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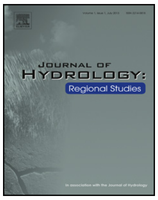

Comparing trends in hydrometeorological average and extreme data sets around the world at different time scales

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ABSTRACT

Study region: The Present work shows trend analysis results for temperature and precipitation around the world and for river discharges in the Americas, Australia and some European countries for a common time period with free access hydrometeorological information.
Study focus: Hydrometeorological data sets for discharge, precipitation and temperature around the world were analysed for statistically significant trends both in average and extreme value data sets between 1970 and 2010. The data was analysed with the Mann–Kenndall trend test at annual, monthly and daily resolutions, to compare the results on a global scale and between the different time resolutions.
New hydrological insights for the region: Results indicate that trends can be found for all variables and on all latitudes, with an increase of global temperature in the analysed time period. Fewer trends were observed in extreme value data. Trends in discharge data were predominantly negative, and precipitation trends were not very common. In some cases, an opposing pattern was observed in the northern and southern hemisphere. The highest number of trends was found at the annual and least on the daily resolution, nevertheless, trend patterns for discharges remained similar at different time scales. Some of the factors that might influence these results are discussed.

1. Introduction and background

Climate change and extreme weather conditions have been a topic of interest for scientists and institutions around the world aiming to explore causes and possible adaptation strategies for this problem. Changes in the global climate cause changes in the hydrological cycle, which thus will impact on ecosystems and the human society (Abghari et al., 2012; Morin, 2011). Many scientific works have explored the existence of trends in hydrometeorological time series, especially for temperature and precipitation data.

Previous investigations on the topic generally indicate positive trends for temperature on all continents, both in the northern (Nicholson et al., 2013; Del Río et al., 2011; Wang et al., 2011; Xu et al., 2010) and southern hemisphere (Aguilar et al., 2005; Falvey & Garreaud, 2009; Stern et al., 2011). Minimum temperatures have been found to increase stronger than maximum temperatures (Hu et al., 2012; Sonali & Nagesh Kumar, 2012; Xu et al., 2010). Furthermore it was found that the change in temperature patterns has had substantial influence on a big number of other hydrometeorological variables, including precipitation and streamflow (Hayhoe et al., 2007; Xu et al., 2010). Fewer trends were observed in precipitation

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series, which were principally positive (Barros et al., 2000; Vargas et al., 2002; Xu et al., 2010), while in some cases hardly any statistically significant trends could be found (Abghari et al., 2012; Mass et al., 2011). Precipitation trends in South America prove to be divided into stations with a negative trend west of the Andes and a positive one east of them (Minetti & Vargas, 2009; Vargas et al., 2002). Wagner et al. (2011) describe an increase of arctic river discharge in the 20th century, as do Genta et al. (1998) for select South American rivers. Abghari et al. (2012) found principally negative discharge trends in Iranian rivers and a study of tropical South America found negative trends in the Andean rivers and positive ones in the Amazon basin (Marengo et al., 1998). Dai et al. (2009) found that 30% of the discharge series of the largest rivers worldwide show significant trends, most of which were negative. Most studies indicate that human activities are a major cause of trends in discharge series, although this was proven only in some of them (Wang et al., 2009; Woo et al., 2008).

Easterling et al. (2000) show a worldwide increase of extreme events for temperature and precipitation over the 20th century. Goswami et al. (2006) and Wang and Zhou (2005) show an increase of extreme rainfall events in India and China, as well as Haylock et al. (2006) and Manton et al. (2001) do for Australia and the pacific region. Bell et al. (2004) show the same for the North American continent and Hu et al. (2012) found a decreasing trend for heavy precipitation, especially in the winter months, in the Yang Tse basin. Studies from Europe indicate an intensification of short-term heavy precipitation patterns (Costa & Soares, 2009; De Toffol et al., 2009). Min et al. (2011) found that for two thirds of all precipitation stations in the northern hemisphere, extreme events have intensified. Bordi et al. (2009) studied linear and non-linear trends in draught and wetness series in Europe, finding trends until the end of the 20th century that are reversed in the first decade of the 21st century and conclude that nonlinear trends are a better tool to describe these developments. A study of streamflow data in the Mekong basin (Delgado et al., 2010) concluded that there is an increased likelihood of floods in the area, although all studied series show negative trends in the time series. Nyeko-Ogiramoi et al. (2013) found that trends were showing an increase of extreme events in temperature, discharge and especially precipitation series in the Lake Victoria basin. Kundzewicz and Robson (2004) find that the number of large floods in Europe increased significantly from 1985 to 2009, and Hirsch and Ryberg (2012) investigate the relationship between flood magnitudes and global CO_2 levels in the US without finding strong indications of it.

Various works focussing on the topic of trend detection in hydrological time series concluded that trends could be found in studies around the world, and that change detection is a challenging research need (Kundzewicz, 2004). Furthermore it was found that usually trends in extreme value series cannot be proven as reliably as in mean series or are not significant (Lindström & Bergström, 2004; Xiong & Guo, 2004).

Although numerous investigations exist, most of them take into account annual or monthly statistics like mean or maxima in a small geographic region. The main objective of the present study was to investigate trends at different time scales on a global scale and compare between results of the northern and southern hemisphere. Therefore, trend analysis was conducted on an annual, monthly and daily level and both trends in average and extreme value datasets were analysed. Another objective was to try to find out if any differences can be found in the number of trends at the different time resolutions that could explain results in a clearer way. Therefore, trend analysis was conducted on an annual, monthly and daily level and both trends in time and extreme value series were analysed.

2. Materials and methods

2.1. Data used in this investigation

In this investigation, only freely available data on a daily resolution was used from various different data sources on the internet. The observed variables were discharge, precipitation and temperature, where for the latter daily maximum and minimum values were analysed. The period under investigation was the 41 years from 1970 to 2010. The intention was to use data from around the world and cover the whole globe the best way possible, which was possible for temperature and precipitation time series, but proved to be difficult for discharge data due to the lack of a global source with data available in the given time period and sufficient data completeness, as described below.

