LETTER

How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis

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How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis

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Abstract

To assess the impact of climate change on freshwater resources, change in mean annual runoff (MAR) is only a first indicator. In addition, it is necessary to analyze changes of river flow regimes, i.e. changes in the temporal dynamics of river discharge, as these are important for the well-being of humans (e.g. with respect to water supply) and freshwater-dependent biota (e.g. with respect to habitat availability). Therefore, we investigated, in a global-scale hydrological modeling study, the relation between climate-induced changes of MAR and changes of a number of river flow regime indicators, including mean river discharge, statistical low and high flows, and mean seasonal discharge. In addition, we identified, for the first time at the global scale, where flow regime shifts from perennial to intermittent flow regimes (or vice versa) may occur due to climate change. Climate-induced changes of all considered river flow regime indicators (except seasonal river flow changes) broadly follow the spatial pattern of MAR changes. The differences among the computed changes of MAR due to the application of the two climate models are larger than the differences between the change of MAR and the change of the diverse river flow indicators for one climate model. At the sub-basin and grid cell scales, however, there are significant differences between the changes of MAR, mean annual river discharge, and low and high flows. Low flows are projected to be more than halved by the 2050s in almost twice the area as compared to MAR. Similarly, northern hemisphere summer flows decrease more strongly than MAR. Differences between the high emissions scenario A2 (with emissions of 25 Gt C yr^{-1} in the 2050s) and the low emissions scenario B2 (16 Gt C yr^{-1}) are generally small as compared to the differences due to the two climate models. The benefits of avoided emissions are, however, significant in those areas where flows are projected to be more than halved due to climate change. If emissions were constrained to the B2 scenario, the area with ecologically relevant flow regime shifts would be reduced to 5.4%–6.7% of the global land area as compared to 6.3%–7.0% in A2. In particular, under the B2 scenario, fewer rivers will change from perennial to intermittent (or transitional) river flows.

Keywords: climate change, river flow, flow regime, runoff

1. Introduction

When assessing the impact of climate change on freshwater resources at the global scale, it is most common to look at changes of mean annual runoff (MAR), i.e. the difference between the long-term averages of annual precipitation and evapotranspiration (Bates *et al* 2008). While changes in MAR are of major interest as they represent changes of total renewable water resources, the assessment of these changes alone is not sufficient for supporting sustainable water management. According to Gosling *et al* (2011), 'the common use of MAR as a measure of the response of hydrological systems to climate change is oversimplistic'. More specific analyses of climate change impacts on runoff components like groundwater recharge (Döll 2009), or on river discharge, i.e. runoff accumulated along the drainage direction, are required.

River discharge (also called river flow) varies over space and time. The relevant temporal scales range from minutes (e.g. in the case of flash floods) to decades (e.g. in the case of water resource assessments). River flow regimes describe the temporal patterns of flow variability. Knowledge about changing river flow regimes is paramount for assessing climate change risks related to freshwater. Estimation of changes in seasonality, interannual variability, statistical low and high flows, and floods and droughts is required to understand the impact of climate change on humans and freshwater ecosystems. River flow regime alterations affect humans with respect to water supply, navigation, hydropower generation and flooding, and they affect ecosystems with respect to habitat suitability for freshwater-dependent biota (Poff and Zimmerman 2010). Of particular relevance for freshwater ecosystems are shifts from perennial to intermittent flow regimes or vice versa, as they have a strong impact on biota living in the river (Bond *et al* 2010) and on riparian vegetation (Stromberg *et al* 2005).

Climate change impact studies for individual drainage basins mostly focus on changes of river discharge and aspects of its temporal variability, in particular seasonality (Kundzewicz *et al* 2007). Global-scale studies on the impact of climate change on river flow regimes are still rare (e.g. Milly *et al* 2002, Hirabayashi *et al* 2008, Döll and Zhang 2010). Our study was inspired by Gosling *et al* (2011) who applied a global hydrology model (GHM) (without the capability to route water downstream) and six catchment models to compute the impact of climate change on MAR in six catchments (one catchment model per catchment). In addition, they simulated the impact of climate change on monthly runoff as well as on monthly low and high flows, and related the changes of these regime indicators to changes in MAR. For the Rio Grande and the Okavango, they found that flow seasonality would not change under climate change, while it would change significantly in the other four catchments. Changes in low and high flows were found to be generally similar to changes of mean annual flows, with some exceptions.

The objective of this study was to better understand, at the global level, how climate-induced changes of indicators of the river flow regime, which are important for the well-being of humans and ecosystems, relate to changes of MAR. We wanted to find out how significant the results of resource-intensive ensemble studies on the impact of climate change on MAR would be for assessing impacts on river flow regimes. We used the state-of-the-art global water model WaterGAP (Alcamo *et al* 2003, Döll *et al* 2003) to translate four climate scenarios (as computed by two global climate models) into scenarios not only of MAR but also of a number of flow regime indicators, and of shifts between perennial and intermittent flow regimes. As flow regimes are affected by human water use, predominantly by irrigation, we also took into account the impact of climate change on irrigation water use. In section 2, both the WaterGAP model and the climate data are described. In addition, we introduce the investigated flow regime indicators, in particular how perennial and intermittent flow regimes are identified globally by WaterGAP. In sections 3 and 4, computational results are presented and discussed. Finally, conclusions are drawn.

2. Methods

2.1. Model description

With a spatial resolution of $0.5° \times 0.5°$ (55 km × 55 km at the equator), the global water resources and use model WaterGAP simulates water flows and storages as well as human water use for all land areas of the globe excluding Antarctica (Alcamo *et al* 2003, Döll *et al* 2003). For this study, WaterGAP 2.1g was applied. Water use, i.e. water withdrawals and consumptive water use, is estimated by separate models for the sectors' irrigation (Döll and Siebert 2002), livestock, households and industry. The WaterGAP Global Hydrology Model (WGHM) computes groundwater recharge, total runoff generation and river discharge, taking into account the impact of human water use and man-made reservoirs on river discharge (Döll 2009, Döll and Fiedler 2008). For each grid cell, the vertical water balance is computed, and the resulting runoff is routed laterally within the cell through a groundwater store and various surface water stores (so-called 'local' surface water bodies that are only fed by runoff of the cell, and so-called 'global' surface water bodies that also receive water from upstream cells). All groundwater generated within one cell is assumed to return to surface water within each grid cell. The effect of surface water bodies on water balance and flow dynamics is modeled by first routing the runoff generated within the grid cell through 'local' lakes, reservoirs and wetlands. The difference between precipitation and potential evapotranspiration is computed for each surface water type within the grid cell, thus taking into account the effect of the surface water balance on cell runoff. The water volume resulting from grid cell runoff is added to the discharge from the upstream grid cell and routed through 'global' lakes, reservoirs and wetlands, and through the river storage compartment. The total runoff of a grid cell may be negative as it includes the water balance of surface water bodies which may be negative. Negative surface water balances occur if water bodies fed from upstream evaporate

more water than falls as precipitation on the water bodies in the cell. Grid cell discharge is assumed to represent discharge in the largest river within the grid cell, and is routed to the next downstream cell according to the global drainage direction map DDM30 (Döll and Lehner 2002). WaterGAP is tuned in a basin-specific manner against long-term average discharge at 1235 gauging stations (discharge data provided by GRDC, grdc.bafg.de), by adjusting 1–3 model parameters (Hunger and Döll 2008).

