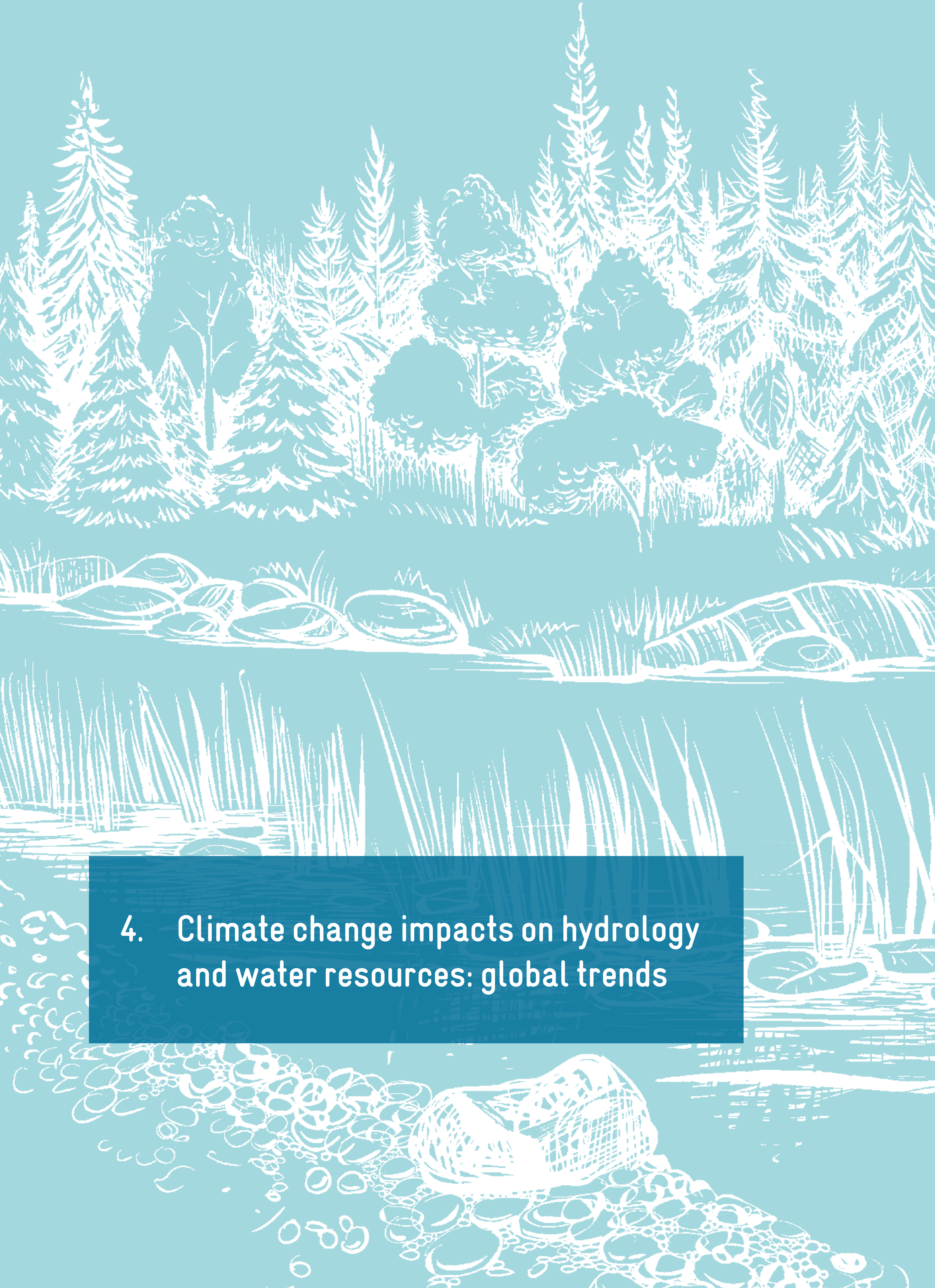


4. Climate change impacts on hydrology and water resources: global trends

The determination of certain impacts on water resources due to climate change remains one critical challenge for the water sector now and in the future. A broader scientific understanding of what is known and what is unknown with respect to global trends is needed. Therefore, this chapter will reflect on potential temperature and precipitation alterations and associated consequences of their interplay. It will also show that some trends – particularly those concerning precipitation – are not easy to determine, resulting in a variance of possible future changes. The chapter continues with a discussion of projected global trends in temperature and precipitation until the end of the century.