Temperature and precipitation data was almost exclusively retrieved from the daily database at the Global Historical Climatology Network (GHCN-D), discharge data was downloaded from national meteorological or hydrological agencies that offered data on a daily basis. Since one of the key criteria for this study was to compare the trends on different time scales, only data available on a daily level was used and other sources that offer data on a monthly level were not taken into account, although they could have increased the geographical coverage significantly. Another aspect that had to be considered was the difference of data quality in different regions of the world, which has already played an important role in previous studies (Haylock et al., 2006; Manton et al., 2001). For this reason, only time series with a maximum of 20% missing data were used, which was the reason for a lower number of stations available in regions like Africa and some parts of South America and Asia, especially Brazilian temperature stations. The list of all stations used in this investigation as well as the different data sources can be viewed in the electronic annex.

The stations used for analysis were chosen randomly among all the available stations. Out of all the stations that met the criteria of at least 80% completeness during the time period from 1970 to 2010, stations were selected, counting on a geographically uniform distribution. In regions with scarce data availability, the majority of stations was chosen, avoiding stations within 100 km of each other. In regions with higher availability of information, a percentage of at least 5% should be used where possible, depending on the number of stations per area, adjusting the distance between stations on this number to conserve a uniform spatial distribution. For discharge data, the percentage was raised to at least 25% due to the smaller availability of data and the distance between stations was not applied. Due to missing information about the basin size or the types of water management applied in them in many countries, it was not possible to further distinguish between these factors for discharge data.

The representativeness of the data therefore depended largely on two factors: the location of available stations and the selection process. In data scarce regions, the available information is represented to a higher degree than in the regions, where stations were selected and the overall uncertainty is higher. The higher uncertainty of the sample was chosen, however, in order not to over represent certain regions compared to those where little information was available, and to have a similar number of stations for all three hydrological variables.

For precipitation and temperature data, the GHCN-D data set was used as the principal data source. Out of the approximately 90000 stations included at the time of the investigation, only 10545 met the criteria for precipitation data and 5573 and 5858 for minimum and maximum temperature, respectively. Out of these, 464 temperature and 442 precipitation stations were chosen, and 29 precipitation stations were added in Colombia, Argentina and Brazil from the national agencies to fill geographic areas without coverage. If a GHCN-D station contained both temperature and precipitation data, it was used for both variables.

A total of about 1500 discharge stations were obtained from different national meteorological organizations, out of which 421 stations were chosen, but due to the lack of availability of data especially in Africa and Asia, they were principally concentrated on the American continent and Australia. However, in order to keep the presentation of the results of this study clear and easier to follow, the authors chose to present the results of discharge data the same way as the other variables, bearing in mind that the results cannot be generalized the same way as for the other variables. All the stations used in this work are shown in Fig. 1.

The results presented in part 3 of this study distinguish between the results obtained in the northern and southern hemisphere. Due to the smaller amount of land mass in the southern hemisphere, and therefore the smaller amount of data available in this region, fewer stations were used there. The stations used divided into 340 discharge stations in the northern and 81 in the southern hemisphere, for precipitation the ratio was 355 to 116 stations, and for temperature 391–73 stations. The principal reason many temperature stations in the southern hemisphere (especially in Brazil) could not be used was the big number of missing values.

2.2. Random variables at different time scales

Each hydrometeorological time series was divided into statistically valid datasets to use for further analysis. The complete time series at a given station was constructed as a random process, containing a series of random variables. Following the methodology presented in Sveshnikov (1966), all the values of the time series recorded at the same period of time were grouped into random variables. This means that for daily data, all average values of the same day of the year formed a random variable, as well as the averages of each month did for monthly data. These random variables each contained 41 values, following from the number of years of observation and were used as the datasets for further analysis.

More specifically, each hydrometeorological variable was constructed as a random field $\boldsymbol{X}$, which contains different random processes, each of which represents a time series from one hydrometeorological station, taking the form of

$$X = \left\{X_1, X_2, \cdots X_n\right\} \tag{1}$$

where n is the number of total stations available for the hydrometeorological variable. Each of the random processes is made up of a series of random variables containing the values obtained along the year and grouped by days or months, according to the time resolution. A process on a monthly basis contains 12 random variables,

$$X_i = \left\{x_{i,1}, x_{i,2}, \cdots x_{i,12}\right\} \tag{2}$$

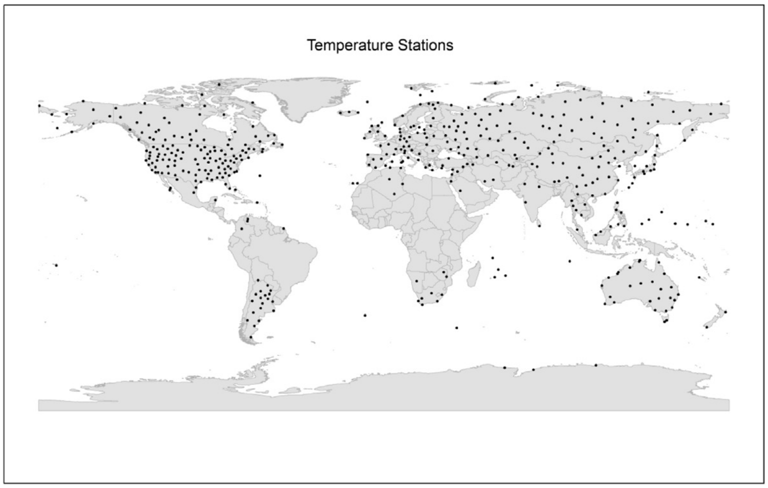
where the second index of each x indicates the month of the year (January to December). A random process representing daily mean values therefore contains 365 random variables. The values of February 29 were not taken into consideration in this study.

$$X_i = \left\{x_{i,1}, x_{i,2}, \cdots x_{i,365}\right\} \tag{3}$$

Fig. 2 shows the distribution of the lengths of the random variables resulting on a daily, monthly and annual scale, showing the percentages of a given length in the 41 years of the period under investigation among all stations. Since the distributions for annual and monthly resolutions were very similar for all hydrological variables, they are presented in one general graphic, as well as one graphic for each variable on the daily resolution.