Important WaterGAP inputs include time series of monthly values of climate variables as well as information on soil and land cover. Monthly climate data are downscaled to daily data, in the case of precipitation using the available number of wet days per month. Monthly climate data, except for precipitation, are provided by the CRU TS 2.1 data set (Mitchell and Jones 2005). As precipitation input, 0.5° gridded monthly time series of the GPCC Full Data Product Version 3 (Rudolf and Schneider 2005) were used, together with the number of wet days from the CRU TS 2.1 data set.

2.2. Modeling climate change impacts

We considered four different climate change scenarios, comparing runoff and river flow regimes resulting from the climate during the time period 1961–90 to runoff and flow regimes resulting from the climate during 2041–70 (the 2050s). The two IPCC greenhouse gas emissions scenarios A2 and B2 (Nakicenovic and Swart 2000) were translated into climate change scenarios by two state-of-the-art global climate models, the ECHAM4/OPYC3 model (Röckner *et al* 1996, hereafter referred to as ECHAM4) and the HadCM3 model (Gordon *et al* 2000). In the A2 scenario, emissions increase from 11 Gt C yr^{-1} (CO_2-equivalent) in 1990 to 25 Gt C yr^{-1} in the 2050s, but they only increase to 16 Gt C yr^{-1} in the case of scenario B2. Due to large climate model uncertainties, the same emissions scenarios are translated to rather different climate scenarios, in particular regarding precipitation.

Changes in mean monthly precipitation and temperature between the periods 1961–90 and 2041–70 as computed by the climate models were used to scale the grid cell values of observed monthly precipitation and temperature between 1961–90 that drive WaterGAP in the control run (delta change method). In a first step, the climate model data were interpolated from their original resolutions to the WaterGAP resolution of 0.5° × 0.5°. Then, in the case of temperature, observed values were scaled by adding to them the difference of the climate model values of future (2041–70) and present-day (1961–90) temperature. The 30 yr perturbed precipitation time series was produced by multiplying observed values by future climate model precipitation as a ratio of the present-day precipitation. If present-day monthly precipitation was less than 1 mm, precipitation was scaled additively, like temperature. The impact of changed interannual variability and the predicted increased variability of daily precipitation could not be taken into account in this study due to the delta change method.

Finally, the impact of altered radiation, humidity or wind speed on evapotranspiration was also neglected.

We simulated not only the impact of climate change on runoff but also on irrigation water use. Thus, the future flow regimes analyzed in this study are impacted by climate change impacts on both runoff and irrigation water use. Irrigation water use in each grid cell is computed as a function of irrigated area (Siebert *et al* 2005) and the 30 yr temperature and precipitation time series. To isolate the impact of climate change, we kept the irrigated area as well as domestic, industrial and livestock water uses constant at the level of the year 2002 in all simulations. Equally, dams remained constant at the 2002 level. Differently from river discharge, computed runoff is essentially unaffected by human water use and thus by the impact of climate change on irrigation water use (except for some effect of water use on the extent of surface water bodies which affects evapotranspiration).

2.3. Flow regime indicators

All indicators were computed based on 30 yr of monthly values. We considered the impact of climate change on MAR (R_{mean}) and on the following indicators of the river flow (discharge) regime in each 0.5° grid cell.

- Q_{mean}: mean annual river discharge.
- Q_{90}: monthly discharge that is exceeded in nine out of ten months (low flow).
- Q_{10}: monthly discharge that is exceeded in one out of ten months (high flow).
- Q_{DJF}: mean river discharge in December to February season.
- Q_{MAM}: mean river discharge in March to May season.
- Q_{JJA}: mean river discharge in June to August season.
- Q_{SON}: mean river discharge in September to November season.

All discharge indicators represent the actual discharge as affected by human water withdrawals. In addition, we also analyzed the climate impact on mean annual river discharge that would occur without any human water withdrawals.

Furthermore, we computed shifts from perennial to intermittent river flow regimes and vice versa due to climate change. There are no general definitions for perennial rivers versus intermittent rivers. Wilhelm (1997) stated that intermittent rivers fall dry at least one month per year. In the US National Hydrography Dataset (USGS 2000), rivers are classified as 'intermittent' if they 'contain water for only part of the year, but more than just after rainstorms and at snowmelt', and 'perennial' if they 'contain water throughout the year, except for infrequent periods of severe drought'. Based on monthly discharge during 1961–90 (with anthropogenic impact, i.e. reservoirs and water withdrawals), we defined three regime types and determined the regime type of each grid cell using WaterGAP. If more than 350 out of the 360 months had a discharge value larger than a threshold value of 0.0001 km^3/month (0.04 m^3 s^{-1}), the cell was classified

as 'strictly perennial'. If this was the case in less than 321 months, it was classified as 'strictly intermittent', otherwise as 'transitional'. The classification algorithm was derived by trial-and-error based on digital data sets that represent information on perennial and intermittent river reaches from maps, the VMAP0 and ESRI Big Rivers data sets. The VMAP0 data set is an updated version of the Digital Chart of the World and contains 'streams/rivers' which are either 'non-perennial/intermittent/fluctuating' or 'perennial/permanent' (VMAP0 hydrography layer, file hydro-water-course-l.shp, field HYC-DESCRI). Also based on the Digital Chart of the World, ESRI produced a global Big Rivers layer with the attributes 'perennial' and 'intermittent' in which only large rivers are included. The threshold value may represent a situation where river flow velocity is 0.1 m s^{-1}, wetted width is 20 m and water depth is 2 cm, i.e. when the river is essentially dry. A flow regime shift was identified if classification differed for the present and future climates, and the number of months with discharge below the threshold changed by at least 3.

