 0.97	-1.01 ± 1.27	+0.24 ± 0.37	+0.31 ± 0.49
NEU	116.5	-59.40	-50.99	-0.43 ± 0.65	-0.37 ± 0.56	-0.79 ± 0.52	-0.67 ± 0.45	+0.36 ± 0.33	+0.31 ± 0.28
SAF	137.4	-89.20	-64.92	-0.38 ± 0.48	-0.27 ± 0.35	-0.56 ± 0.66	-0.41 ± 0.48	+0.18 ± 0.42	+0.13 ± 0.31
SAH	57.3	-53.80	-93.89	+0.01 ± 0.08	+0.0 1± 0.13	-0.04 ± 0.07	-0.06 ± 0.13	+0.04 ± 0.02	+0.07 ± 0.04
SAS	1356.6	-1118.60	-82.46	-5.46 ± 3.41	-0.40 ± 0.25	-7.98 ± 3.73	-0.59 ± 0.28	+2.52 ± 2.54	+0.19 ± 0.19
SAU	20.0	-11.50	-57.50	-0.03 ± 0.11	-0.14 ± 0.54	-0.07 ± 0.11	-0.36 ± 0.56	+0.04 ± 0.05	+0.22 ± 0.25
SSA	143.3	-67.20	-46.89	-0.72 ± 0.27	-0.50 ± 0.19	-1.14 ± 0.25	-0.79 ± 0.18	+0.41 ± 0.10	+0.29 ± 0.07
SEA	510.6	-232.90	-45.61	-9.11 ± 3.02	-1.78 ± 0.59	-8.68 ± 3.39	-1.70 ± 0.66	-0.43 ± 1.92	-0.08 ± 0.38
TIB	72.3	-61.80	-85.48	-0.20 ± 0.22	-0.27 ± 0.31	-0.27 ± 0.24	-0.38 ± 0.33	+0.08 ± 0.09	+0.11 ± 0.12

WAF	338.8	-157.60	-46.52	+2.16 ± 1.35	+0.64 ± 0.40	+0.92 ± 1.22	+0.27 ± 0.36	+1.24 ± 1.12	+0.37 ± 0.33
WAS	182.5	-139.80	-76.60	-0.71 ± 0.43	-0.39 ± 0.24	-0.94 ± 0.41	-0.52 ± 0.23	+0.24 ± 0.25	+0.13 ± 0.14
WNA	79.1	-58.90	-74.46	-0.18 ± 0.26	-0.23 ± 0.32	-0.23 ± 0.36	-0.29 ± 0.45	+0.04 ± 0.14	+0.05 ± 0.17
WSA	51.5	-27.70	-53.79	+0.02 ± 0.12	+0.03 ± 0.23	+0.04 ± 0.14	+0.08 ± 0.26	-0.02 ± 0.06	-0.04 ± 0.12
GLOBE	6451.00	-4220.30	-65.42	-35.04 ± 11.98	-0.54 ± 0.19	-47.89 ± 14.75	-0.74 ± 0.23	+12.84 ± 5.25	+0.20 ± 0.08

*ALA: Alaska/Northwest Canada, AMZ: Amazon, CAM: Central America and Mexico, CAS: Central Asia, CEU: Central Europe, CGI: East Canada, Greenland, Iceland, CNA: Central North America, EAF: East Africa, EAS: East Asia, ENA: East North America, MED: Southern Europe and Mediterranean, NAS: North Asia, NAU: North Australia, NEB: Northeastern Brazil, NEU: Northern Europe, SAF: Southern Africa, SAH: Sahara, SAS: South Asia, SAU: South Australia/New Zealand, SSA: Southeastern South America, SEA: Southeast Asia, TIB: Tibetan Plateau, WAF: West Africa, WAS: West Asia, WNA: West North America, WSA: West Coast South America, GLOBE: Globe (excluding Antarctica).