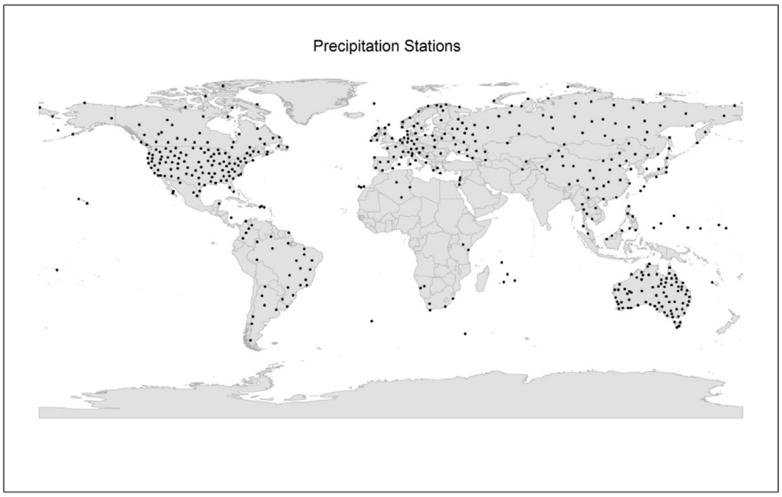
2.3. Definition of an extreme event

Extreme events were analysed by two statistics, first by its occurrence frequency and second its magnitude, for both maxima and minima on an annual and monthly basis. Precipitation minima were not analysed.



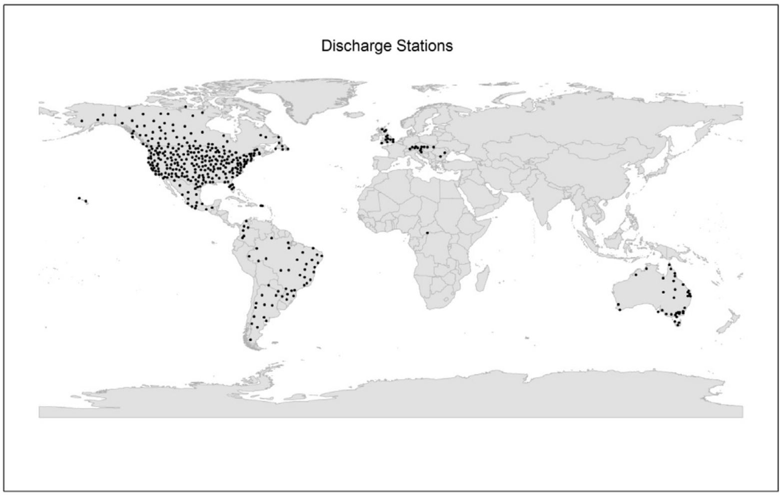
Temperature Stations

a. Locations of the temperature stations used.



Precipitation Stations

b. Locations of the precipitation stations used.



Discharge Stations

c. Locations of the discharge stations used.

Fig. 1. Locations of used hydrometeorological stations.

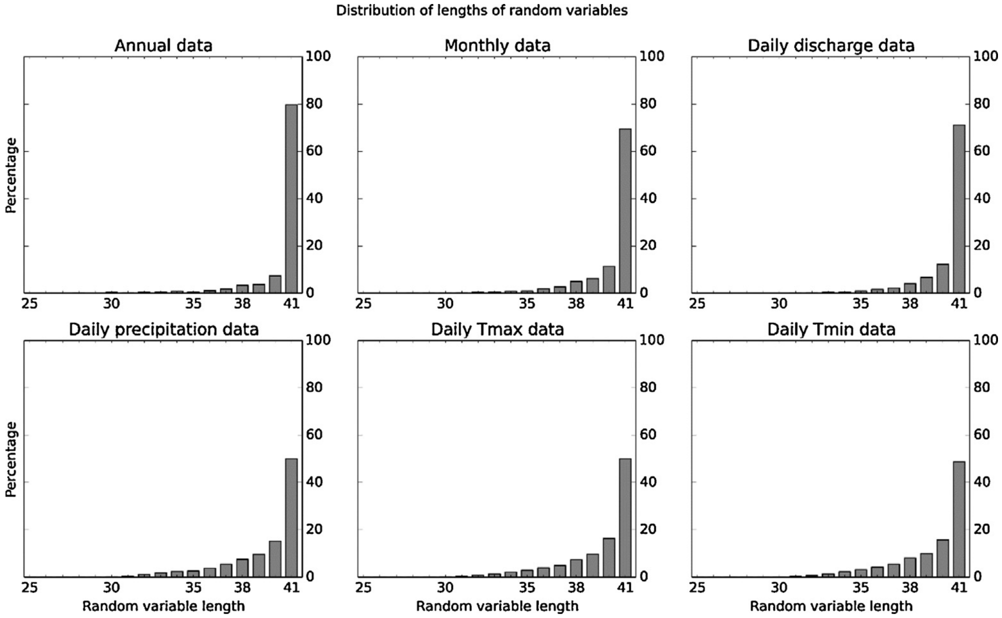


Fig. 2. Distributions of random variable lengths.

For the first statistic, the frequency of occurrence, it was necessary to analyse data on a daily resolution. As in previous works (Aguilar et al., 2005; Goswami et al., 2006; Manton et al., 2001), a threshold was calculated for each of the random variables based on the 1st and 99th percentile.

To calculate the threshold that defined an extreme event, 12 different cumulative distribution function (CDF) were adjusted to the random variables to find the best fit. The Kolmogorov Goodness of Fit test (Massey, 1951) was applied and the distribution with the lowest mean error was chosen to be the best fit, which resulted to be the Gamma function among all the variables. It was used to calculate threshold values that represented the above mentioned percentiles. The numbers of daily values above the 99th percentile value, as well as those below the 1st percentile were counted on a monthly and annual scale and again formed random variables.

