Stockholm University

Master Thesis

Degree Project in
Climate Science 30 hp

The spatio-temporal evolution of groundwater-dependent precipitation

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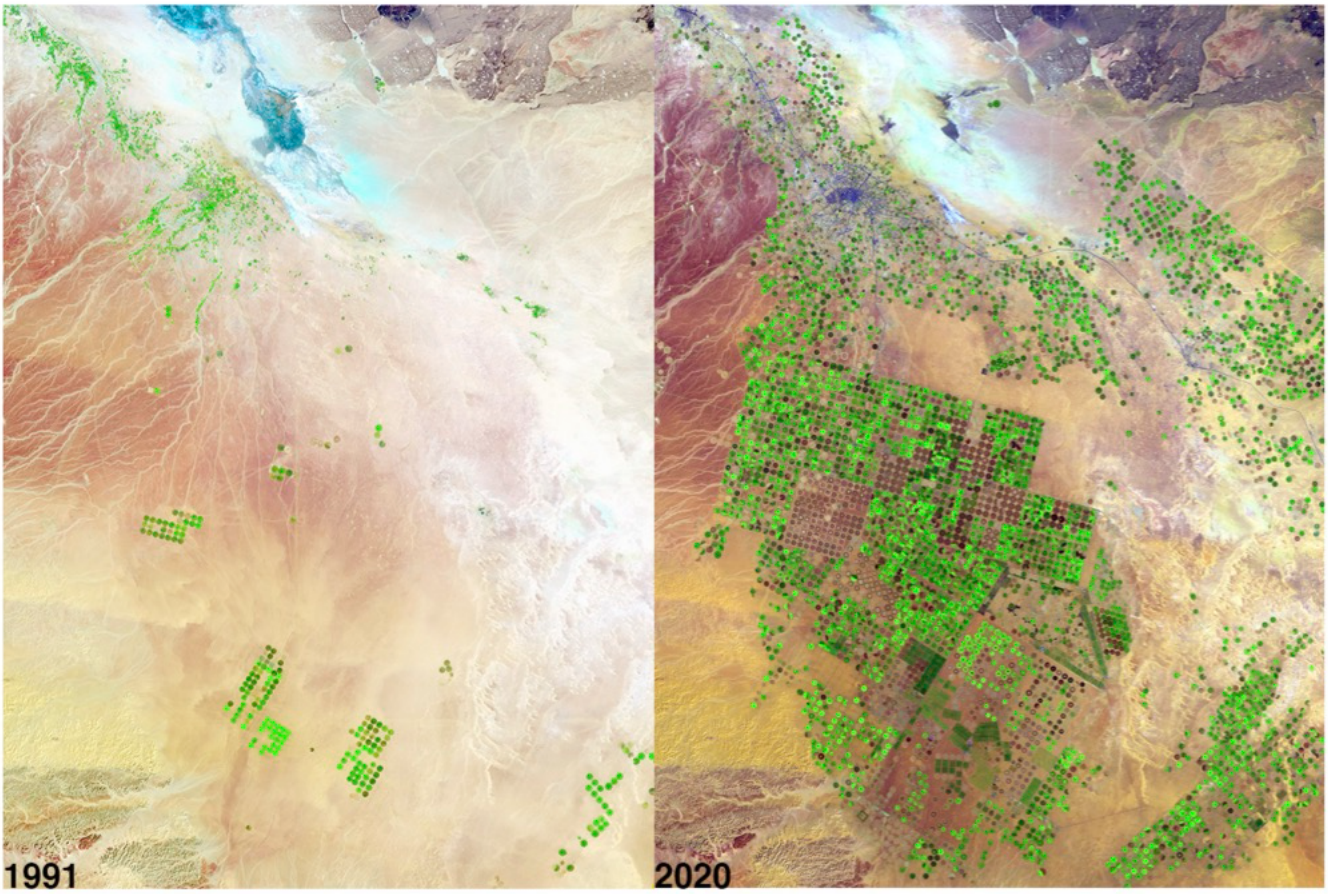

Stockholm 2021

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Abstract

A substantial portion of groundwater abstracted from aquifers is used for irrigation and evaporated to the atmosphere, contributing towards downwind precipitation over both land and ocean. While the fate of evaporation fluxes from land have been analysed, the atmospheric pathways of evaporation originating from groundwater abstraction have not yet been globally quantified. This study analysed the geographical distribution, the seasonality and the magnitude of groundwater-dependent precipitation (P_{gw}) at a global scale and for a selection of countries and river basins. The Eulerian moisture tracking WAM-2layers model was used to process meteorological and groundwater abstraction input data from 1980 to 2010. Results show considerable contributions of groundwater to precipitation downwind of the most heavily irrigated areas, leading to net groundwater losses over these areas. Globally, 40% of the P_{gw} precipitates directly in the oceans, and do not contribute to biomass production in terrestrial ecosystems. Some of the countries with the highest rates of groundwater abstraction (India, the USA, Pakistan and Iran), receive low volumes of P_{gw} and are net losers of groundwater resources. The countries with the highest net gain of groundwater are China, Canada and Russia. At river basin scale, the Indus, Ganges and Mississippi basins are net losers of groundwater to downwind P_{gw}, while the Yangtze, Tarim and Brahmaputra basins receive more P_{gw} than their groundwater withdrawals. The share of precipitation that originates from groundwater varies considerably with seasons, and can be especially high when low local precipitation levels occur in combination with high upwind groundwater abstraction. Furthermore, precipitation dependence on groundwater (ρ_{gw}), has steadily increased between 1980 to 2010 in all studied areas and globally. Our study suggests that the countries and basins with a high and increasing dependency on P_{gw} to support their precipitation can potentially be vulnerable to groundwater availability upwind.

Acknowledgements

I would like to express my most sincere gratitude to my supervisor Lan Wang-Erlandsson for the opportunity to work on this project and for all her time, patient support and guidance. I will forever cherish her teachings and encouragement. I am also deeply grateful for my co-supervisor Agnes Pranindita for all her support, her passionate participation and input. Further, I would like to thank my co-supervisor Yoshihide Wada for his time and insightful feedback. In addition, I would like to acknowledge my study director and co-supervisor Agatha de Boer for all her valuable guidance throughout my studies and direction to successfully complete my dissertation.

Finally, I am also very thankful to my family and friends for always being there for me. I dedicate this achievement to my parents, that despite the distance they made me feel their love and support at all times.

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1 Introduction

1.1 Background

1.1.1 Increasing agricultural demand for groundwater abstraction

Agriculture is by far the largest consumer of freshwater in the world. While agriculture is primarily supplied by rainwater (green water), irrigated agriculture is supported by 70% of the total freshwater withdrawals from rivers, lakes and aquifers (blue water) (Wada, Van Beek, & Bierkens, 2012). Over the past half century, the area destined for irrigation-agriculture has doubled, covering now approximately 300 million hectares or 38% of the cultivated land of the world (Watto & Mugera, 2016) and consequently tripling the freshwater withdrawals (World Water Assessment Programme., 2009). Already now, irrigation consumes up to 90% of the water fraction that is available for human use (Siebert et al., 2010).

A substantial part of irrigation water originates from groundwater abstraction from aquifers. The total amount of global groundwater abstraction is estimated to be around 600 to 1500 $km^3\ yr^{-1}$ (Konikow & Kendy, 2005; Wada et al., 2012; Watto & Mugera, 2016), from which an estimated 545 $km^3\ yr^{-1}$ are destined for irrigation purposes (Siebert et al., 2010). In highly irrigated areas like India, up to 60% of the irrigated land now depends on groundwater abstraction (Weekly et al., 2001). These numbers are highly uncertain, mainly due to the inconsistencies of many countries to report their water abstraction data and from the different definitions of what constitutes an irrigated land (Siebert et al., 2010). Groundwater usage is also poorly monitored in many developing countries. Groundwater abstraction destined for irrigation practices has increased continuously in the past decades, frequently exceeding the aquifers recharge capabilities and causing groundwater depletion (Wada, Van Beek, & Bierkens, 2012). The overexploitation of groundwater and aquifer depletion can have several environmental impacts like land-surface subsidence, soil salinization, water scarcity and vegetation loss. Also, it can affect people's livelihoods, causing economic distress and social and political conflicts (Watto & Mugera, 2016). Based on water balance (i.e., calculating the ratio between groundwater abstraction and the aquifers natural recharge rate), the global groundwater depletion has been estimated to range between 110 to 300 (±40) $km^3\ yr^{-1}$ (Salem et al., 2018; Wada et al., 2010; Zeng et al., 2017)

Climate change is expected to reduce precipitation in semi-arid areas and increase precipitation variability, affecting agricultural areas and adding further pressure on freshwater reservoirs (World Water Assessment Programme., 2009). This could lead to an intensification of groundwater abstraction in the coming years. Irrigated land now covers a greater area than urban land and by 2030, it is projected to expand to approximately 340 million hectares (Faurès et al., 2002). Hence, as we continue to unsustainably exploit aquifers around the world for agriculture to maintain food production for a growing population that is expected to reach 8.5

billions in the next 10 years (United Nations, 2015), it is important to understand the fate and effects of the evaporation of these high volumes of groundwater abstraction.

1.1.2 *Effects of Irrigation on precipitation*

Groundwater abstraction used for irrigation results in increased evaporation, comprised of transpiration (which contributes towards biomass production) and the evaporation fluxes from interception and soil moisture (which are unproductive). Evaporation fluxes are both energy and moisture fluxes. Hence, the effects of increasing evaporation by placing large volumes of water on otherwise dry surface soils, modifies the land surface energy balance and also increases the moisture release to the atmosphere (Tuinenburg et al., 2012).

Energy balance perturbation is a direct effect of irrigation that occurs by the increase of soil moisture, which reduces surface air temperature (Puma & Cook, 2010). The addition of water to the soil increases latent heat and reduces the sensible heat flux from the soil to the atmosphere. This shift from sensible to latent heat flux, generates a cooling effect (Huber et al., 2014). In some regions of the Great Plains in the U.S.A., there is up to a 400 % increase in latent heat flux, as a result from increased irrigation moisture, with a sensitive heat flux decrease of 64.3 %, caused by evaporative cooling (Huber et al., 2014). The Indian subcontinent presents the highest surface cooling (∼3 K) due to irrigation, while other irrigated regions in Asia, Europe and North America also experiencing a significant cooling effect (∼0.5 K) (Puma & Cook, 2010). Surface cooling can in turn reduce moist convection and decrease precipitation over the irrigated land (Im et al., 2014). Additionally, the cooling effect generated by irrigation could lead to an underestimation of the warming effect by greenhouse gases, as it acts as an opposite climate forcing. Specially in regions like California, where the majority of the climate stations are located in areas with some irrigated land (Kueppers et al., 2007). Furthermore, in southern Asia, the irrigated land surface cooling effect is reducing the land-sea temperature gradient that drives the monsoon circulation. If the strength of the monsoon decreases, weaker winds would bring less oceanic moisture to land, and decrease terrestrial precipitation (Tuinenburg et al., 2014). Simulations considering irrigation and greenhouse gases, have estimated a 40 % decrease in the inter-annual variability of the circulation of the South Asia summer monsoon (Shukla et al., 2014). As one third of the global population lives within the Asian monsoon influence, the reduction of precipitation has considerable negative impacts on agricultural production and people's livelihoods in this region (Gadgil & Rupa Kumar, 2006).

Water balance perturbation can be caused by anthropogenic activities that alter the input of moisture to the atmosphere, modifying precipitation patterns (Tuinenburg et al., 2014). Ocean evaporation provides moisture for 60 % of the land precipitation over terrestrial areas (about 100,000 to 130,000 km^3 yr^{-1}), and terrestrial evaporation supplies the remainder 40 % of the moisture. The process of terrestrial evaporation returning as terrestrial precipitation is referred to as terrestrial moisture recycling. The fraction of terrestrial evaporation that contributes to terrestrial precipitation (i.e. the precipitation recycling ratio)

(Keys et al., 2019), is variable in space and time. For example, the mean annual recycling ratio can be up to 80 % in some regions of China and in other parts of the world, and the dry season recycling ratio is substantially higher than mean annual values (Van Der Ent et al., 2010). The degree and variations in terrestrial moisture recycling depend primarily on the distribution and scale of evaporation and transpiration from land surfaces (Keys et al., 2019). Therefore, vegetation on land plays an important role in regulating moisture recycling, as it is a significant source of atmospheric moisture.

Total terrestrial evaporation is estimated to range from 61,000 to 72,500 km^3 yr^{-1} (Gordon et al., 2005). A substantial part of this is regulated by vegetation, without vegetation total terrestrial evaporation would be halved (Keys et al., 2016; Kleidon et al., 2000). Several populated areas highly depend on upwind precipitation coming from vegetation-regulated evaporation (Keys et al., 2016). This terrestrial hydrological connectivity through moisture recycling can be remote, making it harder to predict and estimate the impact of land-use modifications and changes in the allocation of water resources. For example, studies suggest that a complete deforestation of central Africa could lead to a reduction of precipitation of 5-15 % in the Great Lakes region and up to 25 % in the northern Black Sea (Avissar & Werth, 2005), while cities like São Paulo and Rio de Janeiro, receive 20-30 % of their precipitation from upwind vegetation (Keys et al., 2016).