3. Results

3.1. Climate change impacts on MAR and discharge

Averaged over 30 yr, runoff is approximately the difference between mean precipitation P and mean actual evapotranspiration (AET), and is essentially unaffected by human water withdrawals. Figure 1(a) shows the per cent change of MAR until the 2050s (2041–70) as compared to the period 1961–90, in case of emissions scenario A2, using climate scenarios derived by either the climate model ECHAM4 or HadCM3. In figure 1(a), green and pink color mostly indicate cells with a negative mean runoff, which only occurs if there are lakes or wetlands that are fed by discharge from upstream. Surprisingly, there are a number of cells where MAR ($P-$AET) will become less negative, i.e. increase, even though the surrounding positive runoff values decrease (due to decreased precipitation and increased temperature), e.g. in northeastern Brazil and southern Africa and southern Australia (figure 1(a), in green). This is caused by decreased inflow into the surface water bodies from upstream cells, which leads to a reduction of the effective open water area and thus a reduced cell AET. If this decrease of AET exceeds the decrease of P due to climate change, MAR becomes less negative.

Maps of MAR changes like those of figure 1(a) do not show changes in river flow volumes unless the grid cell is at the upstream edge of the river basin and thus does not receive any inflow from an upstream cell. For all other grid cells, climate change impact on river discharge is different from climate change impact on runoff because discharge aggregates runoff from cell to cell along the drainage direction. Hence the locations of many rivers that are fed by large upstream areas are clearly visible in the maps that show the impact of climate change on discharge (figure 1(b)–(d)) but not in the runoff maps (figure 1(a)). Examples include the Amazon, São Francisco (northeastern Brazil), Nile, Zambezi, Mekong and Siberian rivers where

changes in upstream runoff are obviously carried downstream. The effect of flow accumulation and lateral routing can be analyzed by comparing the impact of climate change on mean runoff (figure 1(a)) with the impact of climate change on mean discharge that would occur if there were no human withdrawals (figure 1(b)). In the ECHAM4 A2 scenario, for example, mean river discharge of the Amazon in the downstream (eastern) section would increase even though runoff in these grid cells would decrease. Discharge change reflects more strongly the increased runoff in the upstream (western) part of the basin. In the HadCM3 A2 scenario, both discharge and runoff decrease in the downstream section of the Amazon, but discharge less than runoff as runoff decrease in the upstream part of the basin is smaller than in the downstream part. In this scenario, it is the São Francisco in northeastern Brazil that is predicted to have an increased mean river discharge in its downstream section even though runoff is reduced very strongly there (figure 1(b)). At a smaller spatial scale, the strong runoff decrease at the North American Pacific coast, for the HadCM3 A2 scenario, translates into a smaller decrease of discharge due to more runoff in the headwater area.

Actual mean annual river discharge can be much smaller than natural mean annual discharge that results from the aggregation of upstream runoff. Around the year 2000, mean annual discharge had decreased by more than 10% on one sixth of the global land area (excluding Antarctica and Greenland) compared to natural conditions without man-made reservoirs and water withdrawals (Döll 2009). As the same absolute changes to lower values result in higher per cent changes, per cent changes of actual river discharge due to climate change (figure 1(c)) are higher than per cent changes of river discharge that would occur if there were no human water withdrawals (figure 1(b)). For example, if river discharge is decreased by 50% due to water withdrawals, any per cent flow increase due to climate change would double as compared to considering natural flows. Due to the coarse change classes in figure 1, this effect is visible only in areas with strong anthropogenic discharge reductions (e.g. central USA and Canada, Spain, Turkey). For 7% (ECHAM A2) and 5% (HadCM A2) of the global land area (excluding Antarctica and Greenland), per cent changes of river discharge altered by human water withdrawals are at least 10 percentage points higher (e.g. 30% instead of 20%) than changes of discharge that is assumed to be unaffected by water withdrawals.

3.2. Climate change impacts on low and high flow

The broad global patterns of climate change impact on monthly low flows Q_{90} (figure 1(d)) are similar to the patterns for mean annual discharge Q_{mean} (figure 1(c)). The pattern of change of Q_{90} derived from the output of either of the two climate models is more similar to the pattern of change of Q_{mean} computed with the same climate model output than to the pattern of change of Q_{90} derived from the output of the other climate model. However, at smaller scales, there are significant differences between climate-induced changes of mean annual discharge and low flows. Per cent decreases
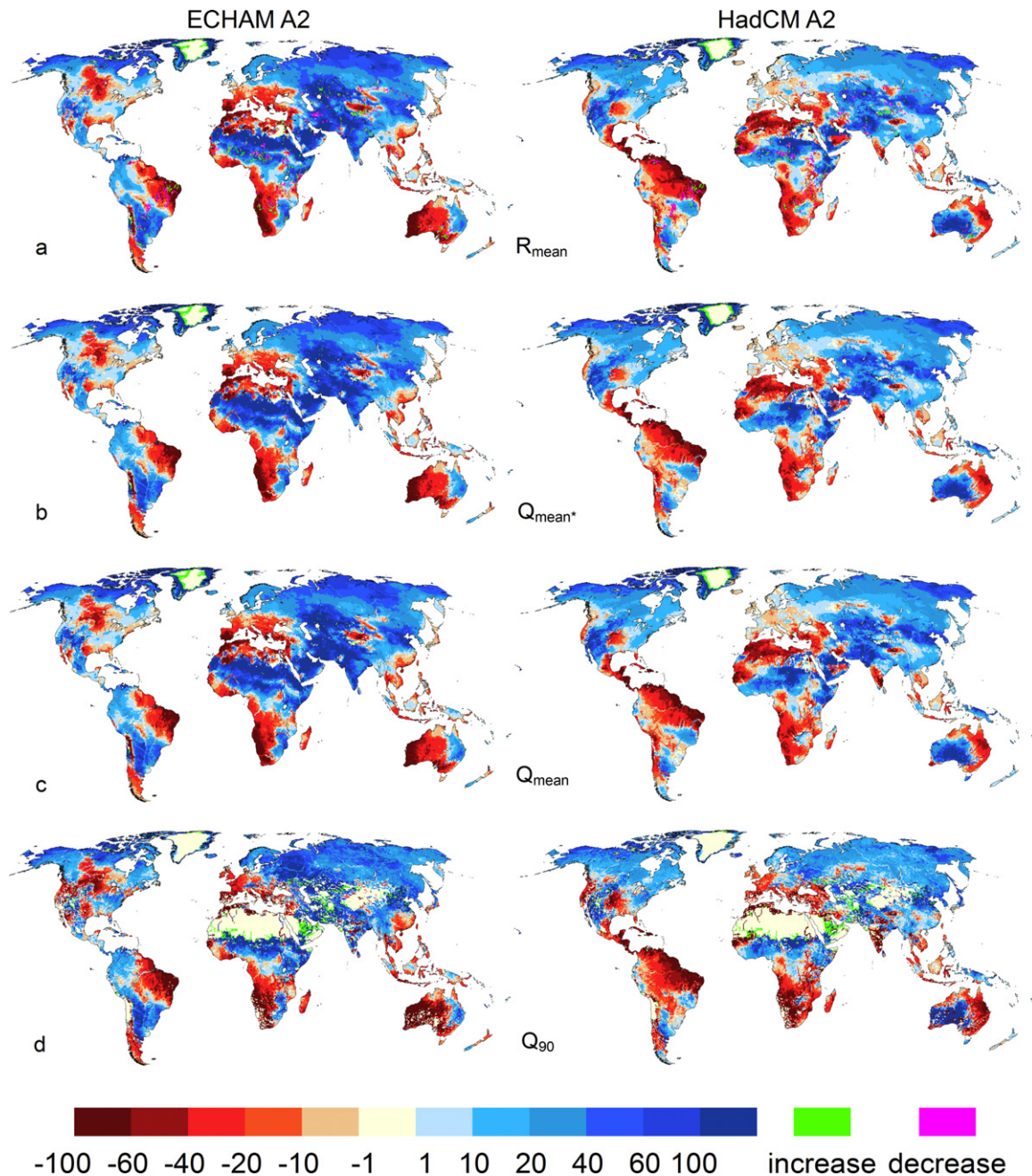
Figure 1. Impact of climate change on MAR R_{mean} (a), on mean annual river discharge Q_{mean*} that would occur without water withdrawals (b), on mean annual river discharge Q_{mean} (with water withdrawals) (c) and on low flows Q_{90} (with water withdrawals) (d) by the 2050s. Per cent changes between 1961–90 and 2041–70, as computed by WaterGAP applying climate change scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the IPCC greenhouse gas emissions scenario A2. For cells where MAR (a) is less than or equal to zero in 1961–90, runoff changes are indicated by green in the case of increasing future runoff (or less negative difference between precipitation and actual evapotranspiration) and pink in the case of decreasing (more negative) future runoff, while no change is represented by light yellow (class −1 to 1). For cells where discharge is equal to zero in 1961–90, increasing future discharge is indicated by green, while no change is represented by light yellow ((b)–(d)).