Lastly, an analysis of associated climate impacts on water resources and hydrological extremes (floods and droughts) is performed.

Key Messages of Chapter 4

- **The water cycle is an essential part of the climate system, and therefore very sensitive to climate variability and change. Empirical evidence shows that seemingly insignificant variations in climate patterns often lead to significant changes in hydrological flows and regional water availability.**
- **While most GCM projections agree regarding an expected increase in temperature, the direction of the precipitation trend (negative or positive) is unclear for large parts of the world.**
- **Temperature rise leads to enhanced evapotranspiration, potentially increasing pressure on local water resources – even in regions with increasing amounts of precipitation.**
- **Climate change might lead to a severe decrease in water availability: An additional 40% of people might suffer from absolute water scarcity due to the impacts of climate change at a global warming of 2°C above present, compared with the effects of population growth alone.**
- **Trends in hydro-climatic extremes and climate variability can be more robust (higher model agreements) with regard to their trend direction, often indicating an increase in droughts.**
- **In some regions, groundwater storage has the potential to reduce the pressure on surface water resources, if withdrawals stay below recharge rates. However, groundwater storage is also affected by a changing climate, thus, expected impacts on renewable groundwater resources can be significant.**

4.1 Trends in global temperature and precipitation

The following simulations on temperature and precipitation build upon the consideration of RCPs, which were introduced in the previous chapter. Based on RCP2.6 and RCP8.5, the simulations show that there is little disagreement regarding temperature increases simulated by different Global Climate Models (GCMs) under specific scenario conditions. However, similar agreement on trend direction is not perceivable regarding precipitation changes. Consequently, there is much more variability and uncertainty in projecting precipitation trends. *Figures 5 on the right* and *Figure 6 on page 46* provide more detail on mean temperature and precipitation trends until the end of the century, based on RCP2.6 and RCP8.5.

➔ *The direction of the precipitation trend (less or more precipitation) is unclear for large parts of the world.*

For only about 66% of land surface area, at least 80% of precipitation projections agree on the direction of the trend under high-GHG concentration conditions (RCP8.5, *see Figure 5 on the next page* under low-concentration conditions (RCP2.6, *see Figure 6 on page 46*), similar levels of agreement can only be seen for 19% of the land surface area. Nevertheless, an increase in precipitation dominates generally for both scenarios. However, many of the world's largest river basins are located in regions in which precipitation trends do not match up in magnitude, or even show opposing trends, for example the Niger or the Amazon (*see Chapter 5*).