To analyse the changes in magnitude of extreme events, the monthly and yearly maximum and minimum values were calculated and represented as random processes and variables as described above.

2.4. Trend tests

Trend analysis for all the above mentioned data sets was conducted using the Kendall τ (or Mann–Kendall) statistic. This non-parametric test uses consecutive pairs of data values in the data sets to compare for a positive or negative difference, which does not take into account the magnitude of this difference (Kunkel et al., 2010).

The statistic S of the Kendall test depends on the ranks of the data and subsequently is formed by applying the Theil–Sen approach, being X a value of the data set and $j > i$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}\left(X_j - X_i\right) \tag{4}$$

S has an approximate normal distribution for a data set larger than 8 values (Morin, 2011) with a mean of 0 and a variance depending on the sample size and the number of ties t_i:

$$\sigma_S = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)\right] \tag{5}$$

The null hypothesis of the test of no present trend is rejected for a the significance level α, if the normal value of the test statistic z,

$$z = \frac{S - \operatorname{sign}(S)}{\sigma_S} \tag{6}$$

is larger than the critical value for the probability 1-$\alpha/2$ (Morin, 2011; Helsel & Hirsch, 2002).

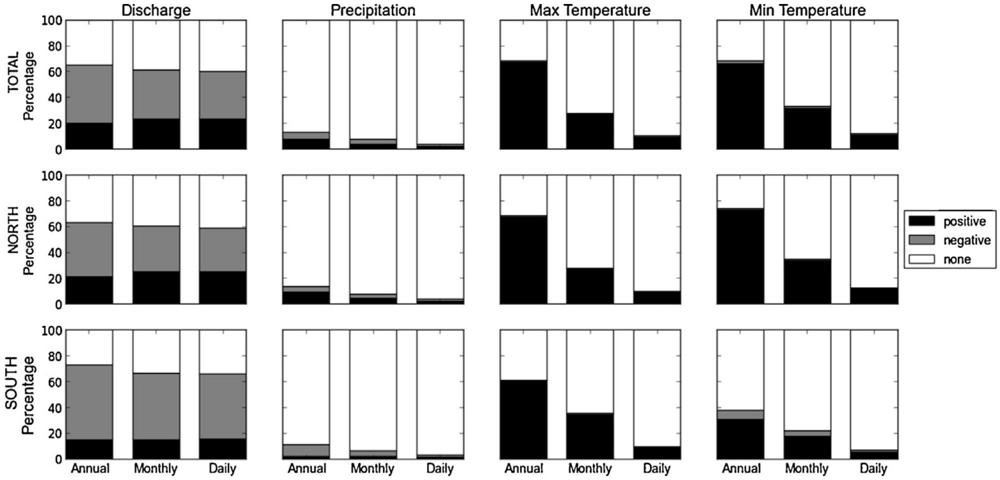


Fig. 3. Percentage of data sets with statistically significant trends: total, northern and southern hemisphere.

Previous works analysing the Mann–Kendall test, propose that the variance of the analysed data influences on its outcome. According to Yue et al. (2002a,b) and Morin (2011), the power of the Mann–Kendall test to correctly detect trends depends on a variety of different factors, where the power of the test is described to be a decreasing function of the coefficient of variation of the random variable, where also the sample size plays an important role. According to the results of Yue et al. (2002a,b), the power of the Mann–Kendall test significantly increases at coefficients of variation rates below approximately 0.2 for a sample size of 40. Various authors (Hamed & Ramachandra Rao, 1998; Hamed, 2008; Yue et al., 2002a,b) suggest that positive serial correlation within the data set increases the variance of the Mann–Kendall test statistic and hence the possibility to detect a trend that actually does not exist (Type-I error). However, the estimation of the autocorrelation coefficient is highly biased (Koutsoyiannis, 2003) and was therefore not considered in this investigation.

2.5. *Execution of trend analysis*

Trend analysis was only conducted on the datasets representing random variables as described above and the results presented in this work are based exclusively on them. This leads to 365 trend tests on the daily, 12 on the monthly and 1 on the annual resolution per hydrometeorological station.

For each hydrometeorological station, a random process for daily and one for monthly values was constructed, as well as one each for monthly maxima, minima, and number of both high and low extreme events. Annual values formed one random variable per station for analysis on the annual level. The same was the case for the annual maxima, minima and numbers of extreme events. For all the random variables contained in random processes, a trend test was conducted and the number of significant trends was recorded.

Furthermore, the numbers of significant trends of monthly datasets were aggregated on a three-month basis to permit seasonal analyses for the seasons MAM (March–May), JJA (June–August), SON (September–November) and DJF (December–February). The values for each season were obtained by summing the values of each of the three months.

3. Results and discussion

3.1. *Trends in average data sets*

The overall results of trend analysis for all three variables are displayed in Fig. 3. More negative than positive trends can be observed for discharge data, in all time resolutions and in both northern and southern hemisphere. The contrary is the case for temperature data sets, which show almost exclusively positive trends and hardly any negative ones on all latitude ranges. The clearest result was obtained for minimum temperature in the northern hemisphere, where over 70% of the included stations show a significant positive trend. However, minimum temperature, other than maximum temperature shows a higher number of negative trends in the southern hemisphere, which can be found principally for stations in and close to the tropical regions as well as at the southernmost stations in Argentina. Trends in precipitation data were found fewest of all the variables, only around 12% of the annual and 3% of the daily random variables show a significant trend, which can also be seen in Fig. 4.