of Q_{90} are often higher than per cent decreases of Q_{mean}, e.g. in Australia and South America, and there are areas where Q_{90} decreases, while Q_{mean} increases (e.g. in Great Britain for ECHAM4 A2 or in western France for HadCM3 A2, figures 1(c) and (d)). The strong differences between the climate-induced per cent changes of mean annual flows and low flows become obvious if per cent change of Q_{90} as a fraction of per cent change of Q_{mean} is considered (relative

change, figure 2(a)). There are not many cells where the per cent changes of Q_{mean} and Q_{90} are rather similar (green color). Predominantly, the per cent change of Q_{90} is larger than that of Q_{mean} (dark yellow). Where Q_{mean} decreases in the future (indicated by cross-hatching in figure 2), this means that the relative discharge variability increases. For ECHAM4 A2, for example, this is the case in southern and northeastern South America, southern Africa, most of Australia, France
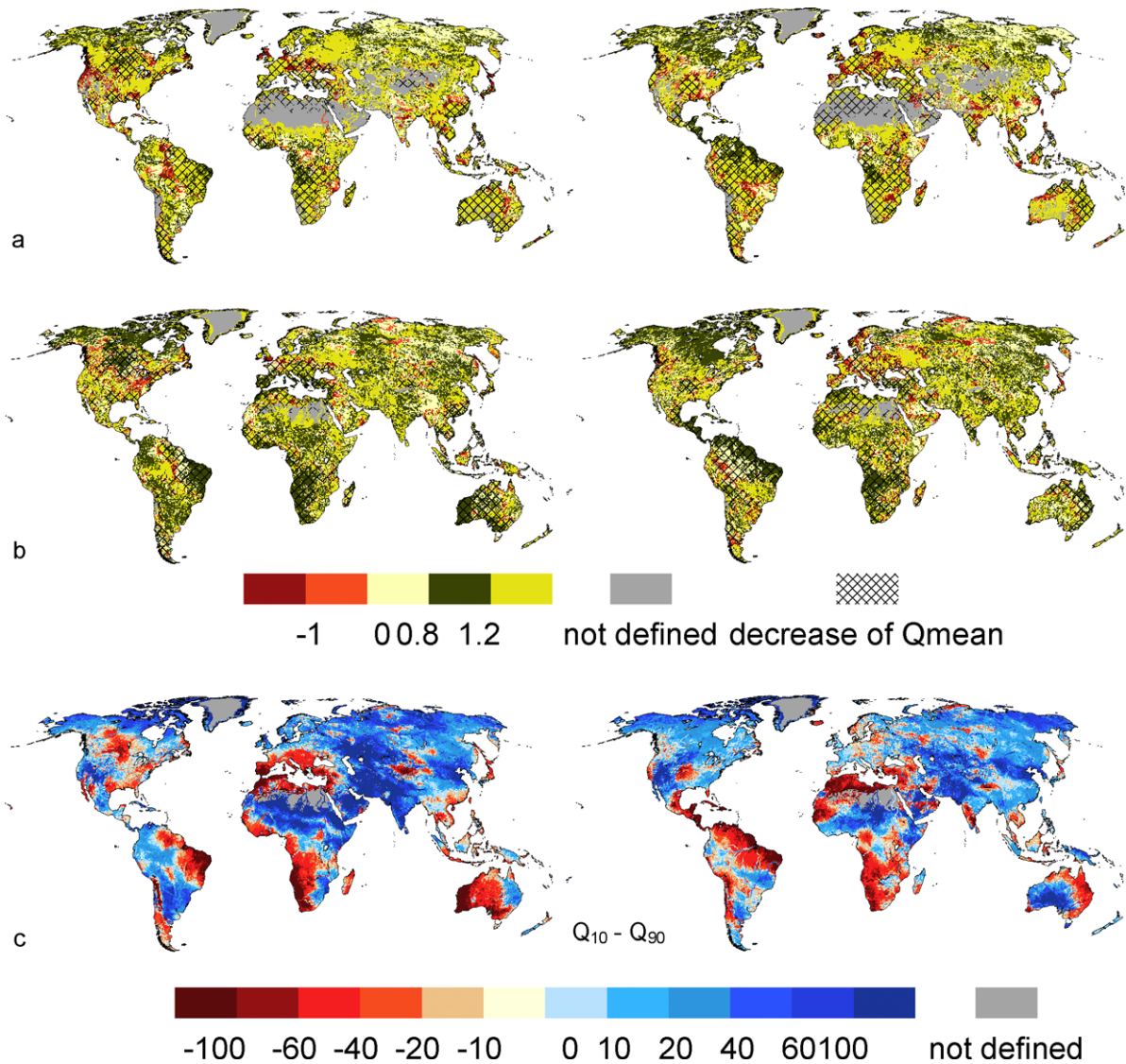
Figure 2. Climate change impact on low flows Q_{90} (a) and high flows Q_{10} (b) as compared to the climate change impact on mean annual river discharge Q_{mean}, and climate change impact on monthly flow variability (c), for climate scenarios ECHAM A2 and HadCM A2. Per cent changes of Q_{90} (Q_{10}) as a fraction of per cent changes of Q_{mean} between 1961–90 and 2041–70. Negative values indicate that the direction of change differs between Q_{mean} and Q_{90} (Q_{10}) ((a) and (b)). Per cent change of Q_{10} minus Q_{90} between 1961–90 and 2041–70 (c).