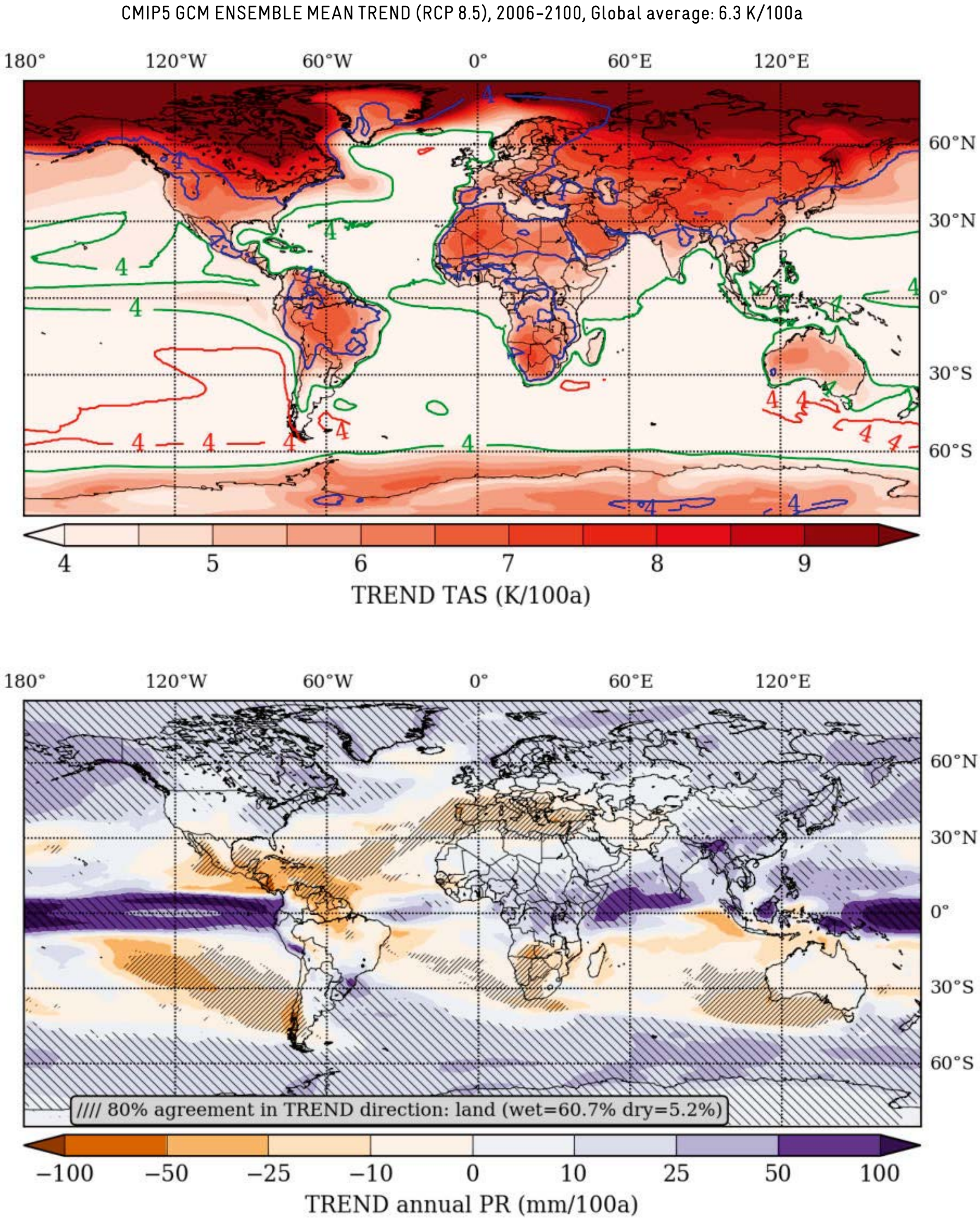
➔ *Overall, if climate change is kept at a moderate level, impacts on precipitation will be less pronounced.*

Regardless of these challenges associated with the determination of trends, a general statement in terms of prospective alterations is possible: Impacts on temperature and precipitation are expected to be less pronounced if climate change is kept at a moderate level, that is, if it follows an RCP2.6 concentration scenario, instead.

In addition, further global key trends on temperature and precipitations can be observed:

- By the end of the century, the global temperature might increase by another 1°C compared to the current state under the most optimistic projections (RCP2.6), and by another 6°C in the most pessimistic scenario (RCP8.5).
- In general, a temperature increase is more distinct in high latitudes and high mountain and dryland areas, and less pronounced in the tropics and over water surfaces.
- Precipitation trends are mostly positive due to the intensification of the water cycle, as more radiative forcing leads to more energy in the hydro-climatic system.
- Higher precipitation does not necessarily translate into enhanced water availability, because more precipitation can be compensated by an increase in evapotranspiration reinforced by warmer temperatures.