Trends in monthly data sets show different patterns during the year. For discharge, each month shows more negative than positive trends, with the exception of January in the northern hemisphere. There, more positive trends are observed between October and January than in the rest of the year. Most total trends are observed from June to August in the north and from August to October in the south. For precipitation, most total trends are detected in the DJF season (winter) in the north

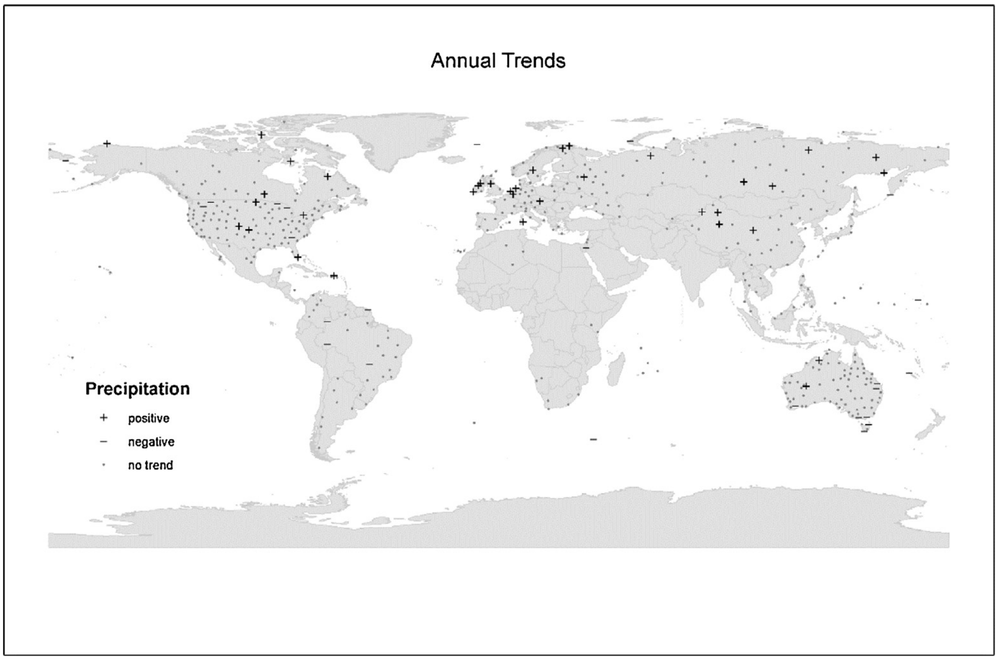


Fig. 4. Trends in annual precipitation data sets.

and in MAM (fall) in the south. According to the trends in annual random variables, in the north for all seasons there are more positive than negative trends, and the opposite behaviour in the south, with the exception of DJF (summer) showing more positive trends, especially in December. From July to September, no positive precipitation trends are found in the southern hemisphere on the monthly level, however very few trends are observed at this level. For temperature, differences are observed in each month, according to the season, where more trends occur in the spring and summer months than in the winter months (see Fig. 5). Most trends in the northern hemisphere are observed in JJA (summer) for both maximum and especially minimum temperature, where the number is almost 50% higher than in the other seasons, with the highest number of trends in August, while least trends are detected in DJF (winter). In the southern hemisphere the biggest number of trends occurs in SON (spring) season with the peak in October. There are more trends in maximum than minimum temperatures. As for the annual data, the great majority of trends are positive and hardly any negative trends are found. However, the number of positive trends for minimum temperature in the southern hemisphere is lower than for maximum temperature, while in the northern hemisphere, the contrary is the case. The results are presented in Fig. 6.

Daily data sets hardly show any different results than monthly results. For precipitation, a peak in the number of stations with a trend can be found at the end of February and the beginning of March, where there are a lot more positive than negative trends in the northern hemisphere.

3.2. *Trends in extreme value data sets*

Extreme value data sets show fewer trends than average data sets. More trends can be found for minima in both discharge and temperature data, while for precipitation no minima were evaluated. For discharge and temperature, as in average data sets, opposing patterns can be observed: for discharge data, maxima generally become less frequent and less intense (see Fig. 7), while minima intensify and happen more frequently during the observed time period. For temperature random variables, trends towards more frequent and more intense maxima are observed in the majority of the data sets and less frequent and less intense minima. According to the results for average data sets, extreme values for precipitation show intensified and more frequent maxima in the northern hemisphere and fewer and less frequent ones in the southern hemisphere. The results are shown in Fig. 8.

In monthly extreme value data sets, trends in magnitude are more frequent than in the occurrence of extreme events for precipitation and discharge. This is especially the case for discharge data, where more intense minima and less intense maxima are observed. Most of these combinations are found in SON (fall) and least in DJF (winter) in the north. In the south, the same combinations are found, also with the greatest number in SON (spring), although the differences between the seasons and months are not as clear. For precipitation, more intense and more frequent maxima are observed between March and August in the north and less intense and fewer maxima in the south throughout all months and seasons. Only for temperature extremes, the number of trends in extreme value occurrence is higher than in magnitude, where a decreasing number of minima is found throughout all months in the northern hemisphere. This number is clearest in SON (fall) in the