Similarly, irrigation can contribute to precipitation at local and regional scales by directly adding precipitable water vapor to the atmosphere. By quantifying the irrigation-induced evaporation that supplies precipitation on land, we can estimate the impact of human activities, and the sensitivity of the climate to land modifications (Van Der Ent et al., 2010). Studies have shown that in regions with heavy irrigation, evaporation causes precipitation to increase considerably downwind (Puma & Cook, 2010). Examples of this are eastern Pakistan, northern and central China and in particular northern India, where up to 25 % of the total precipitation comes from irrigation (Wei et al., 2013). Irrigation effects are usually most expected in or around the irrigated areas, yet atmospheric models have shown that irrigation can enhance considerably downwind precipitation distant from the irrigated land. California's Central Valley irrigation for example, causes an increase of 15 % in the regional summer precipitation, contributing to downwind precipitation in remote locations like Nevada and Idaho. Additionally it increases the Colorado River streamflow by 30 % during the summer months (Lo & Famiglietti, 2013; Z. Yang et al., 2017). In the Texas High Plains, it has been estimated that less than 10 % of the water used for irrigation returns to the source region, meaning only 10 % is locally recycled, while the maximum precipitation effects occur about 90 km downwind (Moore & Rojstaczer, 2002).

Additionally at the river basin level, the water balance is one of the most important hydrological aspects to consider (Oki et al., 1995), as some of the most intensely populated human settlements occur near and around water resources. In fact, the major river basins in the world now support over 70 % of the global population (Lakshmi et al., 2018), and the largest continuous areas of irrigated-agriculture usually occur along the major rivers of the world. Therefore, an equilibrium in the water budget in a river basin is essential for the basin to maintain its ecosystem functions, so equal amounts of water entering and exiting the watershed are necessary to preserve water availability and a sustainable human-environment interaction.

1.1.3 Current understanding of groundwater-dependent precipitation

Studies towards understanding the fate of evaporation from irrigation and its mean global impact on precipitation have been mapped, for a ten year-period from 1986 to 1995 (Wei et al., 2013). Also, special focus has been given to track the irrigation-dependent precipitation from highly irrigated areas like California's Central Valley (Lo & Famiglietti, 2013; Z. Yang et al., 2017), the Great Plains (Harding & Snyder, 2012), India (Tuinenburg et al., 2014), and China (B. Yang et al., 2016; Zhao et al., 2012). Additionally, a comprehensive study of the recycling ratio at a country scale has been done, studying the atmospheric moisture sources and the dependent precipitation (Dirmeyer et al., 2009). However, the specific impact of groundwater-base irrigation on precipitation has not yet been analysed, and to the best of our knowledge a mapping of the destination of groundwater abstraction remains to be investigated. As intensive groundwater abstraction has become an issue that causes groundwater depletion in heavily irrigated areas (Wada, Van Beek, & Bierkens, 2012), it is important to analyse to what extent this unsustainable practice is artificially contributing to rainfall in different parts of the world. Better understanding of the specific contribution of groundwater to precipitation would for example help tease out specific seasonal patterns of groundwater-induced precipitation and contribute to a more precise understanding of groundwater policies and management on precipitation.

1.2 Research questions

The main objective of this study is to provide an overview of the moisture recycling effect of groundwater abstraction on precipitation and net groundwater balances for key countries and river basins worldwide. Our specific research questions are:

1. Which are the countries and basins in the world that have the largest net gain or loss of water originating from groundwater abstraction?
2. How have groundwater dependent precipitation and net groundwater balance changed globally, and for key countries and basins over a 30-year period from 1980 to 2010?
3. To what extent does annual and seasonal precipitation over land and ocean depend on moisture supply originating from groundwater abstraction?

To answer the research questions, we track the destination of groundwater abstraction using the Eulerian moisture tracking WAM-2layers model, to analyse the geographical distribution, the seasonality and the magnitude of groundwater-dependent precipitation (P_{gw}).

2 METHODS AND DATA

2.1 DATA

The meteorological data used for moisture tracking (see Sect. 2.2 and 2.3) is taken from the publicly available ERA-Interim reanalysis, which is provided by the European Centre for Medium Range Weather Forecasting (ECMWF). The ERA-Interim is a project that reanalysed and replaced the ERA-40 analysis, which developed a better representation of the hydrological cycle (Dee et al., 2011). The values for evaporation and precipitation are used in 3-hourly intervals, while other meteorological data such as wind speed and humidity are given in 6-hourly intervals. Likewise, the groundwater data is given into daily values divided in 3-hourly intervals, on a 1.5° x 1.5° grid. All data are for the years 1979 to 2010. The results of our calculations are provided for a 30-year period, from 1980 to 2010, as 1979 is used as a spin-up year in the moisture tracking simulation.

The global groundwater abstraction data was taken from the International Groundwater Resources Assessment Centre (IGRAC) database, monthly groundwater abstraction results are created by combining available gridded and socio-economic data with simulation results from the global hydrological model PCRaster Global Water Balance (PCR-GLOBWB) developed at Utrecht University, forced with the Climatic Research Unit Timeseries (CRU TS 2.1) data set, and the ECMWF ERA-40 and ERA-Interim data over the period 1979-2010. For full documentation, see (Van Beek et al., 2011; Wada et al., 2010, 2011; Wada, Van Beek, & Bierkens, 2012; Wada, Van Beek, Sperna Weiland, et al., 2012). Additionally, groundwater monthly data was downscaled to 3 hours data using the diurnal distribution of ERA-Interim evaporation.

For the purpose of this study, we will consider that all groundwater abstraction goes to irrigation practices and enters the atmosphere as evaporation. This assumption is based on the estimates that globally more than 70 % of the total groundwater abstraction is use for irrigation (Siebert et al., 2010), and in India and Pakistan where the most heavily irrigated areas are located, that percentage can be higher than 90 % (Margat & Van der Gun, 2013). By assuming that all groundwater abstraction goes to irrigation our simulation will constitute the upper theoretical limit of the contribution of groundwater to precipitation.

From the global grid-base groundwater abstraction data to calculate the groundwater abstraction in any given country or basin, country and basin masks were used to limit the area of interest. Additionally, the ERA-Interim reanalysis land-sea mask was used to differentiate the ocean and land grid cells. Continental bodies of water without a direct connection to the ocean have been considered as land.

2.2 ATMOSPHERIC MOISTURE TRACKING MODEL WAM-2LAYERS

The model used was the Water Accounting Model (WAM-2layers), a numerical water transport model that tracks atmospheric moisture. It is designed so that the volume of evaporation and precipitation that enters and exits as an air parcel in the model is tracked forward and backwards in time (Van Der Ent et al., 2010). The Eulerian method is applied to calculate in each grid cell the atmospheric water balance, which is done at each time step:

$$\frac{\partial S_a}{\partial t} + \frac{\partial (S_a u)}{\partial x} + \frac{\partial (S_a v)}{\partial y} = E - P \tag{1}$$

where S_a is the atmospheric moisture storage, t is time, u and v are wind components in zonal (x) and meridional (y) direction, E is the evaporation and P is the precipitation [L^3 T^{-1}]. Water enters as evaporation and moves as atmospheric moisture between grid cells vertically and horizontally, based on wind direction and speed, until it exits the atmosphere as precipitation. Hence, applying the mass-conservation principle we can assume, considering no major changes in the atmospheric moisture storage, that evaporation is equal to precipitation, averaged over a period of one year (Van Der Ent et al., 2010).

However, the assumption made in the model that evaporation is equal to precipitation has its limitations, as there is a small residual in the data-assimilation. Therefore, there is a slight inconsistency between the amount of moisture that enters the atmosphere through evaporation and the resulting precipitation. Nevertheless, the main goal of this research is not affected by this inconsistency and the overall results remain significant and representative. For further details about the mathematical framework and the numerical implementation of the WAM-2layers, see Van Der Ent et al., (2010); Van Der Ent et al., (2013); Van der Ent, (2014). Our data analysis was made using the model´s developer python scripts (Van der Ent, R. J., 2020).

2.3 Potential groundwater-dependent precipitation

The same water balance can be applied in the model to track moisture from an origin of interest. In this case the source of interest is groundwater abstraction (gw). Then, applying the same water balance principle (Eq. 1), we have that:

$$\frac{\partial S_{a\mathrm{gw}}}{\partial t} + \frac{\partial (S_{a\mathrm{gw}} u)}{\partial x} + \frac{\partial (S_{a\mathrm{gw}} v)}{\partial y} = E_{\mathrm{gw}} - P_{\mathrm{gw}} \tag{2}$$

where $S_{a\mathrm{gw}}$ is the atmospheric moisture that comes from groundwater abstraction, E_{gw} the evaporation from groundwater abstraction, and P_{gw} the potential groundwater-dependent precipitation. Therefore, if considering a well-mixed atmosphere, the potential dependent precipitation (P_{gw}) is equal to the precipitation coming from the fraction between the atmospheric moisture storage that comes from groundwater abstraction ($S_{a\mathrm{gw}}$), and the total atmospheric moisture (S_a):

$$\frac{S_{a\mathrm{gw}}}{S_a} P = P_{\mathrm{gw}} \tag{2.1}$$

Additionally, precipitation recycling ratio (ρ) is defined as the fraction between the precipitation that is recycled locally and the total precipitation, and it describes how the precipitation in a specific region depends on the evaporation from within the region. Similarly, we can also calculate the relative dependence of precipitation on groundwater, as the precipitation recycling ratio of groundwater origin (ρ_{gw}), in any given area by knowing the ratio between the P_{gw} and P as follows:

$$\frac{S_{a\mathrm{gw}}}{S_a} = \frac{P_{\mathrm{gw}}}{P} = \rho_{\mathrm{gw}} \tag{2.2}$$

The ρ_{gw} can range from zero to one, zero meaning that none of the precipitation in the region of study comes from groundwater abstraction, and one means that all of the precipitation depends on evaporation from groundwater abstraction.

We have here assumed that all of the groundwater abstraction goes to the atmosphere, and do not account for the portion of the abstracted groundwater that percolates without contributing towards evaporation. The ratio of abstracted groundwater that percolates is highly uncertain and not available as a global dataset. Hence, P_{gw} represents here the maximum potential groundwater-dependent precipitation. Future analysis can provide a more realistic estimate based on country level information of the fraction of abstracted groundwater that goes to irrigation (Margat & Van der Gun, 2013), and the fraction of irrigated water that is subject to conveyance loss, management loss, and application loss (Rohwer et al., 2007).

2.4 Net gains and losses of groundwater

We refer to groundwater balance (B_{gw}) of a region (r), as the difference between P_{gw} and groundwater abstraction (GW_{a}):

$$P_{\mathrm{gw}} - GW_{\mathrm{a}} = B_{\mathrm{gw}} \tag{3}$$

If groundwater abstraction and P_{gw} are equal in any given area, it means that the area is in equilibrium with its groundwater resources, and that all the atmospheric moisture added through evaporation, returns as P_{gw}. Whereas a groundwater gain or loss will occur if groundwater abstraction and P_{gw} are not equal. In other words, groundwater abstraction was subtracted from P_{gw}, so that negative values indicate that the abstraction volumes are greater than the recycled precipitation, and groundwater is being lost. On the contrary, positive values indicate a water gain, where the area considered is gaining more moisture from the groundwater abstraction in adjacent regions.

In order to calculate the groundwater balance at a country and basin level, regional masks were applied to the P_{gw} and GW_{a} maps to limit the area of interest. The results are provided as the total volume, calculated from the sum from all grid cells within the country or basin, in monthly and yearly rates. The regions (r) considered are individual grid cells, all land areas, and a selection of countries and basins. The countries and basins with the largest contributions to groundwater abstraction were selected, as well as those that received the highest absolute P_{gw} yearly volumes, calculating their fraction of P_{gw} from the global P_{gw}.

Additionally, the selection was based on the countries and basins with the highest yearly mean ρ_{gw}.

3 RESULTS

3.1 GLOBAL DISTRIBUTION OF GROUNDWATER ABSTRACTION AND P_{GW}

The spatial distribution of mean annual groundwater abstraction and precipitation with groundwater origin for the Northern Hemisphere for the years 1980, 1990, 2000 and 2010, are shown in Figure 1. The highest volumes of groundwater abstraction are located in heavily irrigated areas like northern India and central and northern Pakistan, Iran, northeast China and western USA (Figure 1a). In northern India and central Pakistan, the rates of groundwater abstraction reached up to 600 mm yr^{-1} in 2010. Over the three decades, the rates and areas of groundwater-based irrigation have both increased.