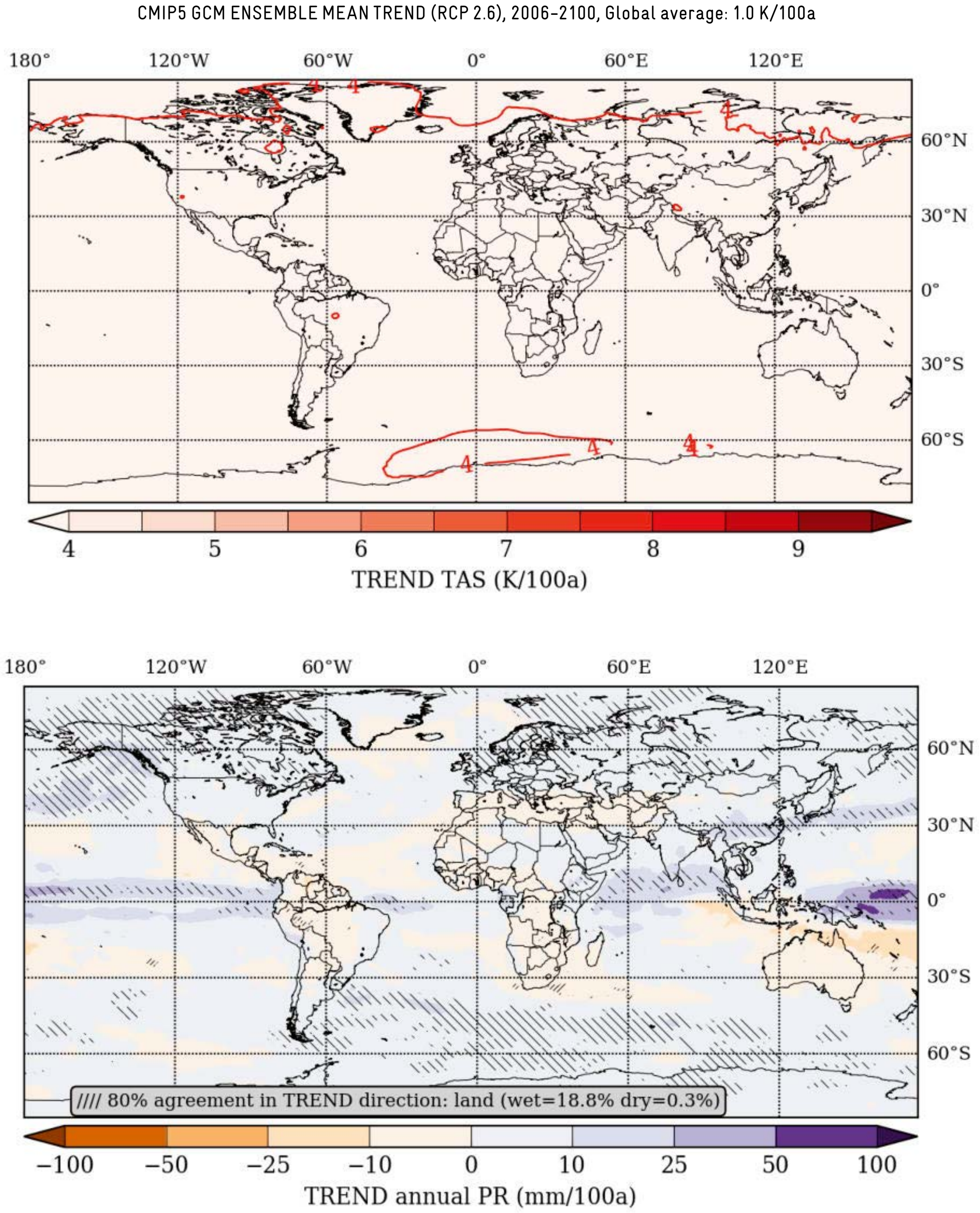
➔ *To enhance datasets, a combination of in situ and remote sensing assessments is needed. Available data should be integrated into databases with user-friendly interfaces.*



CMIP5 GCM ENSEMBLE MEAN TREND (RCP 8.5), 2006-2100, Global average: 6.3 K/100a

In the upper graphic, green lines encircle areas, for which the mean of the model ensemble projects a warming rate of 4 K / 100a, while red and blue lines refer to the single warmest and coldest model of the ensemble. In the lower graphic, shaded areas indicate where at least 80% of the model ensemble agrees in the direction of the trend (\\\ indicates positive, /// negative trend).

Figure 5: Mean trend in average annual temperature and average annual precipitation until the end of this century under RCP8.5 (high radiative forcing and temperature increase) (Data processed at Potsdam Institute for Climate Impact Research).



Same illustration features as *Figure 5*

Figure 6: Mean trend in average annual temperature and average annual precipitation until the end of this century under RCP2.6 (low radioactive forcing and temperature increase) – Data processed at Potsdam Institute for Climate Impact Research.

4.2 Global-scale trends in per capita water availability

From a global perspective, a key takeaway of most reports and publications on climate change impacts on water is that climate change might eventually lead to a severe decrease in water availability, thereby increasing the number of people living under absolute water scarcity (see, for example, IPCC, 2013; World Bank, 2014).