and South China (figure 2(a) left). Where Q_{mean} increases, dark yellow in figure 2(a) indicates that discharge variability is reduced. According to both climate models, Q_{90} increases more strongly than Q_{mean} in the eastern USA, Scandinavia and the European part of Russia. There, winter low flows will likely increase due to more winter precipitation as rain. However, in most of the Asian part of Russia and in some parts of Canada Q_{90} increases less then Q_{mean} (light yellow).

On a significant fraction of land all around the globe, the directions of change differ between Q_{90} and Q_{mean} (orange and red colors in figure 2(a)). Q_{90} is computed to decrease but Q_{mean} to increase in northern India, parts of the USA, the central part of South America and the northern Nile upstream of the Assuan High Dam (depending on the climate scenario). Cells where Q_{90} increases and Q_{mean} decreases are more rare and are located, among others, in Europe, e.g. in the Alps where winter low flows strongly increase due to higher temperatures and less water storage as snow.

The relative climate change patterns of the monthly high flows Q_{10} are similar to those of Q_{90} with respect to the dominance of grid cells with the same direction of change, but the percentage changes of Q_{10} and Q_{mean} are more similar, in particular where Q_{mean} decreases (figure 2(b)). Where Q_{mean} increases, the per cent change of Q_{10} is predominantly larger than that of Q_{mean} (dark yellow), indicating more strongly increased high flow discharge values. Grid cells with opposite signs of change for Q_{10} are as dispersed as in the case of Q_{90}. In some parts of Siberia, where Q_{mean} increases due to increased annual precipitation, decreased snow accumulation during winter leads to an absolute (red/orange) or relative (light yellow) decrease of Q_{10}. Q_{10} increases in the upstream areas of the Amazon even though Q_{mean} decreases significantly (HadCM3 A2, figure 1(c)). Where Q_{90} and Q_{mean} show opposite signs of change, Q_{10} and Q_{mean} mostly change in the same direction (e.g. western USA and India), and vice versa (e.g. eastern USA, compare

Table 1. Land area (in per cent of total land area of the Earth excluding Antarctica and Greenland) affected by changes of long-term average runoff and river flow regime indicators between 1961–90 and 2041–70, computed by WaterGAP applying climate change scenarios from the ECHAM4 and HadCM3 climate models, each interpreting the IPCC greenhouse gas emissions scenarios A2 and B2. In each field, the range of land area due to the use of the two climate models is given. The extreme classes of changes were chosen in order to see areas where values are at least halved (−50%) or doubled (>100%). The column 'not defined' refers to the area where the 1961–90 values of indicators are less than (only for R_{mean}) or equal to zero. P: mean annual precipitation (climate model output downscaled with delta change method). R_{mean}: MAR. Q^*_{mean}: mean annual river discharge (without water withdrawals). Q_{mean}: mean annual river discharge. Q_{90}: monthly discharge that is exceeded in nine out of ten months (low flow); here, the land area in the −10 to 10% change range also includes the 13–14% of the land area where both current and future Q_{90} is zero. The 'not defined' area refers to the 1–2% of the global land area where future Q_{90} stops being zero. Q_{10}: monthly discharge that is exceeded in one out of ten months (high flow). Q_{DJF}: long-term average river discharge in December to February season. Q_{MAM}: long-term average river discharge in March to May season. Q_{JJA}: long-term average river discharge in June to August season. Q_{SON}: long-term average river discharge in September to November season.

Change (%)	−100 to −50		−50 to −10		−10 to 10		10–100		>100		Not defined
Scenario	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	
P	0–0	0–0	13–15	11–15	44–53	48–56	31–41	29–40	0–2	0–2	0
R_{mean}	5–5	4–4	17–18	16–19	21–26	23–29	42–43	42–44	5–9	3–8	4
Q^*_{mean}	4–5	3–4	18–19	16–19	22–27	24–31	45–46	43–47	4–9	3–8	1
Q_{mean}	5–5	3–4	18–19	16–20	22–27	23–31	44–44	42–46	5–10	3–9	1
Q_{90}	8–9	6–7	16–18	15–18	28–32	29–35	34–36	33–38	6–9	5–10	1–2
Q_{10}	5–5	4–5	18–18	16–18	22–26	23–29	41–42	42–43	6–11	4–11	2
Q_{DJF}	6–7	6–7	17–18	16–17	18–25	19–28	42–42	41–45	7–14	5–12	2
Q_{MAM}	5–5	4–4	20–20	18–18	18–22	18–23	41–41	43–46	10–16	7–14	1
Q_{JJA}	6–7	4–5	24–27	22–26	24–29	26–30	30–34	33–35	5–10	5–11	2
Q_{SON}	8–9	6–7	20–26	18–29	19–22	19–23	36–40	35–44	6–13	5–11	2

figures 2(a) and (b)). The difference between Q_{10} and Q_{90} can be regarded as a measure of temporal variability of monthly river flows, with 8 out of 10 months having discharge within this range (figure 2(c)). It is strongly correlated with per cent change of Q_{mean}, with some exceptions in snow-influenced regions.