Precipitation originating from irrigation sustained by groundwater (P_{gw}) can be seen particularly in the Himalayan range, northern India and Pakistan, southern China, southeast Asia and the east of North America (Figure 1b). Particularly, in the borders between India, China, Nepal, Bhutan, Bangladesh, and Myanmar, where most of P_{gw} occurs, reaching rates of 180 mm yr^{-1}. From 1980 to 2010 an overall increase of P_{gw} is evident, corresponding to the increased groundwater abstraction.

Groundwater abstraction and P_{gw} differ both in magnitude and regional distribution (compare Fig. 1a and 1b). However, the maximum rates of P_{gw} are lower than GW_{a} because

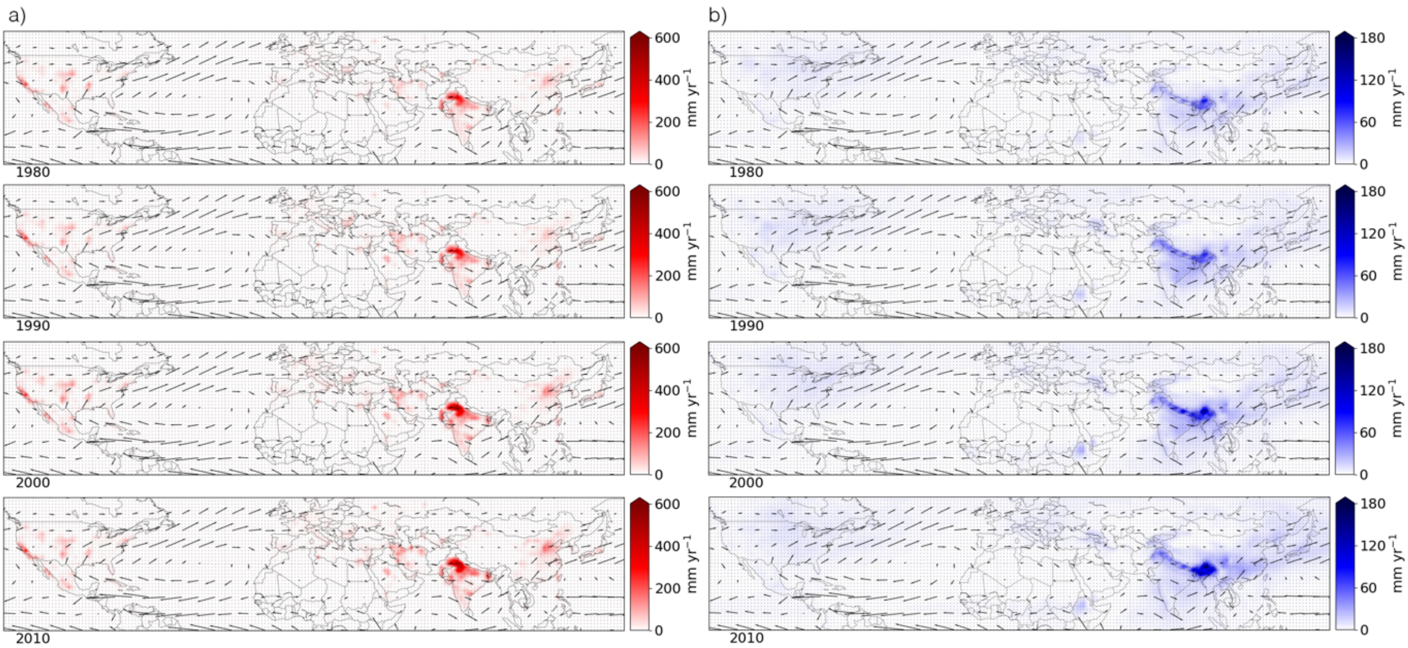

Figure 1. Location and rate of (a) groundwater abstraction (evaporation) between 0 and 60° N, for the years 1980, 1990, 2000 and 2010, and (b) the corresponding $\boldsymbol{P}_{\mathbf{gw}}$. Black arrows show predominant wind direction and intensity.

P_{gw} is spread out by winds over a larger area. In the Northern Hemisphere's mid-latitudes, there is an overall shift of the moisture towards the east, causing significant amounts of P_{gw} from the USA to end up in the North Atlantic Ocean, and from northern India and China to be transported towards the Pacific Ocean. Whereas in the tropical region, the moisture is transported westward, from Saudi Arabia to western Africa and from Mexico into the Pacific Ocean.

Subtracting P_{gw} with GW_a (see Sect. 2.4 for methods) shows the regions with a net gain or loss of their groundwater resources (Figure 2). Net groundwater loss is predominantly located in regions with intense groundwater abstraction. India, Pakistan, northeast China, Europe, the Middle East, Mexico and the USA are mostly having groundwater losses that continue to intensify over time. Northern India and central Pakistan present the highest values of groundwater loss, up to 540 mm yr^{-1} for 2010. The few regions worldwide that gain groundwater are located in and around the Himalayan range, southern China, southeast Asia, Russia, east Africa, Canada, and the oceans, with the highest values presented in the easternmost parts of India. Overall, the Indian subcontinent is the most affected by groundwater abstraction and P_{gw} (Figure 2.b), where the high volumes of groundwater abstracted in northern India and central Pakistan are not being recycled locally, but they are significantly contributing to precipitation downwind. Wind patterns show the moisture

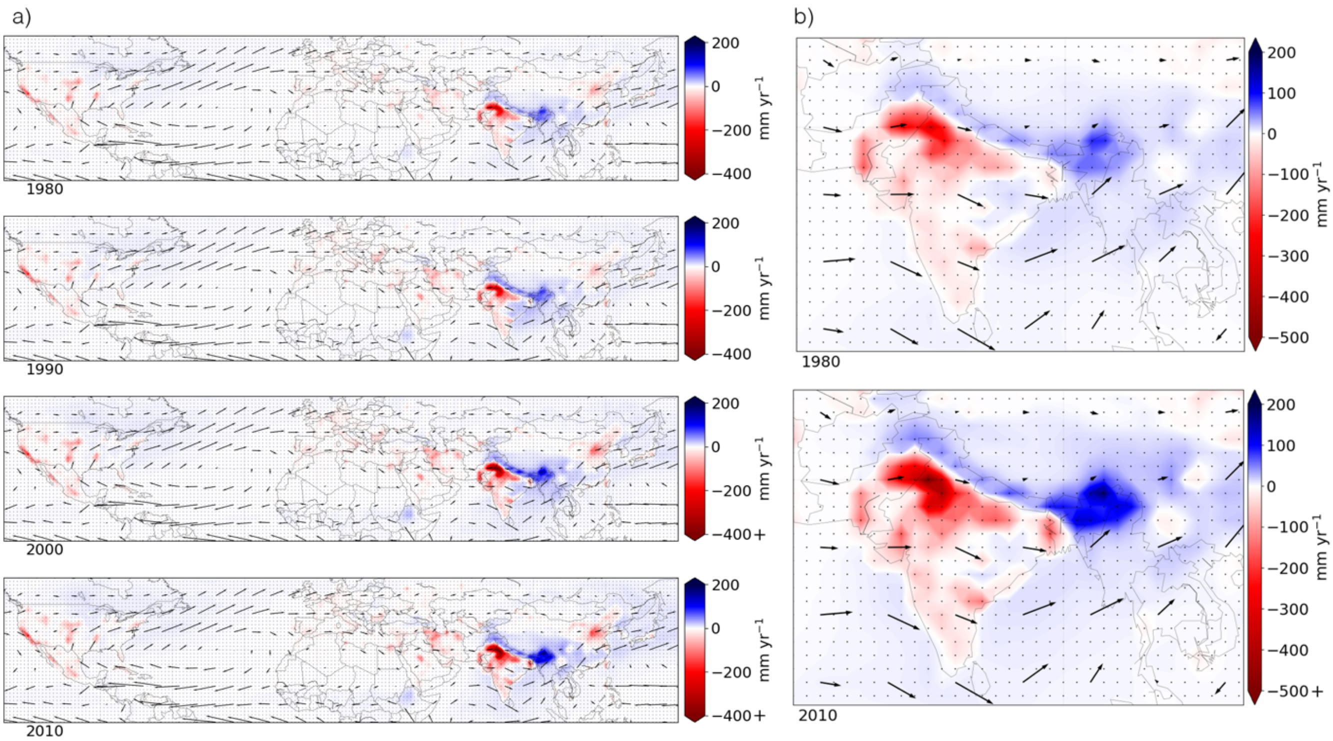

Figure 2. Geographical distribution of the (a) gains and losses of groundwater, defined by the difference between groundwater abstraction and $\boldsymbol{P_{gw}}$. The figure illustrates the regions that have a gain in groundwater (positive groundwater balance in blue) and a loss in groundwater (negative groundwater balance in red). (b) Zoom in over the Indian subcontinent for 1980 and 2010.

transport direction in the Indian subcontinent, showing an overall eastwards trend that sends most of the moisture to the Bay of Bengal and the Himalayan range.

For the Southern Hemisphere, groundwater abstraction and its corresponding P_{gw} differ from the Northern Hemisphere by one order of magnitude (Figure 3). The highest rates of groundwater abstraction of around 30 to 40 mm yr^{-1} are present in South America, more specifically around Brazil's east coast, central and northern Argentina and central Chile. Also, groundwater abstraction is high in and around highly populated cities like São Paulo, Rio de Janeiro, Buenos Aires, Santiago, Cape Town, Jakarta and Melbourne. Additionally, an increasing trend in groundwater abstraction is visible from 1980 to 2010, in particular in eastern South America and southeast Africa (Figure 3a). The resulting P_{gw} presents a rate up to 18 mm yr^{-1} in South America, and the influence of the Northern Hemisphere's groundwater abstraction can be seen in central Africa and in the Indian Ocean (Figure 3b).

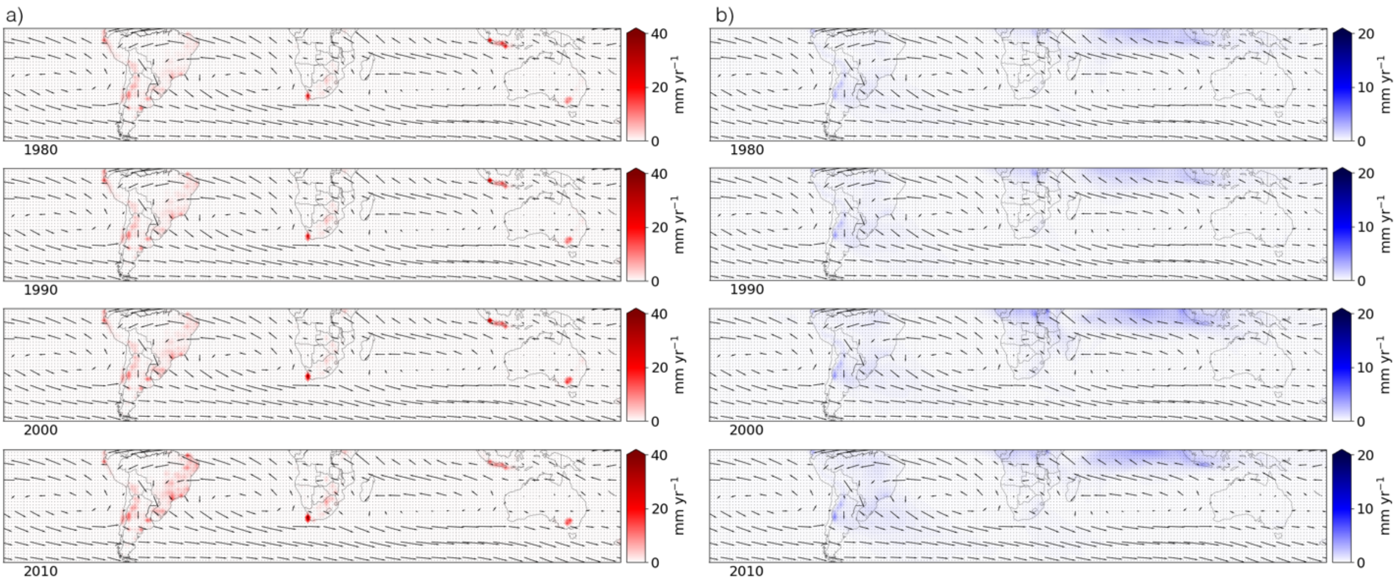

Figure 3. Location and rate of (a) groundwater abstraction (evaporation) between 0 and 55° S, for the years 1980, 1990, 2000 and 2010, and (b) the corresponding $\boldsymbol{P_{\mathrm{gw}}}$. Black arrows show predominant wind direction and intensity.

The net losses and gains of groundwater in the Southern Hemisphere, show similar trends as those in the Northern Hemisphere, as P_{gw} is occurring downwind and not over the areas that most contribute to groundwater abstraction causing net groundwater losses (Figure 4). Our results show that South Africa, Australia and the most irrigated areas of South America are not receiving high volumes of P_{gw} and are net groundwater losers. However, when taking a closer look at South America (Figure 4b), the moisture transport by the predominant winds in the region shows how eastern Brazil is losing moisture towards the Amazon forest, that subsequently moves southwards providing P_{gw} to northern Brazil, Peru, northern Bolivia and Paraguay. While the groundwater abstracted in southern Brazil and Central Argentina is mainly lost to the Atlantic Ocean.