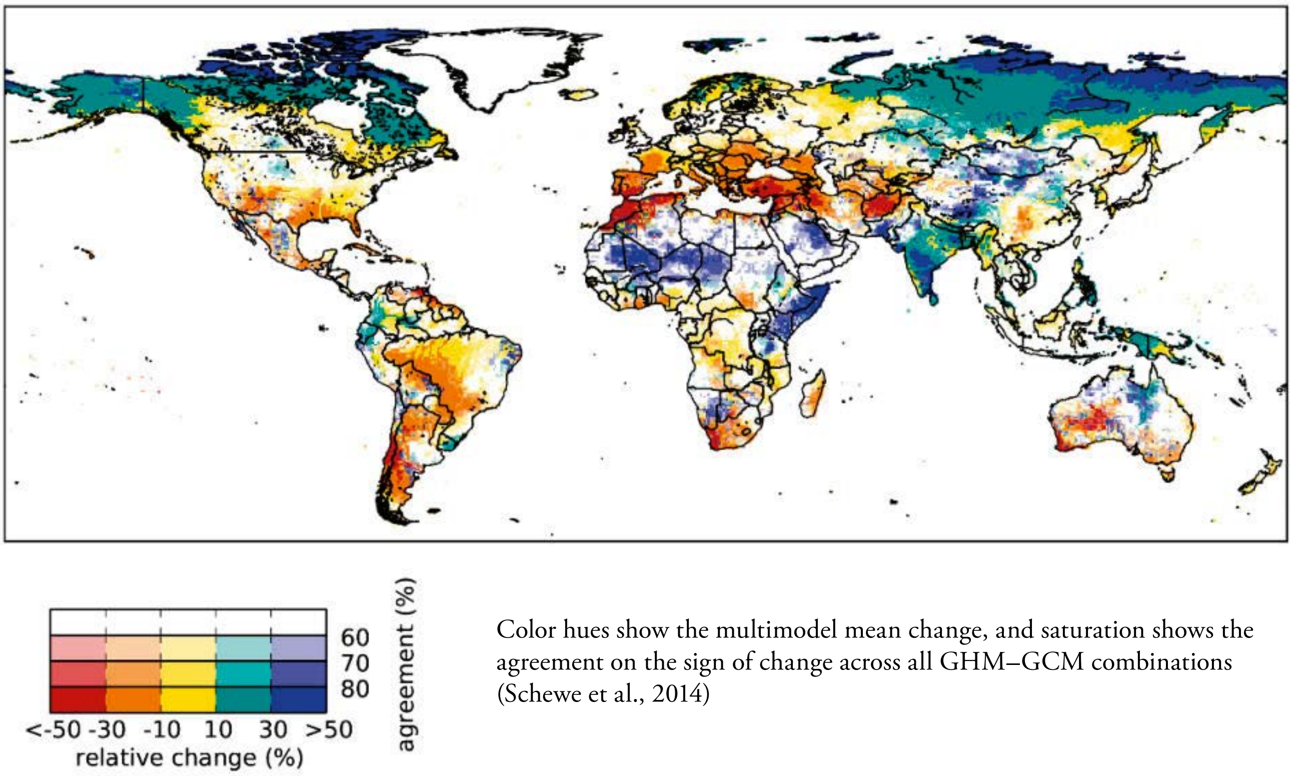
A comprehensive global assessment of future water availability that considers changing water demand due to population growth under climate change is presented in Schewe et al., 2014. The authors use a large ensemble of GHMs provided by the ISIMIP project, which were driven by five GCMs and the RCPs to synthesize current knowledge on climate change impacts on water resources and availability. Population dynamics were considered according to the Shared Socioeconomic Pathways (SSPs).

➔ ***An additional 40% of people might suffer from absolute water scarcity due to the impacts of climate change at a global warming of 2°C above present.***

Their model ensemble average projects that a global warming of 2°C above present (approximately 2.7°C above preindustrial) conditions will mean that an additional 15% of the global population might face a severe decrease in water resources, and that 40% more people might live under absolute water scarcity (< 500 m^3 per capita per year) compared with the effect of population growth alone (ibid.). In the event of unmitigated climate change beyond 2°C, the negative impacts are even more profound. This is in line with the findings of other recent publications (see e.g. Döll et al., 2018).

In conclusion, climate change – in combination with expected future population growth – might significantly increase the pressure on available water resources on a global scale. Therefore, climate change is expected to exacerbate water scarcity in many regions worldwide (*see Figure 7*).

