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Key Points:
- A global assessment of trends in streamflow covering 1951–2010 and 14 subcontinental regions
- The significance of regional trends is assessed, revealing complex spatiotemporal change patterns
- Indicators of mean and extreme (low and high) streamflow often share the same sign of change

Supporting Information:
- Supporting Information S1

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Observed Trends in Global Indicators of Mean and Extreme Streamflow

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Abstract This study investigates global changes in indicators of mean and extreme streamflow. The assessment is based on the Global Streamflow Indices and Metadata archive and focuses on time series of the annual minimum, the 10th, 50th, and 90th percentiles, the annual mean, and the annual maximum of daily streamflow. Trends are estimated using the Sen-Theil slope, and the significance of mean regional trends is established through bootstrapping. Changes in the indices are often regionally consistent, showing that the entire flow distribution is moving either upward or downward. In addition, the analysis confirms the complex nature of hydrological change where drying in some regions (e.g., in the Mediterranean) is contrasted by wetting in other regions (e.g., North Asia). Observed changes are discussed in the context of previous results and with respect to model estimates of the impacts of anthropogenic climate change and human water management.

Plain Language Summary Studies of trends in streamflow data from across the globe are essential for understanding patterns and changes in water availability (e.g., regions of deficit and abundance) and evaluating the fidelity of global water availability models. This study evaluates historical trends in streamflow data, using a new data set of observations from over 30,000 sites around the world. The study is comprehensive, looking at changes in low flows (defined as the lowest day of flow in each year), average flows, and high flows (the highest day of flow in each year). An interesting outcome is that where trends are present in a region, the direction of the trend is often consistent across all indices for that region (consistently drier or wetter), as distinct from the possibility of stronger extremes (wetter maximums and drier minimums).

1. Introduction

Among the most important implications of anthropogenic climate change are the potential for both large-scale changes in water availability (Greve et al., 2018; Schewe et al., 2014) and increases in the magnitude and occurrence of floods and droughts (Hirabayashi et al., 2013; Prudhomme et al., 2014). Simultaneously, the unprecedented scale of on-ground human interventions in the water cycle—including reservoir construction, irrigation, and land cover change—is also affecting terrestrial hydrology and might even exceed the impact of future climate change in some regions (Haddeland et al., 2014).

To better anticipate future changes in the world's water resources and hydrological extremes, it is essential to analyze already observed changes. Among all components of the terrestrial water cycle, streamflow (including river flow) is arguably the variable that has been monitored with the highest station density and the longest temporal coverage (Fekete et al., 2012, 2015; Hannah et al., 2011) and is thus the best we have for investigating past changes in water resources and hydrological extremes.

An increasing number of regional studies have drawn a complex picture of trends in annual streamflow statistics over several (sub)continents, including North America (Burn & Elnur, 2002; Douglas et al., 2000; Hodgkins et al., 2017; Lettenmaier et al., 1994; Lins & Slack, 1999; Mallakpour & Villarini, 2015; McCabe & Wolock, 2002; McClelland et al., 2006), South America (Genta et al., 1998; Marengo et al., 1998; Pasquini & Depetris, 2007), Europe (Blöschl et al., 2017; Gudmundsson et al., 2017; Hannaford et al., 2013; Hisdal et al., 2001; Hodgkins et al., 2017; Stahl et al., 2010), and Asia (Adam & Lettenmaier, 2008; MacDonald et al., 2007; McClelland et al., 2006; Tananaev et al., 2016). It is, however, difficult to generalize from these assessments, as they are often tailored to match conditions in a specific continent, consider different periods, and have variations in method and selected indices. Furthermore, little work has been published for several important landmasses, including Africa and large parts of Eurasia.

Of the global studies that focus on trends in observed streamflow, some are dedicated to changes in the total freshwater fluxes to the ocean, thereby focusing on the outlets of continental-scale river basins (Alkama et al., 2011; Dai et al., 2009; Dai & Trenberth, 2002; Labat et al., 2004; Milliman et al., 2008). Consistent with the regional studies, these highlight spatially complex trend patterns. Although these assessments are of high relevance for ocean and Earth system dynamics, they focus on the net terrestrial water balance and cannot infer regional- to local-scale changes.

Another branch of global studies has assessed streamflow trends of individual water bodies. Some studies have focused on investigating changes in a few carefully selected large river basins (Jaramillo & Destouni, 2015; Kundzewicz et al., 2005; Milly et al., 2005; Svensson et al., 2005), thereby taking advantage of better quality control of the individual records but suffering from relatively small sample sizes and sparse spatial coverage. This is contrasted by other investigations that take advantage of large samples of available time series with sufficient observations (Berghuijs et al., 2017; Do et al., 2017), thereby providing a richer spatial picture of changes in water availability.