Based on the significant differences in groundwater abstraction rates between the Northern and Southern Hemisphere, we will mainly focus further results and discussions on the Northern Hemisphere, where the most heavily irrigated areas of the world are located. Hence, the selected countries and basins are all located in the Northern Hemisphere. However, when talking about global values of groundwater abstraction and P_{gw}, both hemispheres are considered.

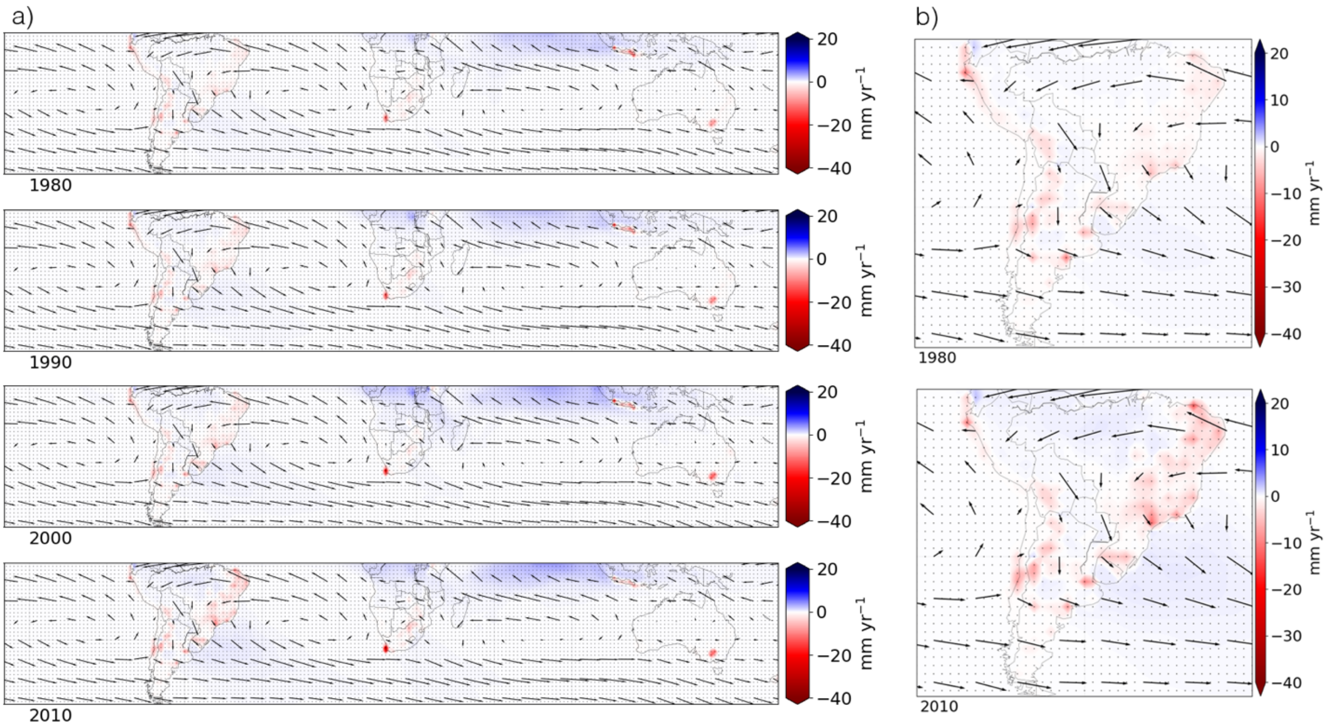

Figure 4. Geographical distribution of the (a) gains and losses of groundwater, defined by the difference between groundwater abstraction and $\boldsymbol{P_{\mathrm{gw}}}$. The figure illustrates the regions that have a gain in groundwater (positive groundwater balance in blue) and a loss in groundwater (negative groundwater balance in red). (b) Zoom in over South America for 1980 and 2010.

3.2 Net gains and losses of groundwater

3.2.1 At global-scale

Groundwater abstraction for the decades between 1980 and 2010 has nearly doubled, going from 487 km^3 yr^{-1} in 1980 to 771 km^3 yr^{-1} in 2010 at a global level (Figure 5a). The resulting P_{gw}, follows the same increasing trend (Figure 5b), and its global distribution indicates the net groundwater gain or loss from the terrestrial water resources. Our results show that a high volume of P_{gw}, i.e., on average around 40 % of the evaporated groundwater, ends up in the ocean. This means that almost half of the total groundwater abstracted in the world will be transported away from the region of origin and precipitate over the ocean. As groundwater continues to increase the ocean net groundwater gain has risen from 195 km^3 yr^{-1} in 1980 to 314 km^3 yr^{-1} in 2010.

3.2.2 At country-scale

The countries that contribute the most to groundwater abstraction are India, the USA, China, Pakistan and Iran (Figure 5a). The stacked graph illustrates the magnitude of the impact these intensely irrigated nations have on the global groundwater withdrawals. Together, India, China and the USA, account for half of the global groundwater abstraction. India has nearly doubled its groundwater withdrawals for irrigation during this period, going from 119 $km^3\ yr^{-1}$ to 199 $km^3\ yr^{-1}$, being the biggest contributor to groundwater abstraction and accounting for 25 % of the total withdrawals in the year 2010. China with an 80 % increase in three decades has gone from 58 $km^3\ yr^{-1}$ to 105 $km^3\ yr^{-1}$, while the USA has increased its use of groundwater by approximately 32 % from 76 $km^3\ yr^{-1}$ to 101 $km^3\ yr^{-1}$. Combined Iran and Pakistan represent 12 % of the total groundwater extracted globally and followed an increasing trend over the 30-year period of 104 %, from 25 $km^3\ yr^{-1}$ to 51 $km^3\ yr^{-1}$, and 23 %, from 34 $km^3\ yr^{-1}$ to 42 $km^3\ yr^{-1}$ respectively. Russia and Canada with lower groundwater withdrawals rates, do not account for a high percentage of the total global abstraction, the former only 2.5 % with 19 $km^3\ yr^{-1}$ and the latter 0.2 % with 1 $km^3\ yr^{-1}$ for the year 2010. Nevertheless, we decided to include these two countries in the analysis as they become more significant when considering P_{gw}.

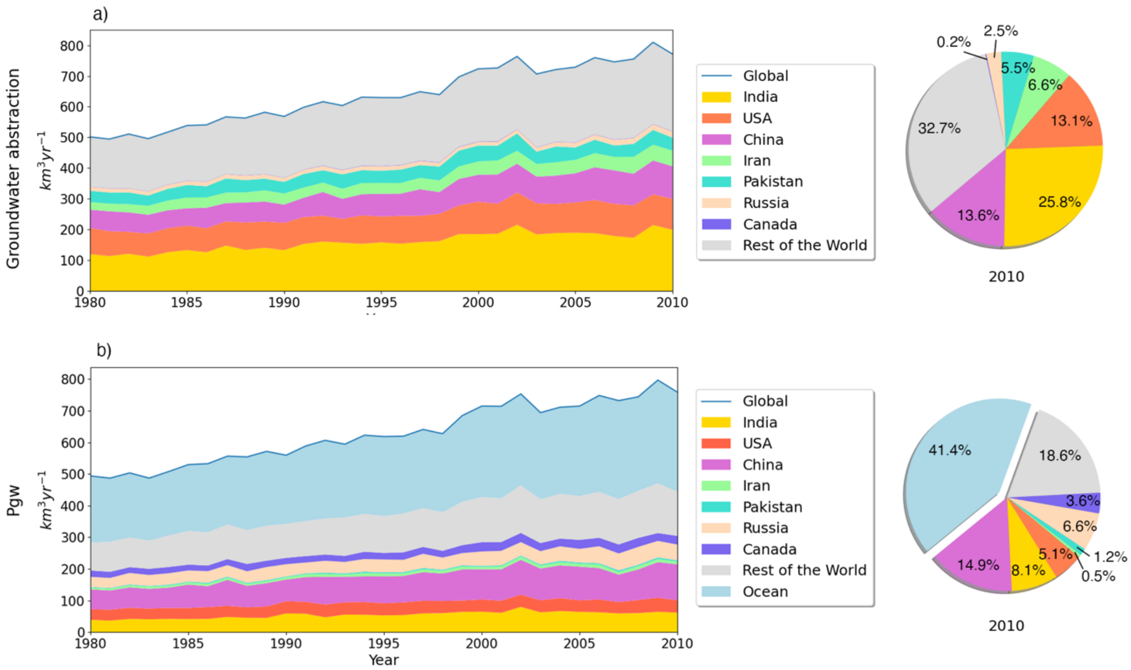

Figure 5. (a) Global groundwater abstraction in absolute values for the period 1980-2010 and selected countries and their relative percentage for the year 2010, and (b) the corresponding $\boldsymbol{P}_{\mathbf{gw}}$.

There is an appreciable difference between the groundwater loss through evaporation and the corresponding P_{gw}, at the country level (compare Fig. 5a and 5b). Countries like India, that contribute the most to groundwater evaporation, receive very little of that moisture back, on average only 30 %. The USA has a similar fraction of their water locally recycled, as little as 38 % of their evaporated groundwater precipitates back within their territories, while Pakistan receives only around 20 %. An extreme case of net groundwater loss is Iran, that on average receives back barely 8 % of the volume from their groundwater withdrawals. On the other hand, China, has a positive groundwater balance, and is the country that receives the most absolute P_{gw} in the world, with 15 % of the total P_{gw} in 2010. China gains on average 9 % more moisture per year from groundwater abstraction elsewhere and is the only of the top five countries in groundwater abstraction that has a positive groundwater balance.

Russia and Canada with small contributions to groundwater abstraction, large land areas and their close proximities to other heavily irrigated countries, make them net gainers in the groundwater balance. Russia receives about 1.5 times more P_{gw}, than its losses through evaporation, while Canada receives about 20 times more of its groundwater budget. Together they received 11 % of the total P_{gw} for the year 2010, and a continuously increasing trend can be seen, especially in Russia, where the P_{gw} has gone from 30 km^3 yr^{-1} in 1980 to 50 km^3 yr^{-1} in 2010.

The analysis of the groundwater gains and losses along the 30-year period for the selected countries, reflects the tendencies and severity of the groundwater imbalances that exist within each country (Figure 6a). India has more than doubled its water loss from 1980 to 2010, reaching rates of 150 km^3 yr^{-1}, our results indicate that India is losing high volumes of P_{gw} to nearby countries and to the ocean, resulting in a negative trend that continues to rapidly intensify. Consequently, India is not only the top supplier of groundwater-induced atmospheric moisture, but also the highest net loser of its groundwater resources. The USA, Iran and Pakistan also present increasing negative trends, losing circa 62, 47 and 33 km^3 yr^{-1} in 2010, respectively. China's groundwater balance trend despite having net gains most of the years, some years it falls around the equilibrium line and even a few years it ends up with a small negative groundwater balance, it also appears to be shifting towards a negative groundwater balance in the latest years of the study period. Russia and Canada are the two nations of the selected countries with the overall highest net groundwater gain.

There is considerable seasonality at the country-scale groundwater balances (Figure 6b). During the spring months of March, April, and May, India presents its peak in water lost, and despite being a net loser when considering yearly periods. At a monthly timescale India gains groundwater moisture during the months of July, August and September, with a drastic groundwater balance inversion happening from May to July. This is due to a sharp decrease in groundwater abstraction during the summer in India (Figure 6f), and not to a significant increase of P_{gw} (Figure 6d). The USA presents net losses throughout the year, with the highest groundwater loss occurring during the months of July, August September. A very similar seasonal trend appears in Iran, while Pakistan presents a less pronounced loss peak in April and a near equilibrium trend from August to December. China's groundwater gains come specifically from the months of April and May, as the rest of the year its groundwater balance is negative, making China's groundwater budget highly dependent on seasonality. Russia and Canada are the only two, of the analysed countries that present net gains throughout the year, both having the groundwater gain peak in August.

To better understand the groundwater net gains and losses variability at country-scale, it is important to compare the absolute values of P_{gw} and groundwater abstraction separately (Figure 6c-f). This allows to identify the temporal and seasonal variations of P_{gw} and groundwater abstraction and understand the predominant factor that determines the groundwater balances.

Figure 6. Net groundwater losses and gains calculated (a) yearly per country from 1980 to 2010 and (b) monthly, considering an average for the period from 2005 to 2010. Temporal variations from 1980 to 2010 of (c) $\boldsymbol{P}_{\mathbf{gw}}$, and (e) groundwater abstraction and monthly averages from 2005 to 2010 of (d) $\boldsymbol{P}_{\mathbf{gw}}$ and (f) groundwater abstraction for selected countries.