Nonetheless, current research highlights large uncertainties associated with such estimates on future conditions, as already discussed in the previous chapter (*see Chapter 3.2 and Figure 3*).



Color hues show the multimodel mean change, and saturation shows the agreement on the sign of change across all GHM–GCM combinations (Schewe et al., 2014)

Figure 7: Relative change in per capita water availability when 2°C temperature increase is reached, compared with present-day temperatures, under RCP8.5.

➔ ***Groundwater storage is affected by a changing climate, thus, expected impacts on renewable groundwater resources can be substantial.***

The impacts of climate change on renewable groundwater resources are expected to be significant (Portman et al., 2013). To date, several investigations have been undertaken at different geographical locations and at different spatial scales to assess the vulnerability of groundwater resources to the direct and indirect impacts of climate change. However, researchers still know little about the impacts of climate change on groundwater recharge, and regional projections are uncertain (Aslam et al., 2018).

Groundwater resources have the potential to reduce the impact of surface water deficits by providing water, for instance, for domestic or agricultural use when surface water is insufficiently available (Kundzewicz and Döll, 2009). For regions with enough consumable (e.g. fresh and high-quality) groundwater, groundwater resources provide a secure source of water, so long as the amount withdrawn is less than the level of groundwater recharge.

According to Kundzewicz and Döll (2009), withdrawals are likely to increase in areas where surface water becomes scarcer (including as a result of climate change), thus decreasing consumable groundwater resources, such as in northeastern Brazil, southwestern Africa, and the Mediterranean region. In addition, overpumping and sea level rise may contribute to saltwater intrusion, thereby limiting the usability of groundwater resources in coastal regions. Already today, groundwater storage is of strategic importance to global water and food security. Its role will probably become even more important under climate change, as more frequent and intense climate extremes (droughts and floods) are associated with an increase in the variability of precipitation, and consequently, surface water availability (Taylor et al., 2013).

Reducing GHG emissions would incur substantial benefits to renewable groundwater resources. Estimates show that the share of the population suffering from water scarcity due to moderately decreasing groundwater recharge by the end of the century is 24% under RCP2.6, compared with 38% under RCP8.5. At the same time, the share of the population spared from any significant changes in groundwater recharge would be 47% (RCP2.6) compared with 29% (RCP8.5) (Portmann et al., 2013). Despite this correlation between GHG concentrations and groundwater recharge, projection uncertainties remain significant, and depend on socio-economic aspects. However, one robust result of Portmann et al. across all employed GCMs is that severe decreases of groundwater recharge (more than 30%) would especially affect dryland regions and, therefore potentially aggravate droughts.

4.3 Global-scale trends in droughts

Climate change will almost certainly lead to an increase in water shortages and severe droughts at the global level (IPCC, 2013; World Bank, 2014; Döll et al., 2018). An ISIMIP- related study by Prudhomme et al. (2014) investigates droughts (defined here as runoff shortage, e.g., instances in which total runoff remains below a given threshold), their hotspots, and related uncertainties. The authors projected a likely increase in the frequency of droughts for most parts of the globe by the end of the twenty-first century, with effects being more pronounced under higher emission scenarios (*see Figure 8*). In addition, nearly half of the considered model simulations under RCP8.5 projected that hydrological droughts could exceed more than 40% of the analysed land area.

➔ ***Some water-scarce areas might experience even more profound water insecurity in the future due to climate change impacts.***

The robustness of the multi-model ensemble, i.e. the degree to which the models agree in their projections, varies across the globe. While for most regions there is a high degree of uncertainty in the projections, some areas with more robust results can be identified. This includes the Mediterranean area, the Middle East, the southeastern United States, Chile, and southwestern Australia – all possible hotspots for a future increase in days under hydrological drought conditions (Prudhomme et al., 2014). Consequently, profound water security issues may arise in some regions that already suffer from droughts. The extent of associated climate impacts will depend in part on water governance structures and regionally specific adaptation options *(see Chapters 5 and 6)*.

Moreover, there are also some regions in which the number and/or severity of droughts may decrease, for example in parts of eastern Africa, Siberia, and the northernmost region of North America (*see Figure 8*). This can possibly be explained by the increase in precipitation in these areas; still, projections remain associated with a high degree of uncertainty (Liersch et al., 2018).