As for regional studies, there is a large heterogeneity between the individual global assessments, including a wide range of research questions, different spatial sampling schemes, and different time periods. Some studies are dedicated to investigating mean flows (Alkama et al., 2011; Dai et al., 2009; Dai & Trenberth, 2002; Jaramillo & Destouni, 2015; Labat et al., 2004; Milliman et al., 2008; Milly et al., 2005), while others focus on floods (Berghuijs et al., 2017; Do et al., 2017; Kundzewicz et al., 2005; Svensson et al., 2005) or low-flow indicators (Svensson et al., 2005). In summary, the heterogeneity of past global-scale assessments makes it difficult to draw generalized conclusions on observable changes of streamflow around the world.

This study updates previous assessments of worldwide changes in streamflow, using a database with unprecedented spatial coverage of streamflow observations and using indicators of low, mean, and high flows. To account for regional differences in data availability, trends are analyzed for three overlapping 40-year periods from 1951 to 2010, maximizing the spatiotemporal coverage of the investigation. Finally, the significance of the observed trends is established at the subcontinental scale.

2. Data

Streamflow observations are taken from the Global Streamflow Indices and Meta data archive (GSIM; Do et al., 2018b; Gudmundsson et al., 2018b), which is available in the public domain (Do et al., 2018a; Gudmundsson et al., 2018a) and holds information from more than 30,000 gauging stations. Annual time series information is available through indices computed from daily values that represent a wide range of flow properties at monthly, seasonal, and yearly resolution. Here the following indices are considered:

1. Low flows are represented through time series of the annual minimum (MIN) and the annual 10th percentile (P10).
2. Average flow conditions are characterized using the annual mean (MEAN) and the annual 50th percentile/median (P50).
3. High flows are represented through time series of the annual maximum (MAX) and the annual 90th percentile (P90).

Daily time series used to compute the GSIM indices underwent a formal quality assessment (Gudmundsson et al., 2018b). The assessment utilized quality flags from individual data providers and automated screening methods that flag implausible values. Only daily records that passed this assessment were used for index calculation. Because the extremal indices (MIN, P10, P90, and MAX) are sensitive to data availability, years with less than 350 valid daily observations were set to missing for each station, as recommended by ECA, & D Project Team, and K. Royal Netherlands Meteorological Institute (2013; hereafter ECA&D13).

Note also that GSIM combines information from all gauging stations from the contributing data bases. Consequently, both near-natural and regulated catchments are included (Do et al., 2018b; Gudmundsson et al., 2018b). In this study no attempt is made to distinguish between these cases. Instead, trends in the complete observational record are documented, as changes in atmospheric boundary conditions and human water management might both trigger changes in streamflow.