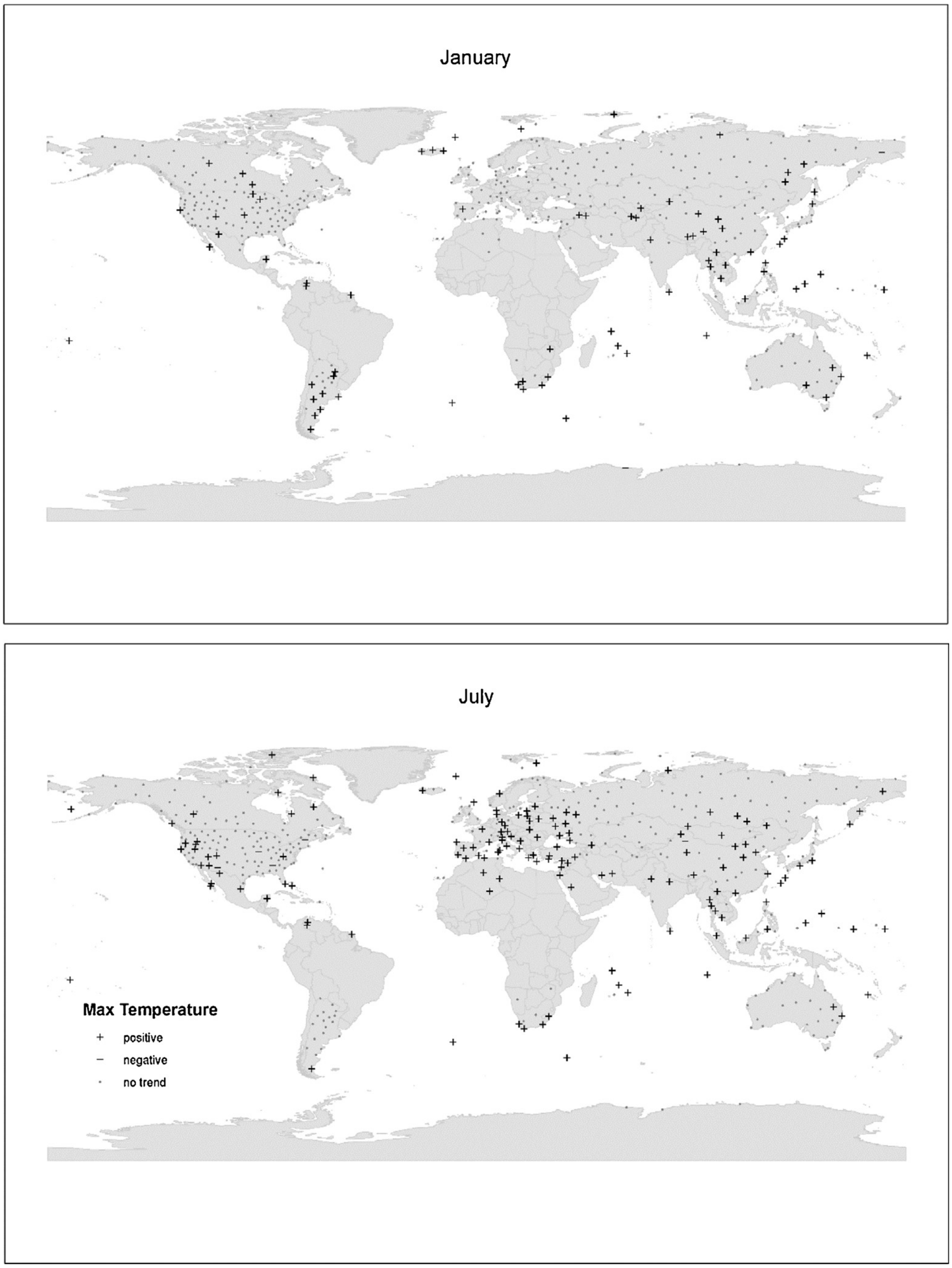


Fig. 5. Comparison between trends in maximum temperature data sets in the months of January and July (summer and winter months).

north, especially in October, and least in JJA (summer), especially in July. In the southern hemisphere, hardly any trends in temperature extremes are observed.

3.3. *Combinations of trends and geographic location*

Stations showing statistically significant trends in both average and extreme value data sets on the annual scale are only common for temperature data, where the majority have a positive trend and less frequent and less intense minima (28% of all data sets), as well as more intense and more frequent maxima (19%). For discharge data, stations with a negative trend and more intense and more frequent minima, as well as less intense and less frequent maxima are found (7%).

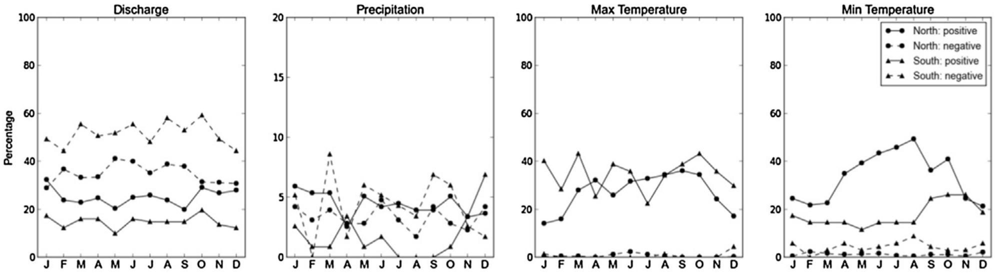


Fig. 6. Percentage of data sets with significant trends on a monthly level for the northern and southern hemisphere. Note that the precipitation chart has different *y*-values for representative reasons!

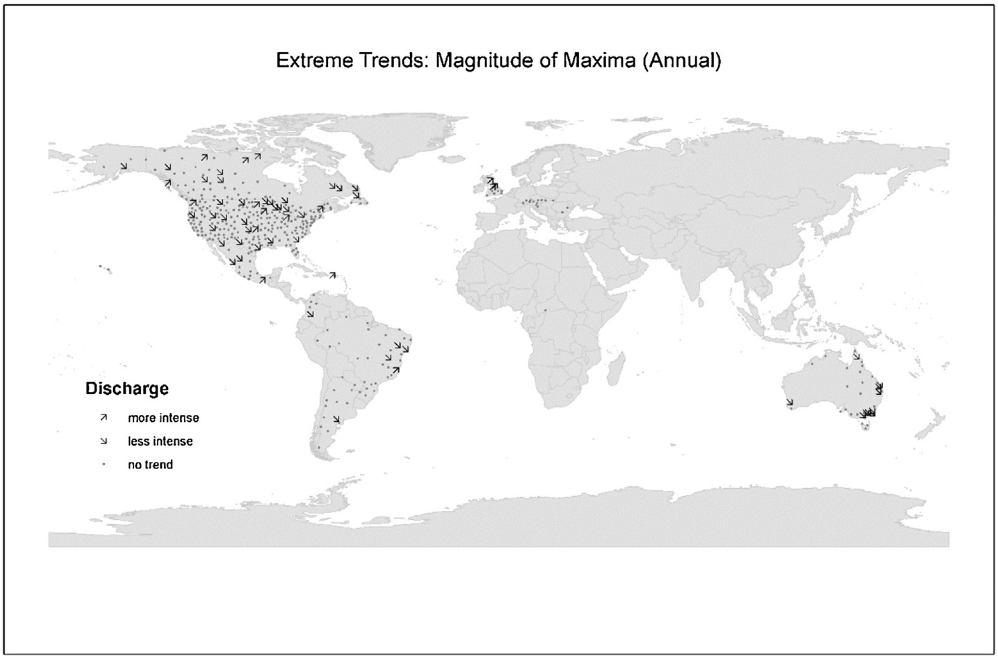


Fig. 7. Trends in annual magnitude of discharge maxima.