Year mean change

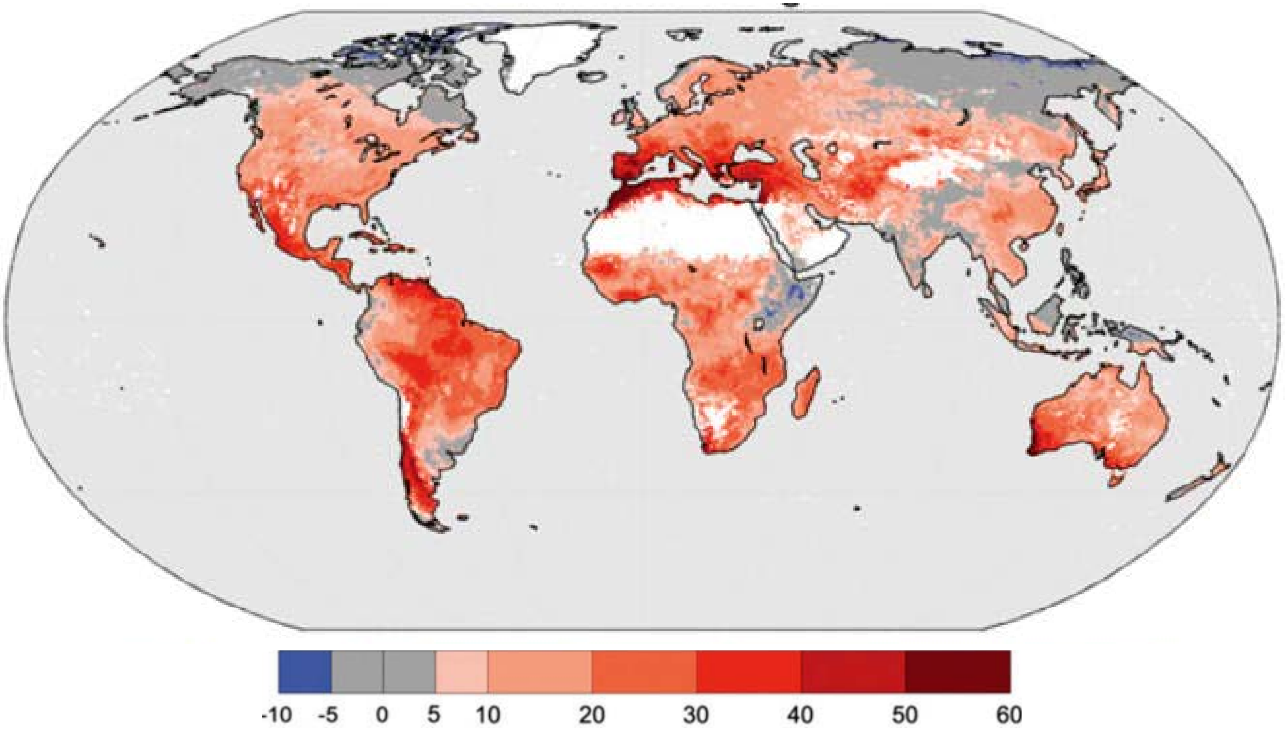


Figure 8: Percentage change of the number of days under hydrological drought conditions for the period 2070–2099 relative to 1976–2005. The figure shows the average of a multimodel ensemble under RCP8.5, with five GCMs and seven GHMs (Courtesy Prudhomme et al., 2014)