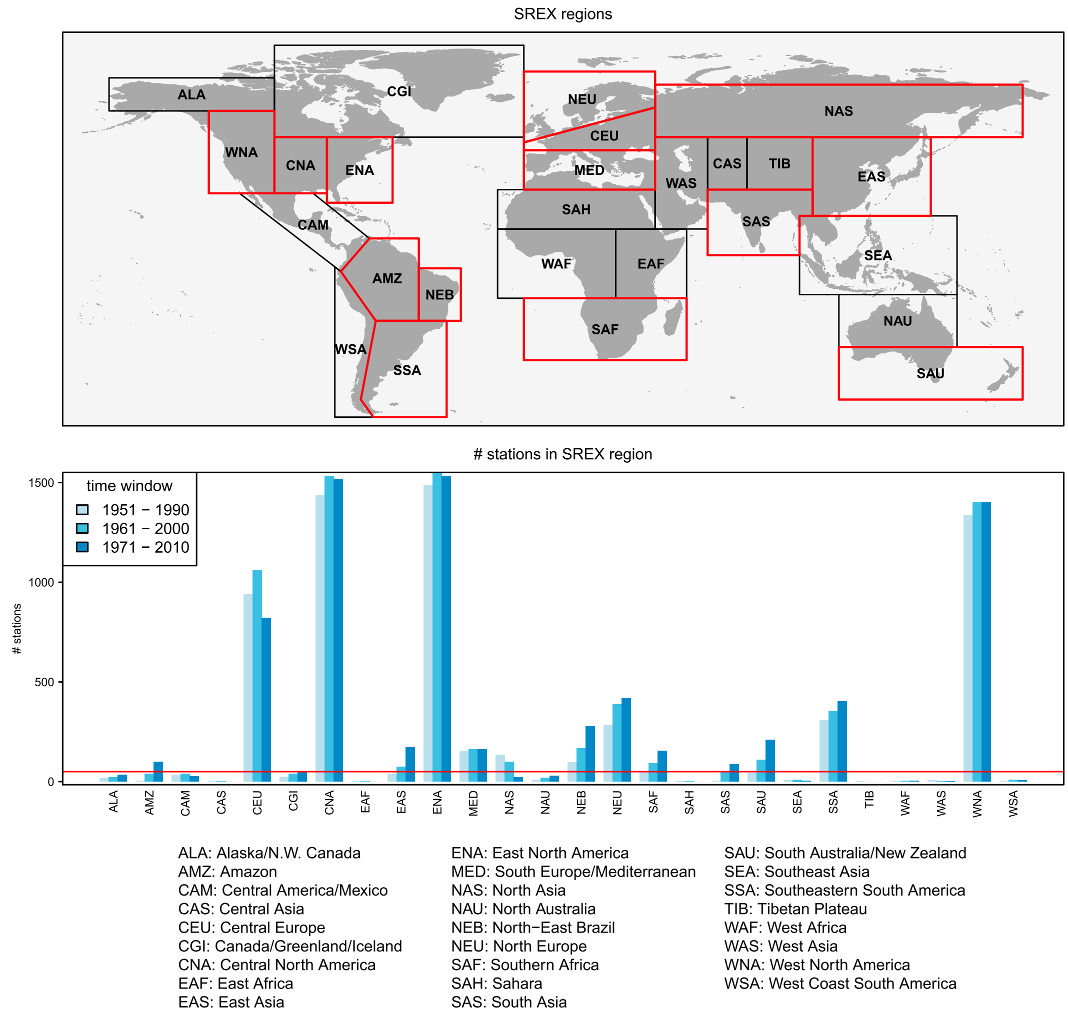

Figure 1. Subcontinental regions defined by the Special Report On Extremes (SREX; Seneviratne et al., 2012). Top: world map of all regions, where regions with more than 50 stations with sufficient data in at least one of the three considered 40-year periods are highlighted in red. Bottom: number of stations with sufficient data for each period and each SREX region. The red line indicates the 50-station threshold.

Given the complex nature of in situ observations entering the GSIM archive, spatial and temporal coverage of the considered streamflow time series varies substantially around the globe. Therefore, and because trends can be influenced by decadal variability, the following 40-year periods were analyzed: 1951–1990, 1961–2000, and 1971–2010. Based on previously suggested data availability criteria (ECA&D13) for trend analysis, only stations where at least 70% of the years are available were considered. This criterion was applied to each of the 40-year periods separately. As a result, the spatial coverage differs across the periods.

The significance of trends is evaluated at the subcontinental scale by grouping stations into 26 regions that were designed for analyzing regional climate change and are defined in the Special Report on Extremes of the Intergovernmental Panel on Climate Change (Seneviratne et al., 2012; later referred to as SREX regions). Figure 1 shows the SREX regions alongside the number of stations that fulfill the data availability criteria for each region and each 40-year period. Only regions and periods with at least 50 stations were considered for subcontinental-scale assessment.

3. Trend Estimation

Following previous studies (Stahl et al., 2010, 2012), trends at individual stations were computed using the robust Sen-Theil slope estimator (Sen, 1968). To make trend estimates from catchments with different sizes and from different climates comparable, they are expressed in units of percent change per decade (i.e., 10 years; Stahl et al., 2012), such that

$$T_s = \frac{\tau_s \times 10 \text{ years}}{\bar{x}_s} \times 100 \qquad (1)$$

where T_s is the trend at location s in units of percentage change per decade, τ_s is the Sen-Theil slope estimator, and $\bar{x}_s$ is the mean of the index time series.

To be able to detect changes at the level of the SREX regions, a resampling method is proposed that accounts for within-region spatial dependence (Burn & Elnur, 2002; Douglas et al., 2000; Wilks, 2011).

The regional trend test is as follows:

1. For a given region, compute the regional trend, $\overline{T_s}$ defined as the average of all T_s in that region.
2. Repeat 2,000 times:

2.1 Resample with replacement the year order of all data within the region while maintaining the spatial dependence within individual years, following the procedure described in Burn and Elnur (2002).
2.2 Compute at each location T_s^*, the trend expressed in percent change per decade of the resampled time series.
2.3 Compute the regional trend, $\overline{T}_s^*$, as the regional mean of T_s^*.

3. Estimate p, that is, the probability of $\overline{T_s}$ on the distribution of $\overline{T}_s^*$ (the bootstrap distribution) as the fraction of $\overline{T_s} < \overline{T}_s^*$.