Globally, Q_{90} increases less with climate change than Q_{mean}. By the 2050s, Q_{90} will have increased by 10–100% on only 34–36% for emissions scenario A2 (33–38% for B2) of the land area while the corresponding area for Q_{mean} is 44–44% (43–46%) (table 1). The area where Q_{90} decreases to less than 50% of its 1961–90 value is almost twice as large as the corresponding area for Q_{mean}. Differently from Q_{90}, the land area fractions of changes in Q_{10} are very similar to those of Q_{mean} (table 1). Besides, the land area fractions of changes in Q_{mean} are very similar to those of R_{mean}, but not to those of precipitation P (table 1). On about half the global land area, precipitation is projected to change by less than 10%, while this is the case for only about a quarter of the global land area for MAR and discharge (table 1). Extreme decreases by more than 50% are not projected at all for precipitation.

3.3. Climate change impacts on seasonal river discharge

Figure 3 shows the very heterogeneous pattern of per cent change of seasonal river discharges as a fraction of the per cent change of Q_{mean} (relative seasonal discharge changes). Climate change will lead to strong changes in the seasonality of discharge almost everywhere. Only on a very small part of the land area will seasonal discharge change approximately like annual discharge (shown in dark green in figure 3). For both climate models, seasonality will remain stable with increasing Q_{mean} in parts of Canada and Australia (while, for

Australia, regions with increasing discharge strongly differ between the two climate models, compare figure 1(c)). In northeastern Brazil and southern Africa, seasonality will remain stable with strongly decreasing Q_{mean}. In most regions north of 30–35°N (southern rim of the Mediterranean Sea), summer discharge Q_{JJA} is projected to decrease. In areas with decreasing Q_{mean} (like in central Europe), Q_{JJA} will decrease more (dark yellow in figure 3), while even in many areas with increasing Q_{mean}, like in northern Europe, Q_{JJA} will decrease (orange and red in figure 3). For winter flows, the opposite is visible (figure 3). In Mexico, a shift from winter/spring to autumn discharge can be recognized (in particular for ECHAM4 A2). In South Asia, Q_{JJA} is projected to increase more strongly than Q_{mean} due to a strengthening of the monsoon, while Q_{DJF} may even decline in some areas.

Patterns of relative seasonal river discharge changes are related to patterns of relative low and high flow changes (figures 2(a) and (b)). If, for example, low flows during 1961–90 occur in northern hemisphere winter, like in the Alps and the European part of Russia, both Q_{DJF} and Q_{90} increase due to increased temperatures and thus rainfall and runoff in winter. In Siberia, where the temperature rise is not sufficient to convert snowfall into rainfall, the increases of both Q_{DJF} and Q_{90} are much smaller. The decrease of spring discharge in eastern USA (with increasing Q_{mean}, figure 3) is connected (at least for ECHAM4 A2) with a clear increase in Q_{90} (figure 3). Globally, more land area will suffer from decreased Q_{JJA} than from decreased Q_{mean} (table 1). This is also true for Q_{SON} but here the two climate models differ more strongly.

3.4. Shifts of river flow regimes from perennial to intermittent or vice versa due to climate change

To assess the capability of WaterGAP to identify the flow regime types 'perennial' and 'intermittent', we compared the
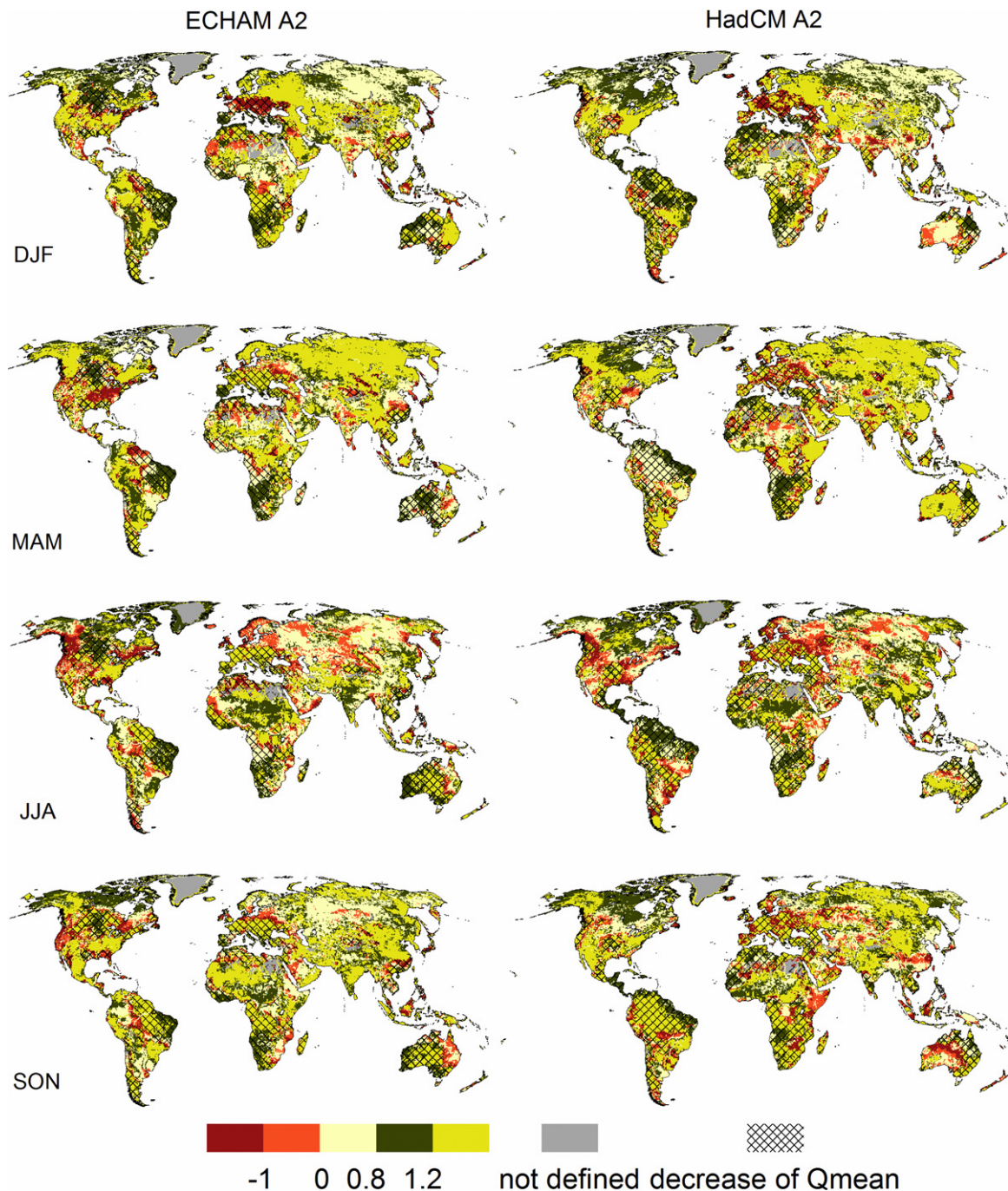
Figure 3. Climate change impact on mean seasonal river flows as compared to the climate change impact on long-term average annual river discharge Q_{mean} for climate scenarios ECHAM A2 and HadCM A2. Per cent changes of mean river discharge from December to February (DJF), March to May (MAM), June to August (JJA) or September to November (SON) are shown, as a fraction of per cent changes of Q_{mean}, between 1961–90 and 2041–70. Negative values indicate that the direction of change differs between Q_{mean} and the seasonal discharges.