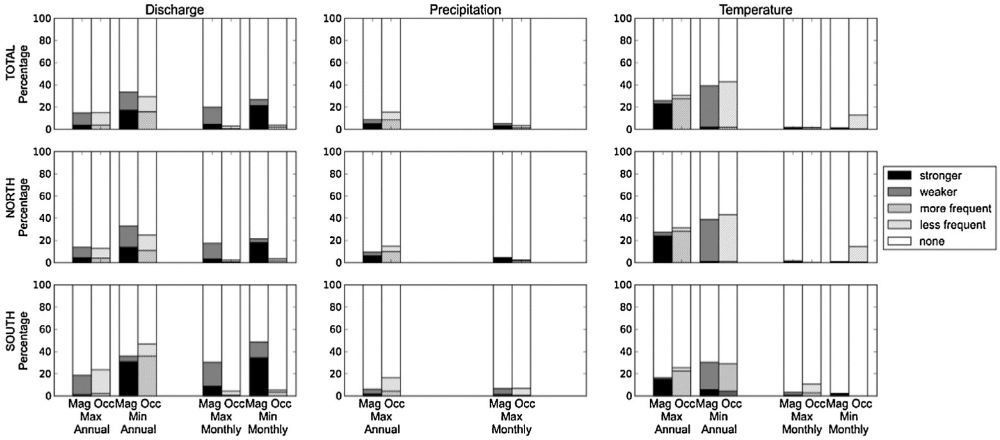


Fig. 8. Percentage of extreme value data sets with statistically significant trends: total, northern and southern hemisphere for Magnitude (Mag) and Occurrence (Occ) of extreme events on an annual and monthly scale. Maxima (Max) are analysed for all variables, Minima (Min) for all except precipitation data.

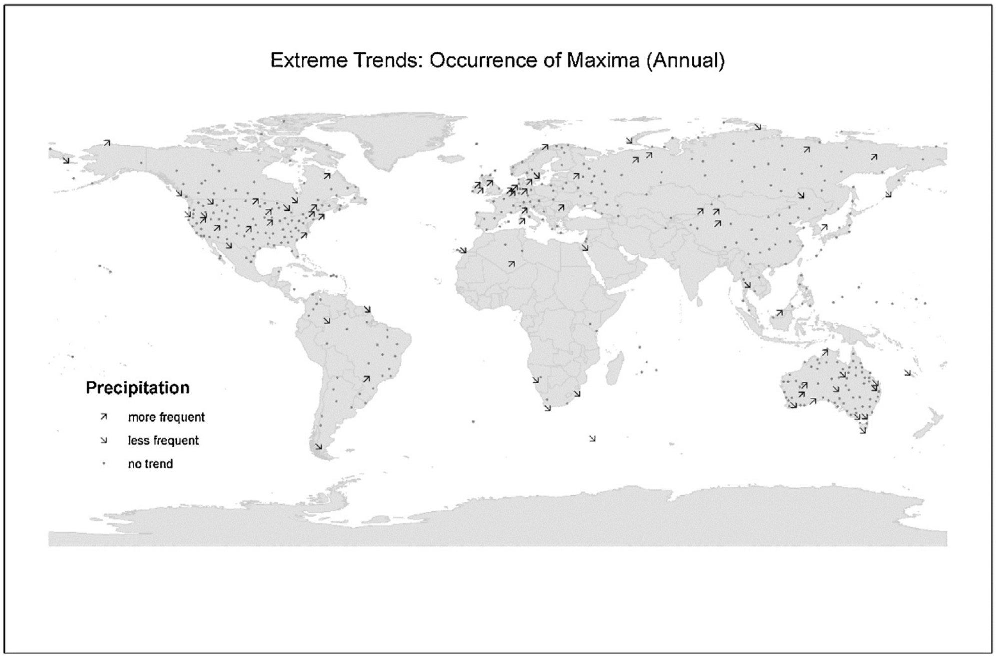


Fig. 9. Trends in the occurrence of Precipitation Maxima.

The clearest geographical distinction that could be seen in the results is the fact that precipitation trends are more positive in the northern and negative in the southern hemisphere, along with more cases of more frequent maxima in the north and less frequent maxima in the south, as shown in Fig. 9. Positive trends in discharge data could be found in the northernmost stations in Canada, and also in the UK. Temperature data sets show positive trends all around the world. Results also showed trends in both average and extreme value data sets for most of the northernmost and southernmost stations, especially for extreme values in temperature data at the northernmost stations.

3.4. *Trends at different time scales*

Taking a look at the results in Fig. 3, it can be clearly seen that the percentages of data sets with a trend vary at different time resolutions for precipitation and temperature data: the number of random variables that show a significant trend decrease in number towards the daily resolution, for example the number of data sets with trends for temperature data on an annual level is about 6 times as high as on a daily level. Only for discharge data, a nearly constant number of about 60% of the series show a trend on all time resolutions.

One of the explications for this behaviour could be the above described differences in the variation between the different variables that influence on the power of the Mann–Kendall trend test. Fig. 10 shows the histograms of the coefficient of variation for all variables at different time resolutions. The coefficients of variation of temperature data are in the above described range below and close to 0.2 and increasing towards the daily resolution, which could explain the decrease of trends being detected on smaller time resolutions. An increase can also be noted for precipitation data sets, while the coefficient does not increase as strongly for discharge data.

On the other hand, the higher number of missing values in daily data series and the therefore lower average length of the random variables on a daily resolution as shown in Fig. 2 lowers the possibility to detect significant trends.