Significance of regional trends is reported at the $p < 0.01$ and $p < 0.1$ level for negative trends and at the $p > 0.9$ and $p > 0.99$ level for positive trends.

Note that this procedure is related to previously suggested closed-form (Helsel & Frans, 2006) and resampling-based (Douglas et al., 2000) regional adaptations of the Mann-Kendal trend test. However, the method introduced here does not require the additional step of computing the Mann-Kendall statistic. Instead, it operates on the variable of interest, the regional trend ($\overline{T_s}$). We note that regional testing procedures have the inherent limitation that they cannot consider subregional variability, with the potential for groups of stations with positive and negative trends to mask each other out.

4. Results and Discussion

4.1. Overview

Figure 2 maps the trend magnitude of the time series indices for each period. Visual inspection of the results highlights that streamflow is not changing uniformly around the world and that the considered period can have significant effects on both the sign and magnitude of the trend.

To better understand the nature of the observed trends, Figure 3 shows the regional trends, which often point in the same direction across all indices. In the following, these regional changes will be summarized and discussed in the context of selected observational studies. In addition, the observed change patterns will be put into the context of model projections of water availability (precipitation minus evapotranspiration; Greve et al., 2018) and runoff (Haddeland et al., 2014). Note that the aforementioned studies are based on different model ensembles, each having their distinct characteristics. Greve et al. (2018) is based on the CIMIP5 ensemble (Taylor et al., 2011) that includes a large sample of global climate models but does not account for human water management and land cover change. Conversely, Haddeland et al. (2014) is based on the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Fast Track ensemble (Warszawski et al., 2014) of global hydrological models driven with selected global climate models that accounts for both climate change and on-ground human activities. Finally, it is noted that ocean-atmosphere oscillations can be an important influence on decadal streamflow variability that have been studied elsewhere in great detail, including, for example, global (Wanders & Wada, 2015; Ward et al., 2010), North America (Burn, 2008; Tootle et al., 2005; Tootle & Piechota, 2006), Europe (Bouwer et al., 2006, 2008; Kingston et al., 2012), and Australia (Kuhnel et al., 1990; Verdon et al., 2004) assessments.

4.2. North America

North America has the highest number of stations of all the continents considered. In West North America (WNA) there is no consistent change pattern. Increasing regional average low flows (MIN