3.2.3 *AT RIVER BASIN-SCALE*

The Indus, Ganges, Yangtze, Mississippi, Tarim and Brahmaputra river basins were selected based on their significant groundwater abstraction contributions and P_{gw}. The groundwater balance for all six river basins from 1980 to 2010 illustrates the temporal trends and identifies the basins that are net gainers or losers (Figure 7b). The Ganges basin is the most affected by water loss, presenting a steady and pronounced declining trend, followed by the Indus and Mississippi basins. The increasing groundwater loss trend means that the more

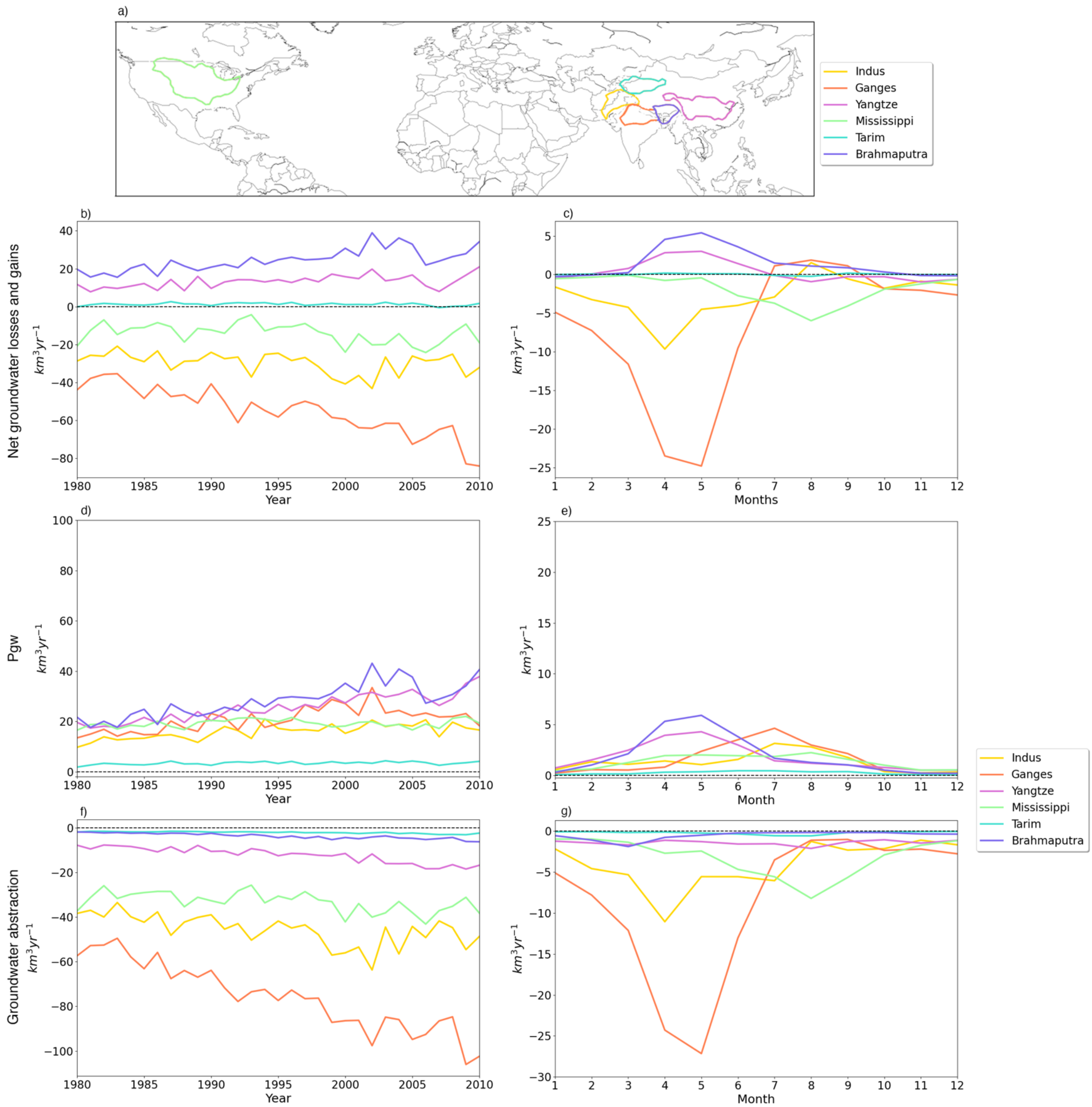

Figure 7. (a) Location of the river basins selected, and the net groundwater losses and gains calculated (b) yearly per basin from 1980 to 2010, and (c) monthly considering an average for the period from 2005 to 2010. Temporal variations from 1980 to 2010 of (d) $\boldsymbol{P_{gw}}$, and (f) groundwater abstraction and monthly averages from 2005 to 2010 of (e) $\boldsymbol{P_{gw}}$ and (g) groundwater abstraction for selected basins.

groundwater is being used within the basin towards irrigation, the more groundwater is lost far downwind. Yangtze and Brahmaputra have a continuously increasing net gain of groundwater resources, with Brahmaputra being the river basin that receives the absolute higher volumes of P_{gw}.

The seasonality of the net gains and losses of groundwater for the river basins, illustrate their monthly groundwater availability (Figure 7c). The Tarim basin has an overall equilibrium in its groundwater budget. It appears that throughout the study period and the different seasons it maintains near zero changes. While most of the groundwater abstracted within the Ganges basin precipitates outside this region during the months of March, April and May, due to most of India's groundwater abstraction happening in the Ganges basin, the seasonal trend of India and the Ganges basin are almost identical, only differing in magnitude. The other two river basins that are losing part of their groundwater resources, Indus and Mississippi, also reflect considerably well the overall seasonal variations presented in Pakistan and the USA, respectively. Yangtze and Brahmaputra gain most of their P_{gw} during the spring months of April and May and follow a similar seasonality as China. However, no net losses are presented within the Brahmaputra basin throughout the year.

3.4 Relative dependence of precipitation on groundwater

3.4.1 Mean annual ρ_{gw} in the Northern Hemisphere

The mean annual relative dependence of precipitation on groundwater (ρ_{gw}) globally is represented for the years 1980, 1990, 2000, 2009, 2010 (Figure 8). The year 2009 was included to illustrate the ρ_{gw} of the year with the highest groundwater abstraction of the study period (Figure 5a). Central and northern Pakistan, northern India, the Himalayan range and southeast China, present the highest levels of precipitation dependence from groundwater, with up to 5 % of the total precipitation in those regions coming from groundwater abstraction. Despite being an overall small contribution to the total precipitation, groundwater abstraction affects almost the entire Northern Hemisphere. The higher values of ρ_{gw} occur within or near the heavily irrigated areas, especially in southern and eastern Asia and North America.

ρ_{gw} has increased significantly from 1980 to 2010 and the impact of increasing groundwater abstraction globally can be seen in the increment of ρ_{gw} mostly in southern Asia, China, the Middle East, the sub-Saharan region, and the USA. Particularly in northern India, Pakistan and the Himalayan range, which since 1980 appear to have the highest dependence on groundwater abstraction. This dependence is carried on over the following decades, and the degree of ρ_{gw} has significantly intensified over these regions and their surroundings for 1990, 2000, 2009 and 2010.

Comparing the distribution of P_{gw} (Figure 1b) and ρ_{gw} (Figure 8) in the Northern Hemisphere, we notice that not necessary the regions that receive the most P_{gw} rely the most on groundwater abstraction. As ρ_{gw} also depends on the total precipitation received in each region, so regions with considerably lower total precipitation may be more dependent on groundwater abstraction even if they receive lower volumes of P_{gw}.

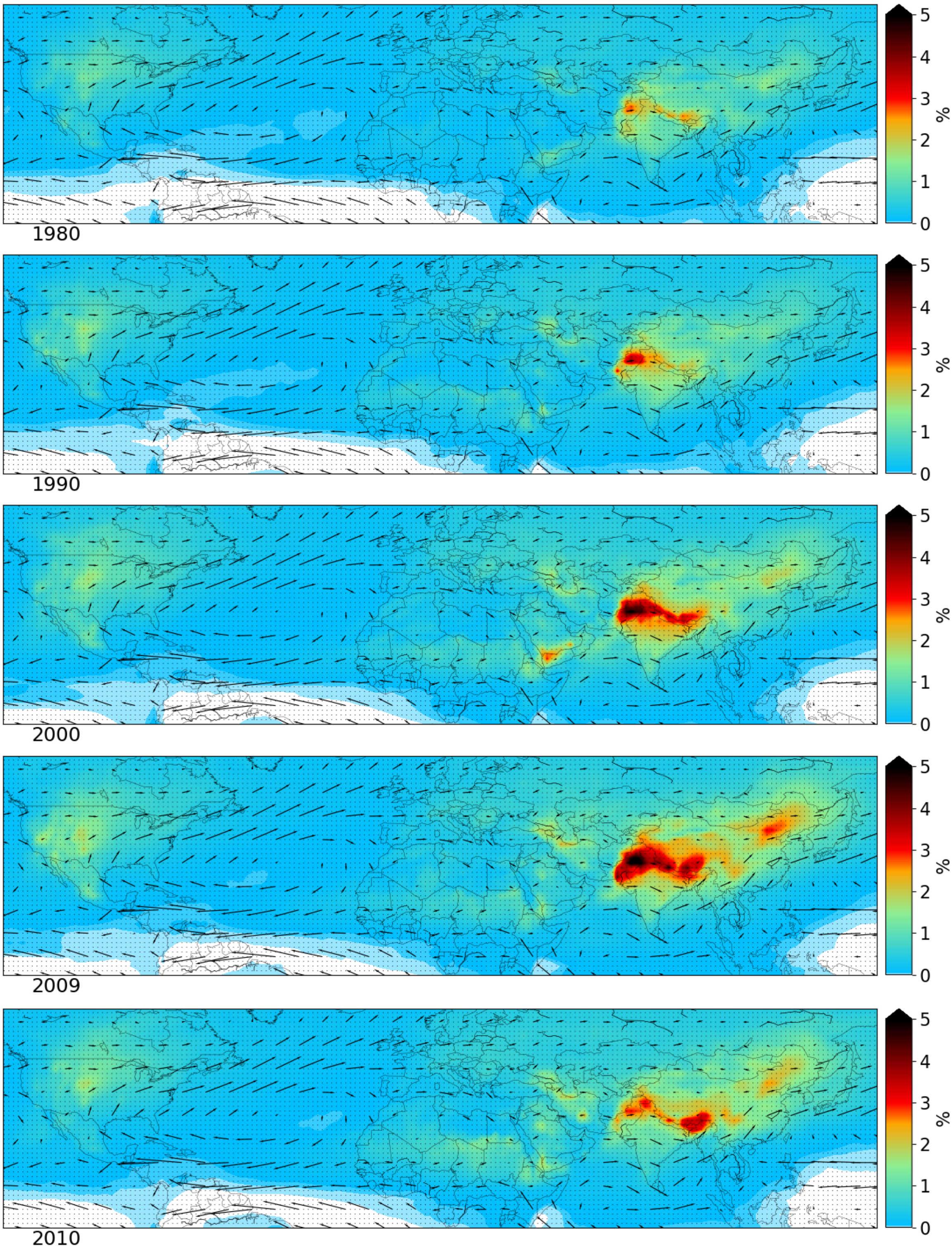

Figure 8. Relative dependence of precipitation on groundwater for the years 1980, 1990, 2000, 2009 and 2010. Black arrows represent wind direction and intensity.

3.4.2 *MEAN SEASONAL ρ_{gw} IN ASIA*

The seasonality of ρ_{gw} illustrates the variations of the degree to which the most heavily irrigated regions in Asia depend on groundwater to sustain a fraction of the precipitation (Figure 9). During the winter months of December, January and February low values for ρ_{gw} are present throughout the continent, with a maximum ρ_{gw} of about 6% in southern China, northern India and around the southern end of the Himalayan range. ρ_{gw} increases significantly during spring, and the highest values of the year appear in April and May. During these months up to 14 % of the total precipitation depends on groundwater abstraction in northern India. For the summer months the dependency of precipitation on groundwater abstraction shifts towards eastern Asia, and in July and August, the middle East and in particular northern Iran highly rely on groundwater for its precipitation, where about 12 % of the precipitation is P_{gw}. Our results show that there is an important seasonal variability of ρ_{gw}, that cannot be seen when considering yearly means, not only ρ_{gw} is considerably higher at a monthly timescale but also the relative dependence of precipitation from groundwater abstraction at a given time of the year, varies geographically.