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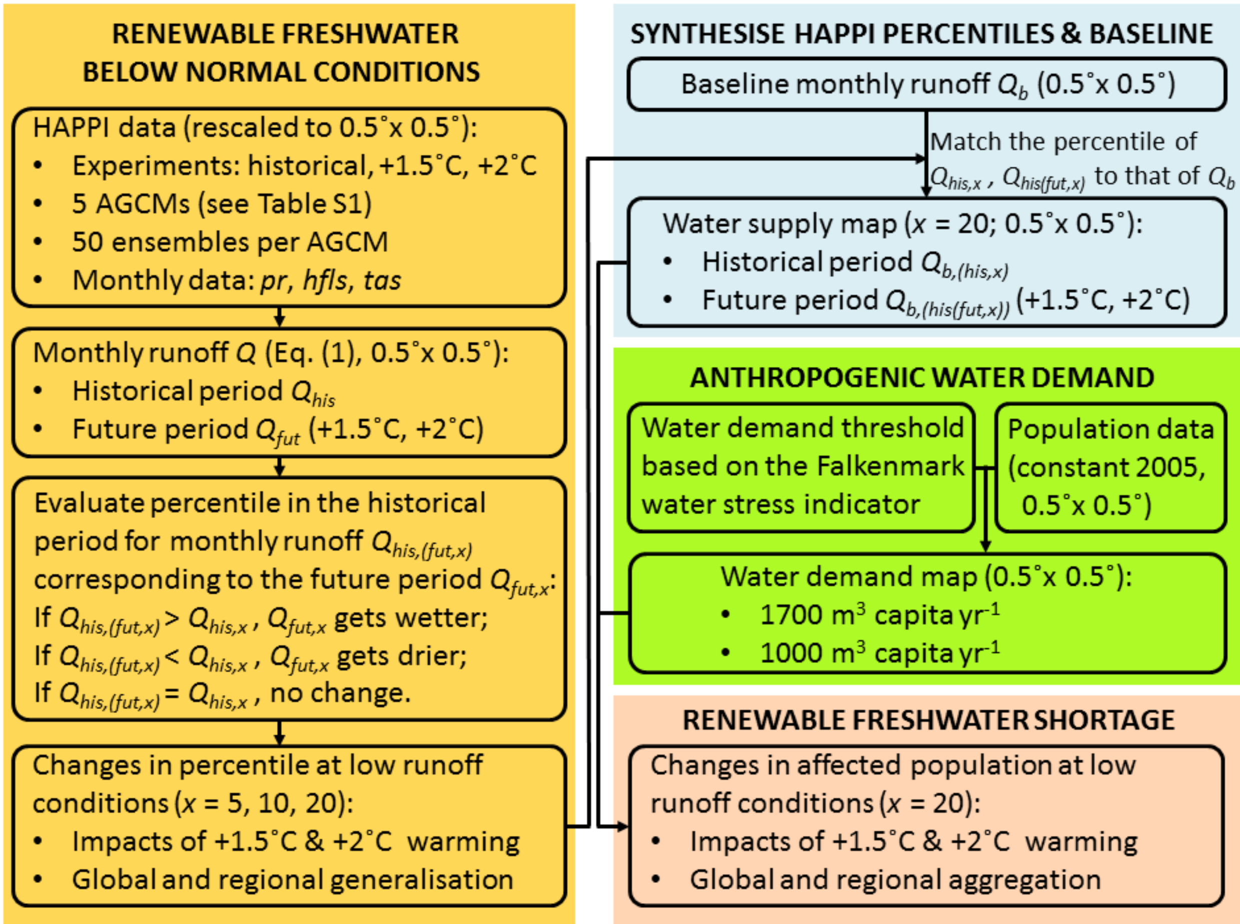

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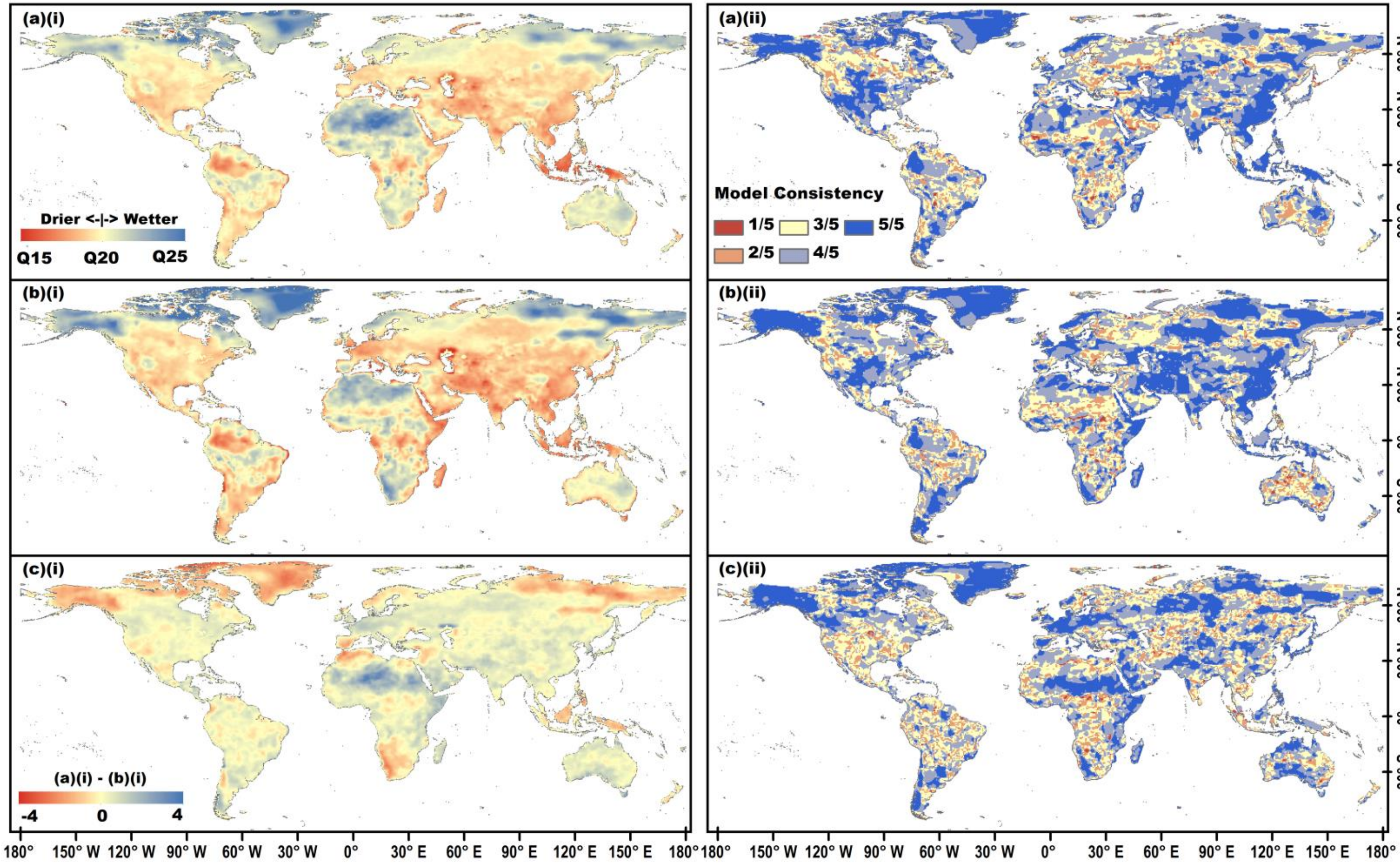