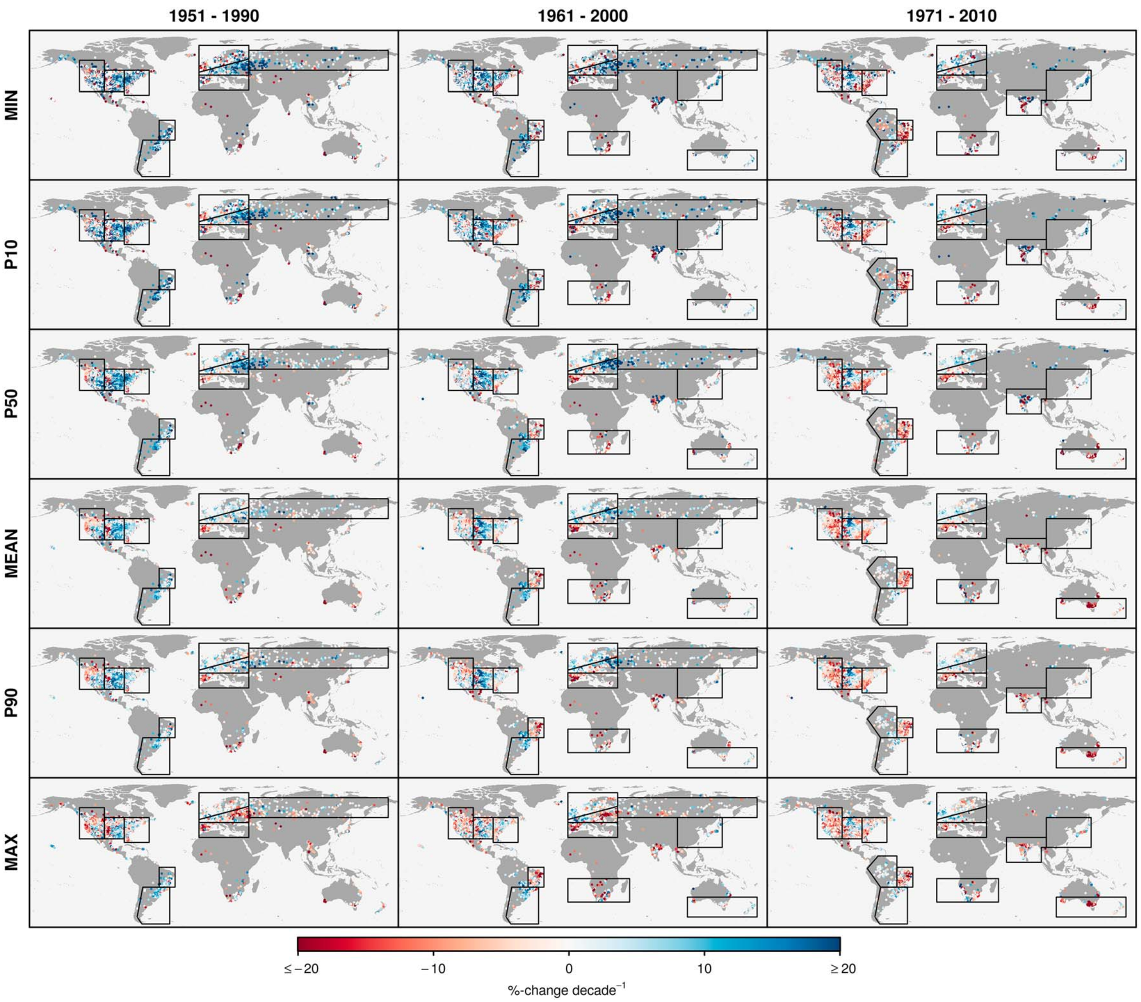

Figure 2. Trends in annual indicators of mean and extreme streamflow. Columns represent three 40-year periods. Rows represent the annual minimum (MIN), the annual 10th percentile (P10), the annual 50th percentile (P50), the annual MEAN (MEAN), the annual 90th percentile (P90), and the annual maximum (MAX). SREX regions with at least 50 stations with sufficient data are highlighted. See supporting information for high-resolution maps.

and P10) are detected for the 1951–1990 and 1961–2000 periods, whereas decreasing mean annual flows (MEAN) and high flows (P90) are found in the 1971–2010 period. In contrast, streamflow has increased significantly in Central North America (CNA) throughout the first two periods (1951–1990 and 1961–2000) across all indices, except for the annual maximum flow (MAX). This wetting tendency weakens in 1971–2010, where only MIN and P10 show a significantly increasing regional trend. There has been an increase in streamflow in East North America (ENA) over the first two periods (1951–1990 and 1961–2000), which is most pronounced for low flows and mean flows but less pronounced for high flows. In 1971–2010, the change pattern reversed, with a significantly declining regional trend for all indices except P90.

Overall, the results confirm previous assessments that focus on observations prior to the year 2000 in the United States (Douglas et al., 2000; Lettenmaier et al., 1994; Lins & Slack, 1999; McCabe & Wolock, 2002). These studies emphasize the tendency for increasing low and mean flows throughout the region, which is particularly pronounced in the central north of the U.S. There is also agreement in the lack of observed annual maximum trends, although only a few studies have focused on the period after 2000 (Hodgkins et al., 2017; Mallakpour & Villarini, 2015).

Based on simulations of the CMIP5 ensemble, Greve et al. (2018) report a clear tendency toward wetter conditions in WNA and ENA with no clear change pattern in CNA. Conversely, Haddeland et al. (2014) report a