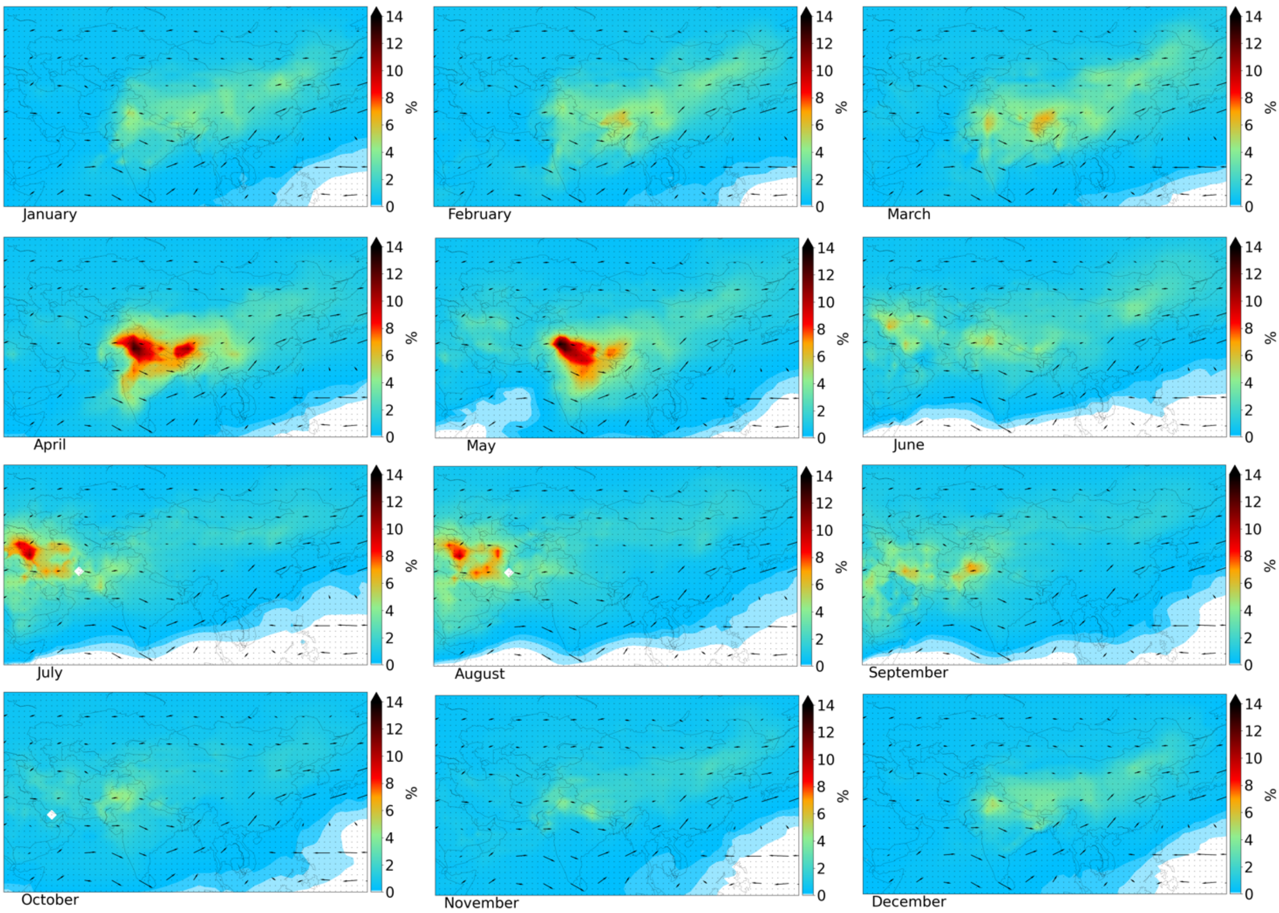

Figure 9. Seasonal changes in the relative dependence of precipitation on groundwater calculated as the mean for the six-year period from 2005 to 2010 for Asia.

3.4.3 MEAN SEASONAL ρ_{gw} IN NORTH AMERICA

In North America, the seasonal variations of ρ_{gw} are more evident in Mexico and the USA (Figure 10). The months of October, November, December, January and February, present overall low ρ_{gw} values. During spring we can see the dependence of precipitation on groundwater abstraction to intensify over central Mexico and central USA. Mexico presents the highest ρ_{gw} during April reaching up to 4 % in central and northern Mexico. For the USA ρ_{gw} significantly increases during June, July and August, in particular in California's Central Valley and the northwest USA, reaching values of ρ_{gw} of up 6 %.

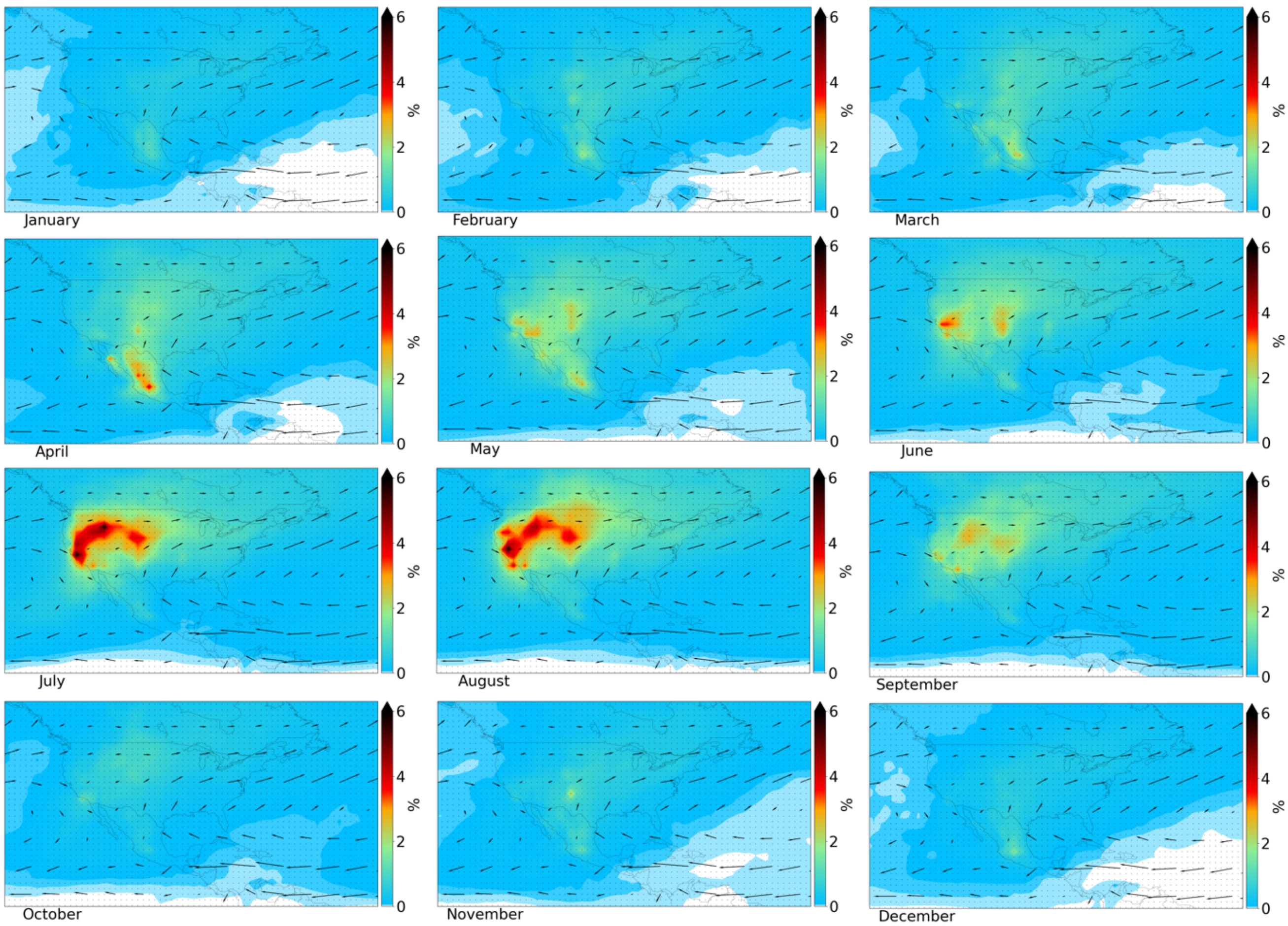

Figure 10. Seasonal changes in the relative dependence of precipitation on groundwater calculated as the mean for the six-year period from 2005 to 2010 for North America.

3.4.2 AT A COUNTRY AND RIVER BASIN-SCALE

The mean temporal variability of ρ_{gw} was calculated for the selected countries and basins (Figure 11), to illustrate the trends over the study period. The countries that most rely on groundwater abstraction to supply a fraction of their precipitation, are Pakistan, India, and China, and all countries present an increasing trend of ρ_{gw}. Pakistan has doubled its dependency, from 0.78 % in 1980 to 1.8 % in 2002, and it has lowered to 1 % in 2010, very similar to that of India, being overall the two countries that most rely on groundwater abstraction to support part of their precipitation. This is also reflected at the basin-scale as the

Indus and Ganges basins present the highest ρ_{gw} values, up to 2.3 %. The USA and Iran are two countries that significantly contribute to groundwater abstraction but have low values of ρ_{gw}. However, in semi-arid regions like Iran the dependence is increasing rapidly, and despite the low amounts of P_{gw} received by this country (Figure 3b), P_{gw} is becoming more significant relative to the total precipitation and has more than double from 0.34 % in 1980 to 0.76 % in 2010. Russia and Canada, based on the large territorial areas, have low mean values of ρ_{gw} and do not depend highly on groundwater abstraction for their precipitation as other sources of moisture (e.g., oceanic moisture) could be more significant in these countries.

Figure 11. Mean relative dependence of precipitation on groundwater for the selected (a)countries and (b) basins, for the 30-year period from 1980 to 2010.

The seasonality of the mean ρ_{gw} varies significantly for the selected countries (Figure 12a). At a monthly timescale, Iran presents the highest levels of groundwater dependence during the months of July and August, where more than 4 % of the total precipitation in the country comes from groundwater abstraction. The seasonality in the USA, and Pakistan looks similar to that of Iran, and the summer months show the countries' highest ρ_{gw} mean. However, China and India rely more on groundwater during the first half of the year, and in particular during the spring months of March, April and May. India reaching 3.7 % ρ_{gw} during April. Contrastingly, Russia and Canada present low values of ρ_{gw} and little variability throughout the year. At the basin level (Figure 12b), the Ganges basin presents the highest ρ_{gw} mean values, during the month of April and May, and up to 5 % of the total precipitation in

Ganges comes from groundwater abstraction. Similar to Ganges, the Brahmaputra and Yangtze basins present their highest ρ_{gw} mean, during the first half of the year, but the peak in these basins is during the month of April, when the Brahmaputra basin reaches 3.7 % of ρ_{gw}. The Indus basin shows a more uniform dependence on groundwater throughout the year, being the months between April and October the most reliable on groundwater and similar seasonal patterns are present in the Tarim Basin. The Mississippi basin also presents higher dependability on groundwater during the summer and beginning of the autumn, with a peak on ρ_{gw} during July and August.

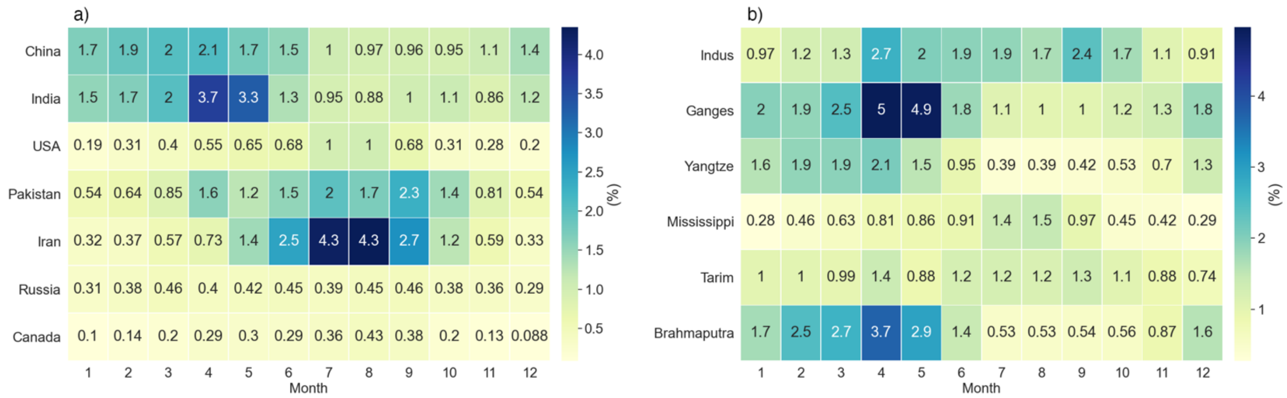

Figure 12. Monthly mean dependence of precipitation on groundwater for the selected (a)countries and (b) basins, averaged over the period from 2005-2010.

4 Discussions

4.1 Land-ocean and transboundary groundwater-precipitation relationships

Almost half of the groundwater abstracted in the world will end up in the oceans having no further use for terrestrial ecosystems. Although groundwater abstraction and total terrestrial evaporation in general have very different geographical distributions, the 40 % of groundwater abstraction that ends up in the ocean closely corresponds to the average ratio of terrestrial evaporation destined for the ocean (Van Der Ent et al., 2010). The main groundwater loss to the oceans occurs near India and China, where most of the P_{gw} that reaches the ocean precipitates over the Indian Ocean, in particular in the Bay of Bengal and in the northwest Pacific Ocean (Figure 1b).