WaterGAP map with information from maps as captured in the VMAP0 and ESRI Big Rivers data sets. The spatial patterns derived from WaterGAP are similar to the patterns on the maps. WaterGAP appears to underestimate intermittency in northeastern Brazil, northern, northeastern and central Australia, Ethiopia and central India, while it identifies intermittent rivers in Spain, different from the maps. However, in northeastern Brazil, many large rivers have been made perennial by dams. While dam effects on river flows are simulated by WaterGAP, the impact of dams

may not be reflected in maps, in particular if they predate dam construction. The intermittent grid cells identified by WaterGAP in Siberia are caused by a lack of water flows during the cold period, and Russian maps might not label such arctic rivers as intermittent.

The global pattern of flow regime shifts under the impact of the HadCM3 A2 climate scenario (figure 4) reflects both the current flow regime and the future climate changes. Flow regime shifts from perennial to transitional or intermittent until the 2050s are projected, for example, for
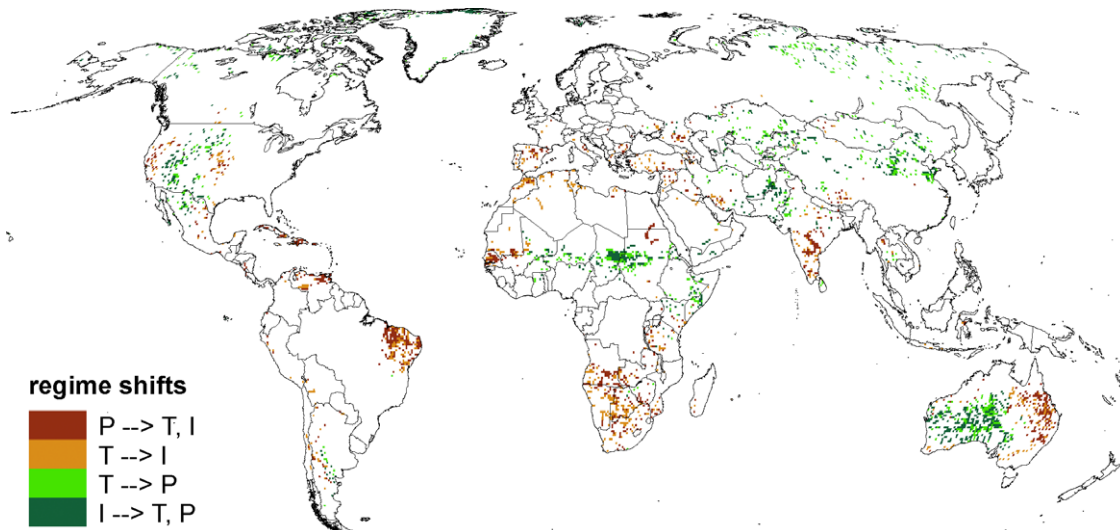
Figure 4. Regime shifts among perennial (P), transitional (T) and intermittent (I) river flow regimes occurring between 1961–90 and 2041–70 due to climate change (as computed with WaterGAP, climate scenario HadCM3 A2).

California, the Caribbean, southern Africa, West Africa and around the Mediterranean Sea (figure 4). Such shifts are also computed for northeastern Brazil and northeastern Australia but, as discussed above, the current regime may already be intermittent (misclassified by WaterGAP). Flow regime shifts to the perennial regime may occur in western USA, parts of China, western and central Australia and on the southern rim of the Sahara. Flow is computed to become perennial in parts of Siberia, Canada and Alaska due to warmer winters. There is certainly a significant correlation between changes in R_{mean} and flow regime shifts under a given climate scenario (compare figure 1(a) right-hand side to figure 4). An even higher correlation is observed between changes in statistical low flow Q_{90} (figure 1(d) right-hand side) and flow regime shifts as Q_{90} takes into account changes in temporal variability (consider, for example, Spain and northern India). With the HadCM3 A2 climate scenario, 6.3% of the global land area (except Greenland and Antarctica) will have experienced flow regime shifts by the 2050s, with the corresponding impacts on freshwater-dependent biota. On 1.8% of the land area, the flow regime will no longer be perennial, and also on 1.8% it will no longer be intermittent. Transitional regimes shift to intermittent ones on 1.4% of the land area, and to perennial ones on 1.3%. Extreme regime shifts from perennial to intermittent, where the fraction of months with (almost) no discharge increases from less than 3% to more than 11% (section 2.3), occur on 0.4% of the land area, e.g. in Venezuela, the Caribbean and India. The reverse occurs on 0.2% of the land area, e.g. in China, Pakistan and the Sahel. With the ECHAM4 A2 scenario, flow shifts are identified on 7.0% of the global land area, with dominant shifts to wetter conditions. In the case of B2 emissions, flow shifts are projected to occur on only 5.4% (HadCM3) or 6.7% (ECHAM4) of the global land area. In particular, the area where flow will no longer be perennial would be particularly reduced. This is true for both climate models.

4. Discussion

It is well known that different global climate models translate the same greenhouse gas emissions scenario into strongly differing climate change scenarios, with precipitation changes being more uncertain than temperature changes (Bates *et al* 2008). Therefore, the presented climate change impacts, which are based on the scenarios of only two climate models, can only be considered to be illustrative but do not show the full range of uncertainty. The aim of this study was not to derive quantitative estimates of climate change impact but to improve our understanding of the relation between the impact of climate change on MAR and the impact of climate change on river flow regime indicators that are more relevant for water management purposes. In this section, we wish to discuss the quality of the modeled impacts on the river flow regime for a given climate change scenario, considering the capability of WaterGAP to simulate river flow regimes under historical climate (section 4.1), and the way in which GCM scenarios are translated into climate input for WaterGAP (section 4.2). In addition, we discuss the relevance of the computed flow regime indicators for the rivers within each grid cell (section 4.3).