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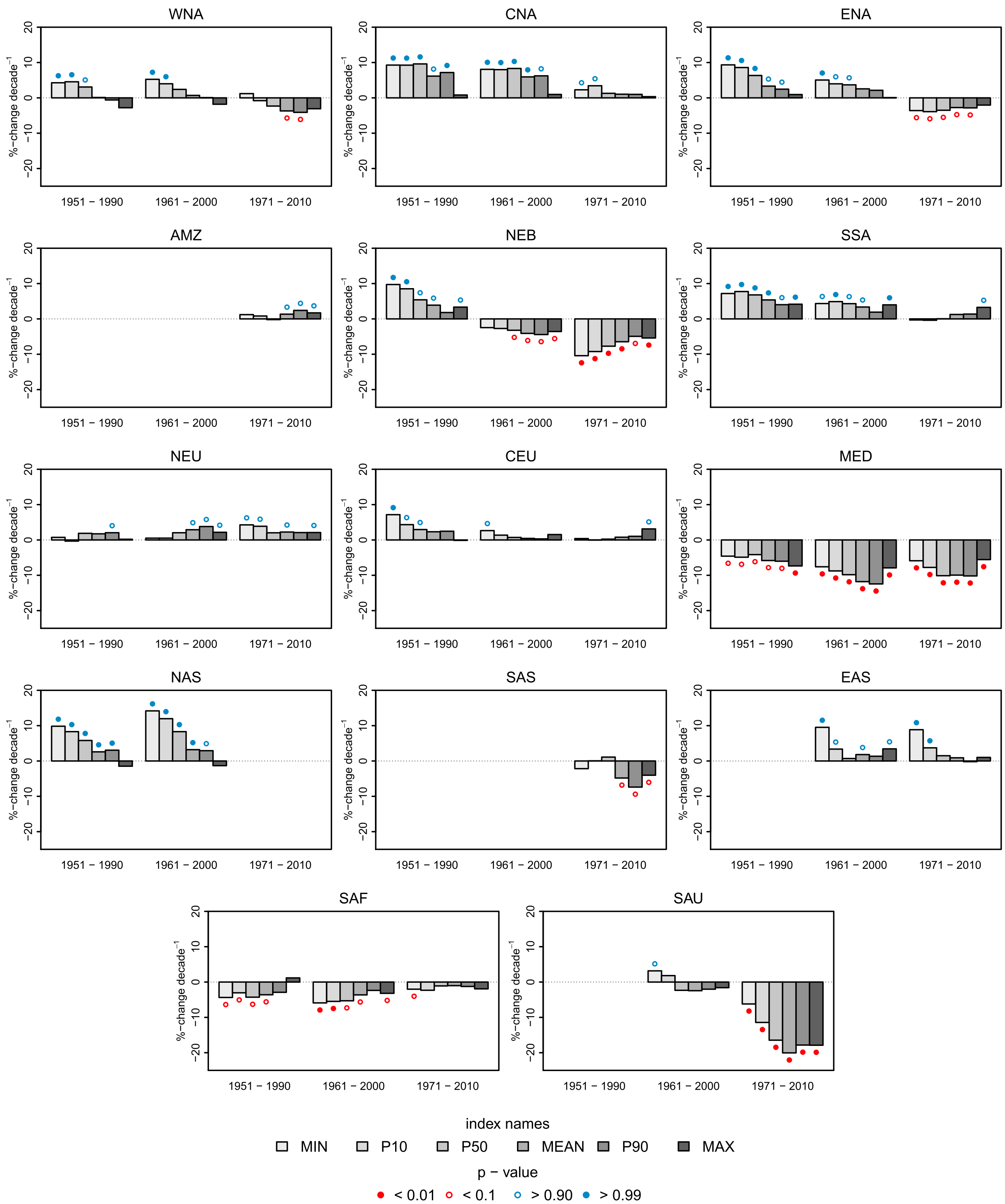

Figure 3. Regional trends for SREX regions with at least 50 stations in one of the considered periods. Regional trends are computed for all indicators of mean and extreme streamflow. Significance of the regional trend is reported as the probability of the observed trend on the bootstrap distribution. Regional trends are only provided for periods with at least 50 stations.

tendency for decreasing water availability, especially in the south of North America, which is triggered by human water and land management as simulated in the considered ISIMIP model ensemble. None of these are directly comparable with the observed change patterns, which exhibit shifting signs in both WNA and ENA throughout the study period.

4.3. South America

In South America, data availability increases throughout the study period. In the Amazon region (AMZ) only the 1971–2010 period has more than 50 stations available. In this period, the median (P50) and high flows (P90 and MAX) show a significant increasing regional trend. In North-East Brazil (NEB) all indices except P10 show a significant increasing regional trend in the 1951–1990 period. This pattern reverses thereafter, and all indices exhibit a negative regional trend for 1961–2000, although not all are significant. In the 1971–2010 period all indices show a significant declining regional trend. Southeastern South America (SSA) has wetting trends in all indices in the first period. In the second period all indices except P90 also show significant increasing trends, but this increasing tendency comes to an abrupt stop in the latter period, where no significant trends are found in most of the indices.

Analyzing streamflow observations in the second half of the twentieth century, Marengo et al. (1998) did find mostly positive trends in the region comprising parts of AMZ and NEB. This is partly consistent with the presented results but does not report the reversing trend pattern in NEB occurring between the first and second periods. For rivers draining to the south Atlantic, Pasquini and Depetris (2007) report complex spatiotemporal trend patterns using observations up to the early 2000s. For a region similar to SSA, Genta et al. (1998) report increasing discharge trends for the second half of the twentieth century with a tendency to level off, which is in agreement with the presented results.

Overall, climate models from the CMIP5 ensemble suggest that both AMZ and NEB have a tendency for becoming drier with increasing global mean temperatures, while SSA is likely to become wetter (Greve et al., 2018). However, an alternative ensemble suggests that SSA might also become increasingly drier in a warmer climate (Haddeland et al., 2014). On-ground water and land management is estimated to only have a limited impact on freshwater resources in most parts of South America (Haddeland et al., 2014).