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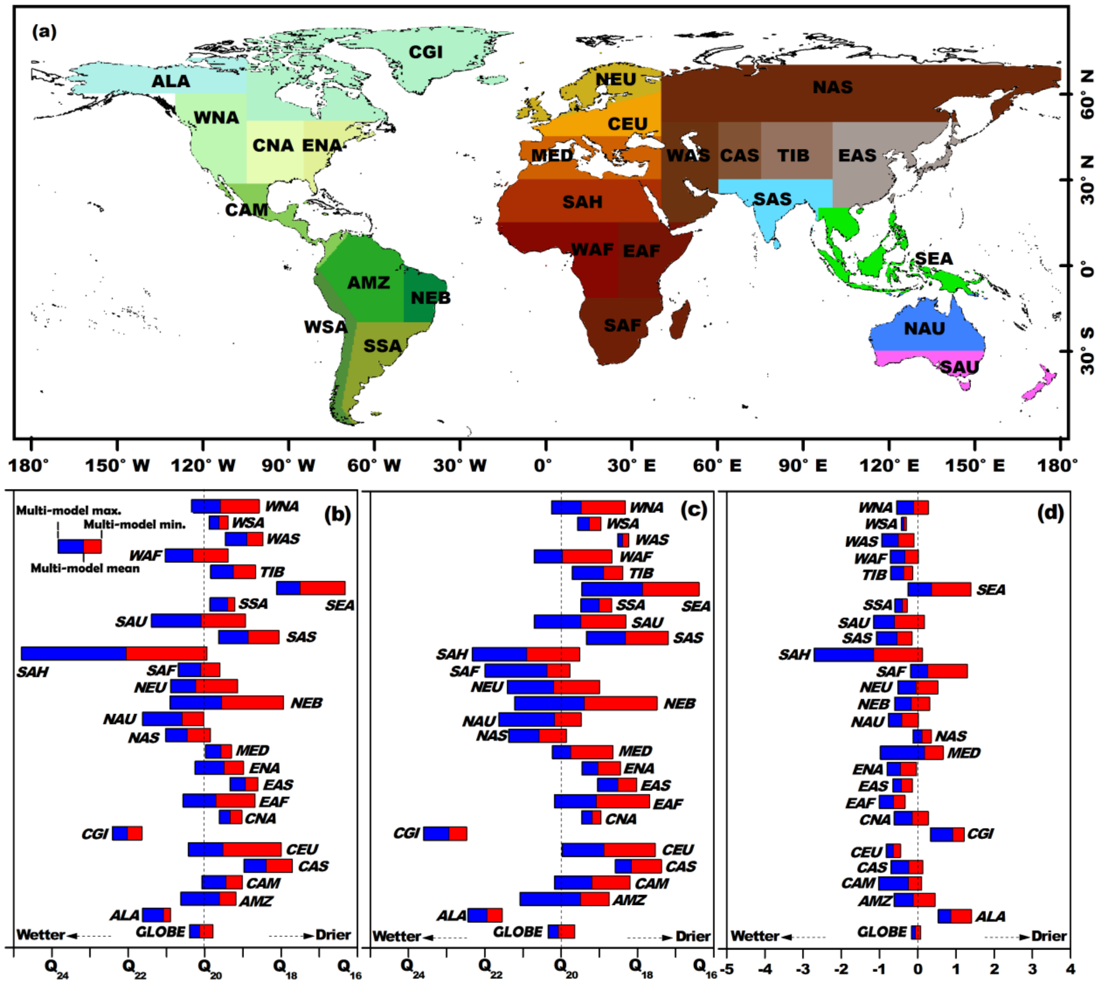

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