4.1. Quality of the modeled flow regime indicators as related to the quality of the hydrological model

Because WaterGAP is tuned against mean annual discharge, it can model MAR and mean annual discharge reasonably well for most grid cells that are located within the 1235 tuning basins covering 48.7% of the global land area excluding Greenland and Antarctica (Hunger and Döll 2008). However, model results for individual grid cells can be completely wrong, in particular if they are in semi-arid/arid areas outside calibration basins (e.g. in western and central Australia). Model calibration also leads to more realistic values for statistical monthly Q_{90} and Q_{10} and mean monthly discharges, but this is mainly caused by adjustment of the mean and not of

the variance. Nevertheless, monthly Q_{90} and Q_{10} were shown to be estimated quite well for most observation stations (Döll *et al* 2003). A comparison of observed and modeled flow regime indicators for four river discharge gauging stations (not shown) indicated that Q_{90} and Q_{10} are modeled quite well, while mean monthly and seasonal discharges may suffer from an inadequate simulation of snow and ice, or water storage in surface water bodies.

4.2. Quality of the modeled flow regime indicators as related to the translation of GCM climate change scenarios into input for the hydrological model

It cannot be assessed how well WaterGAP (or any other hydrological model) can translate climate change to change in runoff and discharge, as appropriate observations are still lacking. Certainly, consideration of the method to produce climate input for WaterGAP under conditions of changed climate is crucial for understanding the uncertainty of the computed flow regime changes. The applied delta change method does not take into account future changes in the interannual variability of climate variables, as mean monthly changes are added to (or multiplied by) time series of observed climate. This will likely lead to an underestimation of the changes in Q_{90} and Q_{10}, and of shifts between perennial and intermittent flow regimes, as interannual climate variability is projected to increase in the future on all temporal scales (Bates *et al* 2008). The delta change method can also lead to implausible shifts in the seasonality of precipitation if the climate model does not model the observed seasonality of precipitation reasonably well. This affects the analysis of seasonal river flows. Alternative methods may avoid these problems but have other drawbacks. Statistical bias correction of climate model output against observed climate, for example, can represent future change of climate variability. However, bias correction alters the climate change signal for specific locations and months (Hagemann *et al* 2011). For most river basins, the long-term average temperature change was found to decrease by bias correction as compared to the original climate model runs, and the precipitation change was found to increase for most river basins (Hagemann *et al* 2011). The uncertainty due to statistical bias correction may be of the same order of magnitude as the uncertainty related to the choice of the GCM or the applied global hydrological model (Hagemann *et al* 2011). An additional constraint of our study is that we did not take into account changes of radiation, humidity or wind speed.

4.3. Relevance of the computed river flow regime indicators

As runoff can be conceptualized as a vertical flow of water per unit land area, with units of, for example, mm yr^{-1}, the runoff computed for any 0.5° grid cell can be regarded as an average value of the grid cell. In contrast, river discharge is defined as the lateral flow of water along a river channel. In the case of global-scale models, it is assumed that there exists exactly one river channel in each grid cell, while in reality there may be many (in particular small tributaries to

one main river). While computed grid cell discharge can be thought of as the sum of the discharges in all river channels within the grid cell, the temporal variability of river discharge is expected to vary strongly among the diverse river channels. For example, small tributaries are expected to have a much higher temporal variability than the main river, e.g. a larger Q_{90}-to-Q_{mean} ratio. Regarding the definition of perennial and intermittent flow regimes, a grid cell identified as perennial in WaterGAP may contain small intermittent tributaries. This has to be taken into account when a map of regime shifts like the one shown in figure 4 is interpreted. Computed river flow regime indicators and their changes should be assumed to be relevant only for the main river within each grid cell.

5. Conclusions

How is the impact of climate change on river flow regimes related to the impact on mean annual runoff (MAR)? With the exception of seasonal flows, climate-induced future changes of the considered river flow regime indicators broadly follow the spatial pattern of increases and decreases of MAR generated in the grid cell. However, there are important differences at the sub-basin and grid cell scales. In grid cells where river flow is fed from upstream cells, the impact of climate change on mean river discharge represents the aggregated response of upstream runoff to climate change, and differs from the impact on MAR. Downstream reaches of major rivers often show an opposite sign of change with respect to MAR and mean annual discharge. Where natural river discharge has been reduced significantly due to human water withdrawals, relative changes (expressed in per cent change) of actual mean river discharge are higher than relative changes of natural mean river discharge or mean runoff. On about 5% of the global land area, the impact of climate change by the 2050s would be underestimated by at least 10 percentage points if the influence of water withdrawals were neglected.

MAR is projected to increase by more than 10% on 50% of the global land area (excluding Antarctica and Greenland) by the 2050s. This is also true for mean annual river discharges and high flows but not for low flows. The area where low flows will increase by more than 10% is approximately eight percentage points smaller. On a significant part of the land area, low flows may decrease even though mean annual river discharges increase.

Climate-induced changes of seasonal river flows are not correlated with changes of MAR. Our global-scale study confirms projected changes of seasonal river flow dynamics in basins where winter precipitation currently is dominated by snowfall. In these basins, winter or spring flows are likely to increase, while summer flows are likely to decrease. In most regions north of 35°N, summer discharge is projected to decrease. Of all four seasonal discharges, June–July–August discharge shows the largest global land fraction with significant river flow decreases and the smallest fraction with significant flow increases, even though in the monsoon areas it is projected to increase.

Flow regime shifts among perennial, transitional and intermittent regimes indicate strong changes in habitat conditions for freshwater biota and therefore a strong impact of climate change on freshwater ecosystems. Flow regime shifts by the 2050s may occur on 6.3–7.0% (A2) or 5.4–6.7% (B2) of the global land area, mainly in semi-arid areas as well as in some cold areas (from intermittent to transitional or transitional to perennial only) where during 1961–90 there was (almost) no river flow in the winter months due to freezing. Shifts from perennial to intermittent (intermittent to perennial) flow regimes correlate with decreases (increases) in mean runoff, but even more with decreases (increases) in statistical low flows.

This study has improved our understanding of the relation between climate-induced changes of MAR, the major indicator of the impact of climate change on freshwater resources, and river flow regime indicators that are relevant for the well-being of humans and freshwater ecosystems. We found that the differences between changes of MAR related to the use of two different climate models are still larger than the differences between the change of MAR and the change of the investigated river flow indicators (except for seasonal discharge). If larger ensembles of climate models were considered, the spread of computed MAR changes would be even larger (Gosling *et al* 2010). Therefore, broad conclusions about climate-induced changes of river flow regimes can be derived from ensembles of mean annual and seasonal runoff. Unfortunately, it seems impossible to define general rules for translating changes of MAR into changes of river flow regime indicators because the relation between these changes depends on the climate model applied.

Acknowledgments

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