Q30 mean change

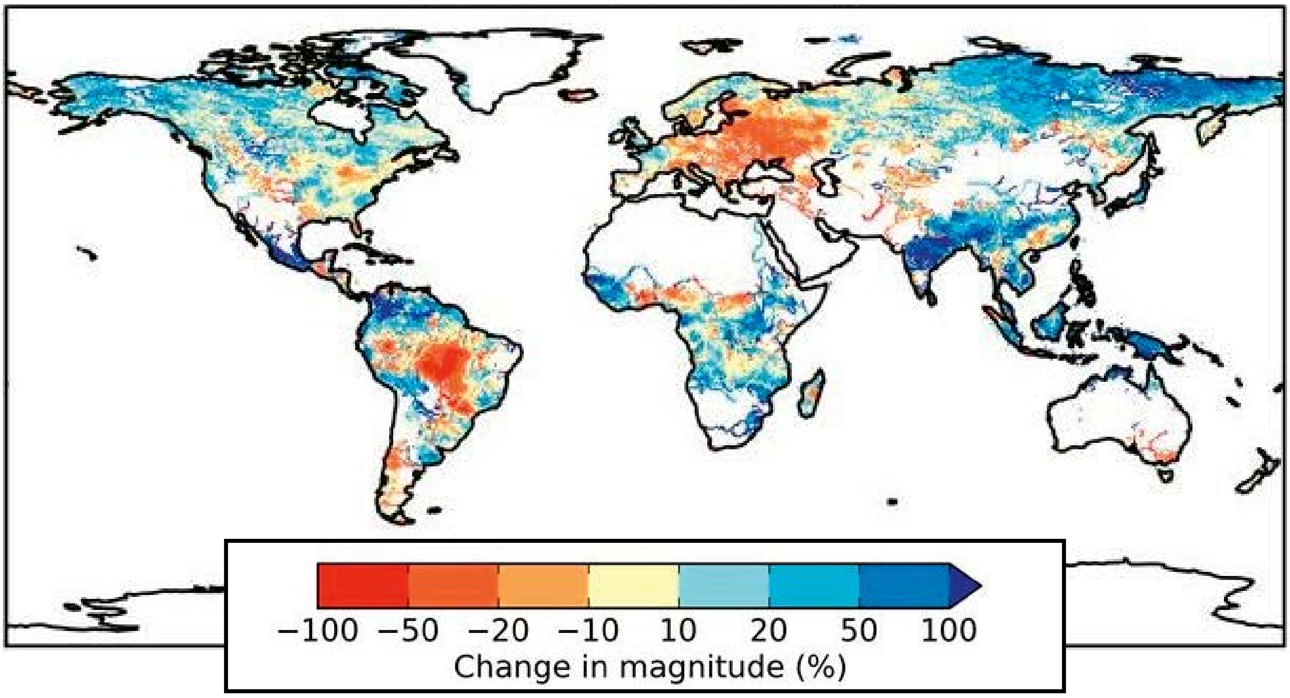


Figure 9: Global changes in discharge levels of moderate floods occurring, on average, every 30 years (Q30) in 2070–2099 under RCP8.5, compared with 1971–2000 (Courtesy of Dankers et al., 2014)

4.4 Global-scale trends in floods

Recent research suggests that climate change will lead to an increase in flood hazards globally (Hirabayashi et al., 2013; Dankers et al., 2014; Willner et al., 2018). Changes in flood hazards-based on ISIMIP simulations – are shown in *Figure 9 on the previous page*, obtained from Dankers et al. (2014). In their analysis, the authors looked at five-day peak flow levels occurring, on average, every 30 years (a quantifier for a moderate flood), and quantified changes in this flood level until the end of the twenty-first century under the RCP8.5 scenario.

From a regional perspective, climate change will not increase flood hazards everywhere. In fact, decreases in the magnitude and frequency of floods occur on roughly one-third (20-45%) of global land surface, particularly in areas where floods are generated mainly through spring snow melts. In most of the model runs, however, an increase in 30-year flood magnitudes was found for more than half of the globe.

An increase in flood hazard does not necessarily lead to an equal increase in flood risk. Flood risk is the combination of flood hazard and exposure and, as such, regions with only moderate flood hazards but high exposure (e.g. large cities in low-lying, flood-prone areas) exhibit a large flood risk, and vice-versa. Willner et al. (2018) used the results of the ISIMIP GHMs to calculate the increase in flood protection that is required to keep river flood risk at present levels. They analysed how flood hazards and, consequently, the required adaptation efforts evolve due to climate change, in comparison to the present state. The analysis was carried out worldwide for sub-national administrative units. They report that strong adaptation efforts are required in (most of) the United States, Central Europe, northeastern and western Africa, and large parts of India and Indonesia. Thus, the need for adaptation against increasing river floods is a global problem, affecting both industrialised and developing countries.

As mentioned before, flood projections by GHMs are associated with strong uncertainty, mostly because both GCMs and GHMs often have problems reproducing the relevant features that lead to flooding (Kundzewicz et al., 2017). For example, the projections presented in Dankers et al. (2014), which use a combination of GCMs and GHMs, show ambivalent trends of moderate floods for Central Europe. However, the projections by Hattermann et al. (2018), which use an ensemble of regional climate models in combination with RHMs, show stronger and mostly positive trends for the same region.

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