The distribution and terrestrial loss of P_{gw} are influenced by groundwater abstraction, hydroclimate, wind patterns and orography (Rudi J. Van Der Ent et al., 2010). In areas with high upwind groundwater abstraction and high precipitation rates, P_{gw} is more likely to occur (Wei et al., 2013). Atmospheric circulation determines the direction and distribution of moisture transport and orography can block moisture transport, enhance orographic precipitation, and thus, regulate groundwater moisture recycling within the continents. This continuous loss of terrestrial freshwater resources to the ocean represents a direct loss of freshwater.

Groundwater abstraction used for irrigation seems to cause local groundwater loss and downwind groundwater gain. It appears to be well supported by the idea that irrigation has an overall negative effect on local water storage, especially when the main source of irrigation water comes from groundwater abstraction (Zeng et al., 2017). Hence, the maximum effects on groundwater dependent precipitation from irrigation practices are present far downwind (Moore & Rojstaczer, 2002; Szilagyi, 2018). Hydrologically connecting remote locations, beyond political and geological boundaries. The transboundary effect of groundwater abstraction is due to irrigation contributing mainly to increasing levels of evaporation and smaller increases of precipitation at a local level (Huber et al., 2014). In other words, while large volumes of irrigation groundwater increase precipitation locally, it does only in small amounts when considered the evaporation increase. Hence, this negative balance between evaporation and precipitation in heavily irrigated regions, suggests that irrigation practices are unsustainable (Wei et al., 2013), while making remote regions dependent on upwind groundwater resources.

The largest volumes of transboundary groundwater moisture transports occur in the Northern Hemisphere, while groundwater abstraction and its corresponding P_{gw} in the Southern Hemisphere are one order of magnitude lower. This reflects the differences in population between the two hemispheres. However, groundwater losses are present widely in South America and are increasing rapidly, in this region it is important to consider the role that the Amazon rainforest plays in moisture recycling. The land-use changes in South America that turn the Amazon rainforest into agricultural land appear to be generating dryer conditions and reducing rainfall (Lawrence & Vandecar, 2015). Hence, deforestation and increased irrigation in the region can affect water availability, and impact the livelihoods of the people, our results confirm that the regions where the largest metropolis of South America are located are net groundwater losers. Meanwhile, in the northern Hemisphere the impact of irrigation and the transboundary effects of groundwater moisture are more pronounced, in particular in Asia and North America.

In Asia, key areas losing groundwater are some of the most irrigated areas in the world i.e., central Pakistan, northern and western India, northeast China and the Middle East, and key areas gaining groundwater are northern Pakistan, the Himalayan region, southern China and southeast Asia (Figure 2). Most of the moisture coming from groundwater abstraction in the Ganges and the Indus basins gets transported away to the Himalayan region and southern China. These relationships are expected and comparable to previous studies, where a northward and eastward shift of moisture from the heavily irrigated Ganges basin, due to large wind patterns, has been identified (Tuinenburg et al., 2012; Wei et al., 2013), with the Himalayan range playing an important role and acting as a barrier for atmospheric moisture. This could be due to surface cooling induced by increased soil moisture content over the irrigated areas in northern India and central Pakistan, that generates a thermal circulation between India and the Tibetan Plateau (Zeng et al., 2017), transporting moisture away. Particularly the Tibetan Plateau, the Yangtze and Brahmaputra basins receive high volumes of

P_{gw}, possibly coming from irrigation in India and Pakistan, making agriculture and human livelihoods in these regions to some degree dependent on upwind groundwater abstraction. However, while southern China is gaining groundwater resources from irrigation upwind, it is losing groundwater resources in the northeast, where the largest agricultural and most populated areas are located (Sun et al., 2006). Hence, despite China having a positive overall groundwater balance, it is not successfully recycling its groundwater resources within the most heavily irrigated areas.

In North America, groundwater loss is occurring in the USA and Mexico, mainly in California's Central Valley and in the Mississippi basin, while groundwater gain occurs in southern Canada and the Great Lakes region (Figure 2). Therefore, the USA is losing its groundwater resources to Canada and to the ocean. However, while Canada benefits from P_{gw} coming from the USA, it is not greatly dependent on groundwater abstraction to support its precipitation, this is reflected in low ρ_{gw} values, during the 30-year study period (Figure 11). The most intense groundwater loss in North America occurs in the heavily irrigated region of California's Central Valley, matching previous studies suggesting that less than 1 % of the total precipitation in this region comes from irrigation (Wei et al., 2013). This could be attributed to evaporation not being able to generate precipitation in dry conditions and instead the moisture gets transported farther away (Wei et al., 2013). The Mississippi basin also is losing its groundwater resources to downwind P_{gw} towards the east of the USA and Canada. Possibly due to the effects of irrigation on precipitation patterns as recent studies have suggested that large-scale irrigation in Nebraska has had an overall increase in evaporation but a decrease in local precipitation (Szilagyi, 2018).

4.2 Temporal aspects: Increase over time and seasonality

Groundwater abstraction has steadily increased over the studied 30-year period. This has not only intensified depletion of groundwater aquifers in heavily irrigated regions but also increased downwind dependence on P_{gw}. In particular in the Indian subcontinent, where the continuous over-explanation of groundwater has increased groundwater losses considerably from 1980 to 2010 (Figure 2b). Together, India and Pakistan, with approximately 57 and 14 million hectares of area equipped for irrigation, respectively (Thenkabail et al., 2009), represent the regions most affected by groundwater loss and most dependable on P_{gw}. The temporal continuous increase of ρ_{gw} in our study (Figure 10), suggests that the countries and basins with the higher dependency on P_{gw} to support their precipitation will likely be the most vulnerable to groundwater availability upwind and to changes in precipitation patterns due to climate change.

Our groundwater balance analysis (Figure 6b) indicates seasonality in the hydrological connectivity between India and China. During the spring months, India presents its peak in water lost, due to high levels of groundwater abstraction. This could be attributed to the high volumes of groundwater needed in the heavily irrigated area of northern India, during the dry conditions of the pre-monsoon season (Shukla et al., 2014). Therefore, the most intense irrigation season in India corresponds to the months of maximum moisture gained in China. However, during the months of July, August and September the roles invert, and India gains groundwater while China losses it. Probably due to the monsoon precipitation that is at its highest during these months, when up to 60 % of the monsoon precipitation falls (Gadgil & Rupa Kumar, 2006). This connectivity between India and China can also be observed in the ρ_{gw}, both presenting the highest ρ_{gw} values during April. This could suggest that both countries rely on the P_{gw}, coming from the same source, most likely the Ganges basin.

At the basin scale, the seasonal hydrological connectivity is also present in the results based on the river basins in India and China. The Ganges is the river basin that presents the largest seasonal variations in our study and is the basin that most relies on groundwater abstraction to sustain part of its precipitation. During the driest months of the pre-monsoon season, the mean monthly ρ_{gw} reaches up to 5 % (Figure 12b). Considering smaller regions within the basin, up to 14 % of the total precipitation comes from groundwater abstraction (Figure 10), being the highest ρ_{gw} in our results. As our ρ_{gw} results only considered recycled moisture from groundwater, they differ in magnitude from other studies that calculated that the amount of recycled moisture within the Ganges basin varies from 5 % during the winter, up to 60 % during summer (Tuinenburg et al. 2012). On the other hand, the Brahmaputra basin located in China, India, Bangladesh and Bhutan (Immerzeel, 2008), is the region with the most positive groundwater balance, as it gains groundwater throughout all seasons, particularly during the spring months. It receives the highest volumes of P_{gw} globally, reaching rates from 100 to 200 mm yr^{-1} (Figure 2b), specially during April, May and June, which could be the result of the high volumes of groundwater used in the Ganges basin during the spring. Similar seasonal patterns are present in the Yangtze basin, further supporting a hydrological connectivity between the Brahmaputra, Yangtze and the Ganges basins.

Meanwhile in North America, the hydrological connectivity between the USA and Canada is most evident during the summer months. The USA presents the higher levels of groundwater abstraction and loss during June, July, August and September, and Canada shows a corresponding positive groundwater balance trend during those months. However, even if P_{gw} is low in California's Central Valley, during the summer months, it presents high values of ρ_{gw}, when 6 % of the precipitation in the west coast of the USA during July and August rely on groundwater abstraction. The northwest of the USA and the Mississippi basin also have higher ρ_{gw} during the summer, as during August the USA abstracts the higher volumes of groundwater.

4.3 Environmental and climate impacts

The increasing groundwater abstraction can be seen over the 30-year period of the study (Figure 1a), which is consequently affecting the environmental and the climate system. The impact of anthropogenic activities like groundwater abstraction and irrigation can already be having a similar impact on freshwater resources as that of a warming climate. In other words, the changes in freshwater reservoirs due to intense irrigation in some regions, correspond to the simulation of a 2.5 °C temperature increase (Ferguson & Maxwell, 2012). An example of the environmental impact of intensifying irrigation practices and the depletion of freshwater resources (including surface water), over the past years can be seen in Saudi Arabia (Figure 13). The rapid increase of groundwater-base irrigation is already drastically changing terrestrial ecosystems and even turning deserts into agricultural land. An additional effect on the global climate of groundwater abstraction is the contribution of carbon emissions from irrigation pumps (Salem et al., 2018), acting as a further positive feedback to global warming.

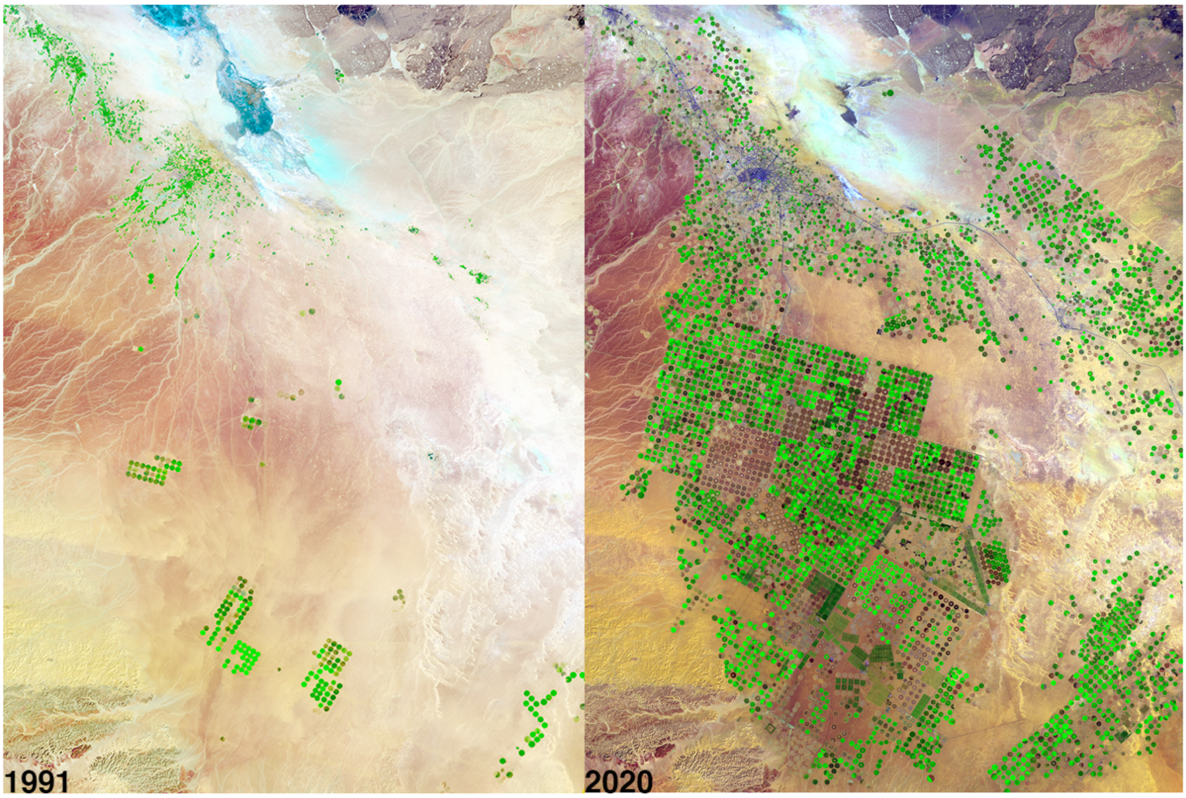

Figure 13. Satellite view of center-pivot irrigation systems in the Wadi As-Sirhan Basin in Saudi Arabia from 1991 and 2020. Pictures obtained from the U.S. Geological Survey https://earthshots.usgs.gov/earthshots/

Furthermore, the intense irrigation in Asia and North America and the use of groundwater resources is increasing evaporation and causing surface cooling (Kueppers et al., 2007), as we have seen this is affecting atmospheric moisture transport and influencing precipitation at local and regional scales significantly. In turn, the perturbation of the atmospheric moisture, and the human induced changes in evaporation and precipitation can cause a decrease of the net sink of moisture over continents and affect terrestrial ecosystems. Recent research shows that in Europe human water use is modifying atmospheric moisture transport and causing a decrease of the strength of the atmospheric sink over the continent (Keune et al., 2018), suggesting a decline in terrestrial water resources and further water stress for regions with intense groundwater abstraction. Similarly in Asia, intense irrigation is causing changes to the South Asian Summer Monsoon intensity, weakening its circulation (Manatsa et al., 2008; Shukla et al., 2014), and possibly causing less terrestrial precipitation (Tuinenburg et al., 2014). Our results align with these findings as groundwater abstraction is not being successfully recycled over the continents, representing a net freshwater loss that enhances freshwater scarcity.