4.4. Europe

Europe is among the best monitored regions with respect to streamflow around the world. In North Europe (NEU), only P90 exhibited a weak increasing regional trend in the 1951–1990 period. In 1961–2000 all indices show a weak incline, while only MEAN, P90, and MAX are significant. In the 1971–2010 period all indices showed a weak increasing trend, with significant MIN, P10, MEAN, and MAX suggesting a slight upward shift of the annual daily streamflow distribution. In Central Europe (CEU), there is a significant upward regional trend in MIN, P10, and P50 in the first period (1951–1990). In the subsequent period (1961–2000) almost no changes occur except for MIN, which shows a weak positive regional trend. In the last period (1971–2010) only MAX shows a weak significant regional trend in CEU. The South Europe/Mediterranean (MED) region (note that all considered stations are in Europe) shows the strongest and the most consistent pattern of the entire study. Here all indices show strong and significant declining regional trends throughout all considered time periods, highlighting an overall reduction of freshwater availability in this region.

Studies focusing on trends in flood frequency (Hodgkins et al., 2017) and drought indicators (Hisdal et al., 2001) report that there is little evidence for changes in these quantities in Europe. However, several studies have documented the tendency for drying in the South of Europe and increasingly wet conditions in the north (Stahl et al., 2010, 2012). Through linking this observational pattern to historical climate model simulations, the observed trends in pan-European freshwater availability have been attributed to anthropogenic climate change (Gudmundsson et al., 2017).

Future climate projections indicate a continuation of the observed trend pattern in Europe with increasingly dry conditions in MED, wetting conditions in NEU, and little change in CEU (Greve et al., 2018; Haddeland et al., 2014). In addition, Haddeland et al. (2014) indicate that human water and land management may also contribute to declining streamflow values in southern Europe, which might have amplified the observed strong negative trend throughout all aspects of the flow distribution.

4.5. Asia

Spatiotemporal data availability is variable over the Asian continent. In North Asia (NAS), all indices except MAX show a significant increasing regional trend for the 1951–1990 and 1961–2000 periods. In the last period (1971–2010) there are less than 50 stations in this large region. In South Asia (SAS) only the 1971–2010 period passes the data availability criteria, having a significantly declining regional trend in MEAN, P90, and MAX. Relatively better data coverage is found in East Asia (EAS), with sufficient data to cover the last two time periods (note that most stations are in Japan). For 1961–2000, MIN, P10, MEAN, and MAX show significant increasing regional trends. For 1971–2010, the regional trends of MIN and P10 are increasing significantly.

Several previous studies have documented increasing streamflow trends in the north of the Asian continent (Adam & Lettenmaier, 2008; MacDonald et al., 2007; McClelland et al., 2006; Tananaev et al., 2016), which appears to persist past the year 2000 and is also visible in hydrological extremes (Tananaev et al., 2016). A regional study in the Indian subcontinent confirms the tendency toward decreased water availability and attributes it to anthropogenic climate change (Mondal & Mujumdar, 2012).

Global climate models project that water availability will increase in NAS as a consequence of global warming (Greve et al., 2018). This is consistent with the observational results of the present study, and only limited impacts of human management on water resources is expected (Haddeland et al., 2014). In SAS climate models indicate that global warming will increase water availability (Greve et al., 2018), contrasting our observational findings. However, the simulations assessed by Haddeland et al. (2014) suggest that human land management is reducing runoff in the Indian subcontinent offering a possible explanation for the observed signal. Also in EAS, climate models project increasing water availability in an warming climate (Greve et al., 2018) and impacts of water and land management are only moderate (Haddeland et al., 2014).

4.6. Africa

Of the entire continent of Africa, only Southern Africa (SAF) has more than 50 stations fulfilling the data availability requirements. In the 1951–1990 period, low-flow indices (MIN and P10) and the annual median (P50) show significant decreasing regional trends. In 1961–2000 this weak drying pattern is reinforced, and all indices except P90 show significant negative trends, pointing at an overall decrease throughout the runoff distribution. In the 1971–2010 period, however, this pattern weakens and only MIN shows a significant decline.

A comprehensive assessment of trends in a region similar to SAF found more decreasing than increasing trends (Fanta et al., 2001), which is consistent with the findings of the present study. Overall, global climate models suggest that increasing global mean temperatures are associated with drying conditions in SAF (Greve et al., 2018), which might even be intensified through reduced flow rates triggered by human water and land management (Haddeland et al., 2014).