3.5. *Discussion*

As stated above, an analysis on the findings for discharge data can only be made for the area, in which data was analysed and therefore does not permit a global conclusion. However, a high number of negative trends and an increase and intensification of minima found in the restricted geographical area can be attributed to human intervention. The high number of water withdrawn from the renewable resources, especially for agriculture and irrigation in the analysed regions and a large number of dams constructed, partly during the research period between 1970 and 2010 have been shown by the data published by the Food and Agricultural Organization (FAO) on Aquanet (AQUASTAT-FAO's information system on water and agriculture, 2015). It also shows an increase of over 40% of water extractions between 1970 and 2010 on a global scale.

The increased number and magnitude of discharge maxima in especially the northernmost stations is most probably related to the increase in temperature globally and especially in these regions. Previous studies, such as by Yang et al. (2002),

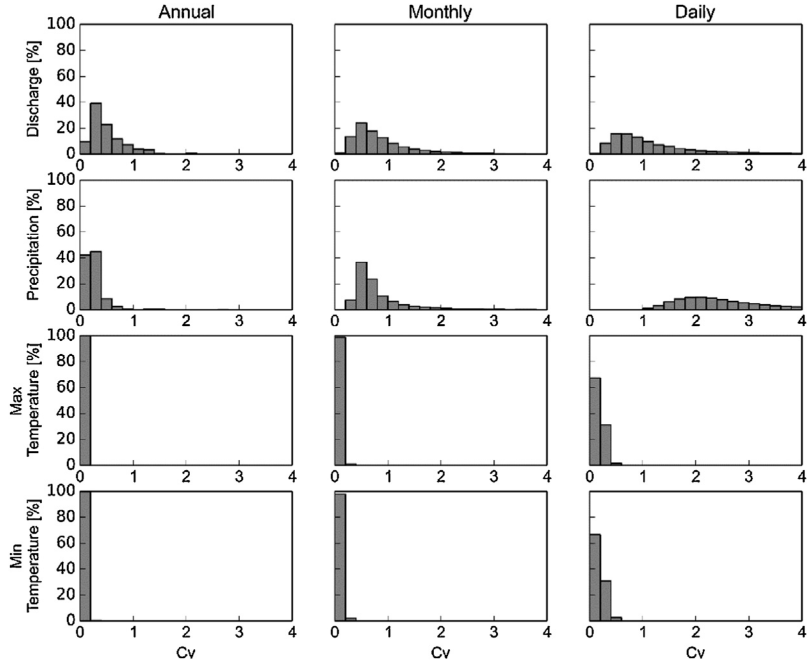


Fig. 10. Histograms of the coefficients of variation among all data sets at different time scales.

have shown changes in the patterns of hydrological processes in winter, which are mostly due to higher temperatures and therefore an increase of runoff.

Many authors and organizations have repeatedly reported a significant increase of global temperature, which is also shown in the current study and therefore not a surprising finding. However, the fact that the increase in temperature, stronger maxima and weaker minima is stronger in the northern than in the southern hemisphere is worth mentioning. Comparative studies, for example the State of the Climate reports published by the NOAA (State of the Climate | National Centers for Environmental Information (NCEI), 2015) have shown that the ocean temperature anomalies since 1880 have not been as strong as for land temperature. This finding might be one possible explanation for the stronger temperature increase in the northern hemisphere.

Trends in precipitation are very few and therefore difficult to discuss. However, the finding of more negative trends and fewer and weaker strong rainfall events in the southern hemisphere, as opposed to other studies are most likely due to the methodology used in the investigation and the stations selected.

Generally it can be said that the selection of a sample of stations increases the uncertainty of the results. Especially in regions, where a lot of information is available, a different choice of stations might have produced different results. The exact degree of reliability of the information was not evaluated due to the differences in different regions. Also, the lack of stations in many areas of the world, especially in the tropical regions and almost all of Africa, do not permit for the results to be generalized in a global way, however they are an indication of how the observations of the three hydroclimatological variables have changed in the evaluated period.

4. Conclusions

This study tested average and extreme data sets for trends at different time resolutions and around the world. Results show that statistically significant trends at the 5% significance level can be found in both average and extreme value data for all hydrometeorological variables at all different latitudes, with fewer trends for extreme value data.

In the most part, the results coincide with the findings of previous studies. Mainly positive temperature trends and a rise especially in minimum temperature were reported by other authors, as well as a small number of detected trends in precipitation data, which are predominantly positive in the northern hemisphere. The same is true for a rising number of precipitation maxima in the northern hemisphere. However, contrary to other studies, results indicate more negative trends in discharge data sets and their extremes, although this result can only be applied to the reduced study area.

More specifically, the results indicate a warming climate all around the world, which most probably influences other variables, although it was not proven in this study. However, it is noted that in areas with stronger warming, trends towards more intense precipitation extremes were found, as well as negative trends in discharge data in the parts of the world where it was available. Also, the fact that in almost all of the northernmost and southernmost stations significant trends as well as an increase and intensification of extreme events for all variables are observed, indicates that the impact of higher temperatures in these regions might be especially strong.

Seasonal analysis suggests stronger warming especially in the spring (south) and summer (north) months than in the winter months.

Although discharge data sets were not available on a global basis, some conclusions could be made for the reduced study area. The fact that the majority of the stations show negative trends while precipitation in many areas increased or does not show any significant trends, could most likely be attributed to increased human influences in the area. Also, the reduced number and lower intensity of discharge maxima leads to the conclusion that human intervention plays a role in these changes.

The results of the trend analysis were influenced by the fact that variability in annual random variables is lower than on monthly and daily resolutions. According to the results, temperature data was most susceptible to this influence.

This study, based on the applied methods, strongly indicates that in the analysed period changes have occurred and that trends could be observed in hydrometeorological data around the world, especially on the annual level. The differences in the number of trends on different time scales were most probably a result of the data structure and the tests applied. The results of this study can be seen as indicators of how climate might behave in the coming years, although probably not in the long term. It also provides an overview of trend analysis results on a global scale, previously only achieved in separate investigations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.12.061.

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