Additionally, as more groundwater is lost to the oceans by irrigation and less moisture is being recycled over the continents, human activities are also responsible for a fraction of the sea level rise. About 40 % of the total groundwater abstraction ends up in the oceans, and recent studies have estimated that about 80 % of all the groundwater that is being depleted from aquifers also would end up in the oceans (Wada et al., 2016), being one of the most important terrestrial contributions to sea level rise.

Therefore, it is evident that land-atmospheric interactions can have a significant impact in the global climate, the environment and our freshwater resources. Humans seem to be aggravating the effects of climate change with the unsustainable use of groundwater resources, which could lead to more frequent and severe droughts and environmental degradation.

4.3 Governance implications

More groundwater is abstracted for human use every decade and appears to have a continuous increasing trend (Figure 5a), this results in net groundwater losses in some of the most populated regions of the world (Figure 2). Our results show that the current trends of groundwater exploitation are unsustainable. The unsustainable irrigation using groundwater resources in not only causing groundwater depletion but could also have social and economic impacts. A higher dependency on groundwater abstraction for agriculture is causing rapid declines of the water table in aquifers and increasing the irrigation costs (Salem et al., 2018), having further negative effects on people's well-being, increasing poverty and decreasing profits from agricultural activities (Sayre & Taraz, 2019). Additionally, irrigation efficiency should be addressed and regulations on agriculture revised, as inefficient irrigation plays an important role in the loss of groundwater resources by intensifying groundwater abstraction (Salem et al., 2018). Adding to these local impacts of groundwater loss due to irrigation, are the transboundary effects of modifying downwind precipitation, which can have further socio-economic impacts in remote locations.

This study shows that groundwater abstraction contributes to hydrological connectivity among countries through moisture recycling. While atmospheric exchange among countries and basins have been studied before (Dirmeyer et al., 2009; Keys et al., 2017), this study provided an estimate of the downwind precipitation that is artificially and unintentionally introduced by moisture supply from groundwater abstraction. Precipitation can be an important natural capital and economic good in precipitation poor countries (Dirmeyer et al., 2009), and substantial investments are already made to manipulate precipitation (e.g., cloud seeding) (Zheng et al., 2020), or more generally secure water availability (e.g., South-North transfer programme in China) (Webber et al., 2017). At the same time, local groundwater abstraction is subject to high costs (e.g., energy, equipment and maintenance) (Salem et al.,

2018) and have negative consequences for local populations (e.g., groundwater depletion). Local and remote benefits of groundwater and irrigation management measures may or may not align. For example, increased groundwater depletion benefits downwind precipitation, but harms local water resources in the long term. However, increased irrigation efficiency can benefit both local crop productivity and contribute towards downwind precipitation. Hence, the presence and potential for groundwater-supplied precipitation across borders may have both technological and geopolitical implications. Therefore, a global collaboration can be important to manage and identify the terrestrial moisture recycling dynamics and its transboundary implications.

The transboundary effects of groundwater-based irrigation as atmospheric moisture recycling should be addressed and recognized as a water resource in national and international governance. A first study on moisture recycling governance has already been proposed (Keys et al., 2017), which illustrates the different ways a realistic integration of moisture recycling can be achieved by governmental institutions and classifies the networks and transboundary connections that exist between countries. Additionally, anthropogenic land-use changes are continuously modifying the flows between blue, green and atmospheric water, as they are closely interconnected. However, regulations and governance seem to apply mostly to blue water resources, excluding almost completely green water and atmospheric water (Te Wierik et al., 2020). As green and atmospheric water also account for a significant and vital part of our freshwater resources that can be modified locally and in remote locations by groundwater abstraction and irrigation, a common land and water governance should be implemented.

4.4 Limitations and Uncertainties

Residuals in the data-assimilation, resulted in discrepancies between the input and output data on average of about 10 $km^3\ yr^{-1}$, i.e., representing the moisture lost in the model calculations and tracking (Figure 14). The fraction lost between the groundwater abstraction input and the resulted P_{gw}, is on average around 1.6 %, for the 30-year period. However, this discrepancy doesn't alter the results significantly, and the overall temporal and seasonal variabilities remain the same.

Further limitations in this study come from the uncertainties in the groundwater data. As our groundwater data does not account for unregulated groundwater abstraction, that is not reported. This could be significant in regions like northern India and Pakistan (Wada, Van Beek, & Bierkens, 2012), where discrepancies in the groundwater data may exist. Additional uncertainties in the data may be produced by the oversimplification of the estimations of water demand and water use for irrigation. Additionally, for a more realistic estimation of groundwater abstraction dependent precipitation, it is necessary to consider the fraction of groundwater abstraction at a country level that is used for irrigation. Furthermore, irrigation practices can present several types of water loss, like runoff, deep soil percolation and transport losses that are not accounted for in this simulation. Water losses can significantly vary from one irrigation system to another, and each technique can have different influences

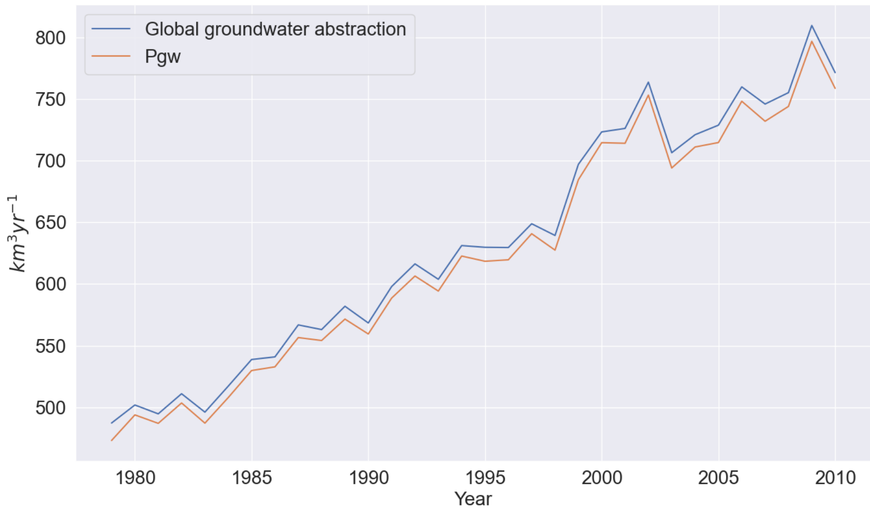

Figure 14. Global values of groundwater abstraction compared to $\boldsymbol{P}_{\mathbf{gw}}$, from 1980 to 2010.

in the total evaporation (Rohwer et al., 2007). However, water losses, irrigation systems and efficiencies were not considered in this research.

Other uncertainty lies in the reanalysis data. It is a challenge to model atmospheric dynamics and accurately track precipitation backwards or evaporation forward. Therefore, limitations of this study may also result from modelling assumptions and simplifications. Nevertheless, good interpretations can be made by knowing the geographical regions of origin of the evaporation and the distribution patterns of the produced P_{gw} globally.

4.5 Future research outlook

Additional research is needed to better understand the fate of groundwater abstraction. To track not only the sources and sinks of groundwater-based irrigation, but also its trajectory. This could help identify more clearly the hydrological connectivity between neighbouring countries and basins and the impact of upwind evaporation on downwind precipitation. Furthermore, a distinction could be made to separately track groundwater depletion, to estimate the precipitation that is sustained by the water loss in aquifers. Additionally, it would be important to consider the fraction of groundwater abstraction that is used for irrigation, calculated either by country or at a continental level, since the contribution of groundwater to the different sectors, like agriculture, domestic and industrial varies significantly between regions. Also, improvements and updates of the global groundwater abstraction data set is needed, and to consider more recent years, in order to properly identify the latest trends. Further research on evaporation from groundwater-base irrigation should focus on the different irrigation systems and their efficiency, also considering groundwater runoff and percolation. Overall, future climate research should continue to study the effects of irrigation, integrating social and ecological aspects as all are intimately interconnected, also considering climate change feedbacks. More importantly, as population continues to increase, it is imperative to analyse the possible outcomes of our unsustainable food production activities and the fate of our freshwater resources.

Accordingly, it is important to better understand the relations between irrigation, the climate and its influence on precipitation, as it could help us explain some of the discrepancies between the observed and the simulated climate responses over the continents (Puma & Cook, 2010). Furthermore, current irrigation practices cannot continue as usual without causing major freshwater scarcity and environmental distress in various regions of the world (Ahmad et al., 2002). Thus, to avoid further groundwater depletion in aquifers, more sustainable irrigation systems should be implemented and analysed, in hopes of reducing groundwater abstraction. As the amount of water that is available for human use is decreasing, due to increasing population and climate changes (Lakshmi et al., 2018), continuous research is needed in tracking and estimating our freshwater resources to better prepare, adapt and mitigate future challenges. Hence, the role of groundwater irrigation-based agriculture should be considered and included in climate models, as it has become a significant part of the hydrological cycle (Kueppers et al., 2007).

5 CONCLUSIONS

Groundwater abstraction and P_{gw} differ in geographical location and degree at a global scale, as around 40 % of the total groundwater abstracted in the world ends up in the ocean. Therefore, some of the countries that contribute the most to groundwater abstraction do not receive high volumes of P_{gw}, like India, the USA, Pakistan, Iran, with India being the largest net loser of groundwater resources. On the opposite end, China shows the largest groundwater net gain globally, and Canada and Russia due to their large territorial expansion also receive large volumes of P_{gw}. A disequilibrium in the net groundwater balance, suggests that groundwater-based irrigation practices are unsustainable, and that specific regions in the world are becoming more reliable on groundwater resources from a neighboring country to sustain a fraction of their precipitation. The seasonal climate variations and the irrigation seasons, lead to opposite trends in monthly groundwater balances at different times of the year. Countries like China and India present opposite trends in monthly groundwater balances, switching between gaining and losing groundwater. The corresponding seasonal variations between neighboring countries emphasizes the sensitivity to changes from groundwater abstraction usages in downwind precipitation, and the hydrological connectivity that exists even between remote locations.

Some of the most important basins in the world are losing their abstracted water to downwind P_{gw} (i.e. the Indus, Ganges, and Mississippi basins), due to not receiving high volumes of P_{gw}, that causes an overall groundwater loss in those regions that continues to intensify as more groundwater is used for irrigation. On the other hand, river basins in China are gaining groundwater (i.e the Yangtze, Tarim and Brahmaputra basins). The Brahmaputra basins receives the most of the P_{gw}, particularly during the spring months. The hydrological connectivity between basins seems to be evident between the Ganges, the Brahmaputra and the Yangtze, where the former groundwater abstraction seasonality is reflected in both the Brahmaputra and the Yangtze river basins. Moisture appears to follow an eastward and northward trajectory from India towards China.

In northern Pakistan and northern India the mean yearly ρ_{gw} can be up to 5 %, and an increasing trend is observed during the 30 year period. Overall, all selected countries and river basins increased their ρ_{gw} during the 30-year period. The Indus basin and in consequence Pakistan are the regions that most rely on groundwater abstraction to support a fraction of the precipitation, at a yearly scale. However, during the summer months of April and May, in northern India, in small regions of the Ganges basin the ρ_{gw} can reach up to 14 %. In western USA and in the middle east, the highest ρ_{gw} occurs during July and August, reaching in some regions of Iran a groundwater precipitation dependence of 12 %.

Based on the resulting trends of P_{gw} and ρ_{gw} from 1980 to 2010, and on the predictions of population growth and irrigation-based agriculture increases, P_{gw} and ρ_{gw} are also likely to increase and become more important for terrestrial ecosystems. However, the future for P_{gw} is uncertain as groundwater is being exploited unsustainably, more research is needed to understand the human-induced changes in atmospheric moisture fluxes and the consequences.

Further anthropogenic land-use modifications and groundwater exploitation, that continue to alter atmospheric moisture fluxes, can bring unexpected consequences on the regional climate and on the livelihoods of a large part of the human population in the near future. Particularly in regions that already present groundwater stress and high vulnerability to climatic changes, like the highly irrigated areas discussed above.

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