4.7. Oceania

In Oceania, only South Australia/New Zealand (SAU) has sufficient data coverage to warrant analysis. Data availability is not sufficient in the period 1951–1990. In 1961–2000, negligible change is observed, except weak inclination in MIN. However, the last period (1971–2010) shows strong and significant negative regional trends of all indices considered, that is, a strong and significant reduction of the entire flow distribution.

Previous assessments of changes in streamflow (Petrone et al., 2010; Zhang et al., 2016) and annual maximum floods (Ishak et al., 2013) have reported declining trends in southern Australia. In southeastern Australia, the first decade of the 21st century was particularly dry, sometimes referred to as the millennium drought (Kiem et al., 2016; Low et al., 2015; Zhang et al., 2016).

On average, the climate models of the CMIP5 ensemble indicate only a weak change in water availability in SAU with increasing global mean temperatures (Greve et al., 2018). However, other simulations suggest that both anthropogenic climate change and human water use may trigger a significant reduction of runoff in south eastern Australia (Haddeland et al., 2014), which is consistent with the observed changes.

5. Summary and Conclusions

To date, there has been low confidence and a lack of consistent evidence regarding sign and magnitude of trends in global river discharge during the twentieth century (Hartmann et al., 2013). Therefore, this study presents a comprehensive update of global-scale changes in indicators of mean and extreme streamflow taken from the GSIM archive (Do et al., 2018b; Gudmundsson et al., 2018b). To enable this global overview across all indicators, the focus of the analyses has been the significance and sign of change at the subcontinental scale, contrasting the common approach to solely report trend magnitudes for individual stations. In contrast to regional studies tailored to specific indices and with varying methods, a key benefit of this study was the opportunity to consider multiple regions and multiple indices with a consistent method. The subsequent analysis highlights that streamflow trends have complex spatial patterns, preventing simple generalizations of regional changes to the global scale.

A striking result is that in most cases the sign of regional trends is consistent across all indices. This implies that the entire flow distribution is changing upward or downward in the respective regions, indicating generally wetter or drier conditions. In other words, increasing low flows are in most cases associated with increasing high flows (and vice versa), contradicting the common notion that flood and drought risk may increase simultaneously. Another feature of the results is that for some regions (West North America, East North America, and North-East Brazil) the sign of the trends has varied with respect to the considered period, suggesting low-frequency variability in the baseline climate signal and that care is needed in the interpretation of the associated change patterns.

Among all considered regions, South Europe/Mediterranean had the strongest signal with consistent negative trends in all indices throughout all considered time periods. Other regions with predominantly negative trends include Southern Africa, South Australia/New Zealand, and potentially South Asia. In addition, Northeastern Brazil experienced drying conditions for the last two time periods but had a consistent wetting trend for the first period. Consistent wetting trends were observed in Central North America, Southeastern South America, North Europe, and North Asia, although the trend weakens for the last period in Central North America and Southeast South America. Overall, these wetting trends are not equally visible in all regions and throughout all indices.

While the number of gauges used in this study is unprecedented, the conclusions in regions with less data are constrained (e.g., Asia) or muted (e.g., Africa), and further gains in data gathering would substantially improve confidence (Do et al., 2018b). Consequently, spatiotemporal coverage of the observations remains a limiting factor. Likewise, both the potentially uneven temporal distribution of available data in individual time series and regional differences in spatial coverage are impacting the results. Finally, the focus on regional trends can mask subregional features. Nevertheless, the presented results provide for an unprecedented view on streamflow trends around the world.

While this study has sought to interpret observed changes in the context of future climate projections (Greve et al., 2018) and model estimates of the impacts of human water and land management (Haddeland et al., 2014), it does not allow for a conclusive attribution of the observed changes to either of these factors. To this end, formal detection and attribution methods (Bindoff et al., 2013; Gudmundsson et al., 2017) are needed, which would allow for systematic testing of the hypothesis that both anthropogenic climate change and human water and land management are impacting renewable freshwater resources and hydrological extremes at the global scale. As end of the century projections of global water resources and hydrological extremes increase in number and sophistication, an appreciation for trends in observed indicators of mean and extreme streamflow provides a stronger basis for understanding future changes.

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All streamflow indices considered are taken from the GSIM archive and are freely available from https://doi.org/10.1594/PANGAEA.887470 (Gudmundsson et al., 2018a). Mr. Hong Xuan Do receives financial support from the Australia Award Scholarship (AAS) and D. R. Stranks Traveling Fellowship. This work is partially funded by the ERC DROUGHT-HEAT project (contract 617518).

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