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# Changes in annual precipitation over the Earth's land mass excluding Antarctica from the 18th century to 2013

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SUMMARY

Precipitation measurements made at nearly 1000 stations located in 114 countries were studied. Each station had at least 100 years of observations resulting in a dataset comprising over 1½ million monthly precipitation amounts. Data for some stations extend back to the 1700s although most of the data exist for the period after 1850. The total annual precipitation was found if all monthly data in a given year were present. The percentage annual precipitation change relative to 1961–90 was plotted for 6 continents; as well as for stations at different latitudes and those experiencing low, moderate and high annual precipitation totals. The trends for precipitation change together with their 95% confidence intervals were found for various periods of time. Most trends exhibited no clear precipitation change. The global changes in precipitation over the Earth's land mass excluding Antarctica relative to 1961–90 were estimated to be: $-1.2 \pm 1.7$, $2.6 \pm 2.5$ and $-5.4 \pm 8.1$% per century for the periods 1850–2000, 1900–2000 and 1950–2000, respectively. A change of 1% per century corresponds to a precipitation change of 0.09 mm/year.



## 1. Introduction

It is now commonly accepted that the global average temperature has increased by about 1 °C over the past century (IPPC 2001, 2007, 2013; van Wijngaarden, 2014). The Clausius–Clapeyron equation shows that the saturation water vapour pressure increases exponentially with temperature. Hence, it is reasonable to expect atmospheric water vapour pressure to increase assuming relative humidity remains unchanged. Our earlier work examined over a quarter billion hourly values of temperature and relative humidity observed at 309 North American stations during 1948–2010 and found small increases in water vapour pressure coinciding with a small decrease in relative humidity (Isaac and van Wijngaarden, 2012). It has been suggested that a higher water vapour pressure may increase precipitation (Wentz et al., 2007). Indeed, the IPCC has reported that precipitation increased in some regions by as much as 1% in each decade of the 20th century (IPPC 2001, 2007, 2013; Dai et al., 1997).

Anthropogenic influence on twentieth-century precipitation trends has been found (Zhang et al., 2007) by examining data provided by the Global Historical Climatology Network (GHCN) (Vose et al., 1992). This dataset was comprised of 7500 stations. Each station had a minimum of 10 years of data and the majority of stations had less than 50 years of data. The trends during 1925–1999 and 1950–1999 show precipitation in the regions from the equator to 20°N increased by about 1 mm/year while from the equator to 20°S decreased by about 2 mm/year. This qualitatively agrees with some of the global climate models. However, relatively few of the GHCN stations are located near the equator which includes the Amazon rain forest and parts of the Sahara desert.

Three large studies have examined global precipitation records for decades in the last part of the 20th century (Li et al., 2014). The Climate Prediction Center produced 17 years of monthly analysis (Climate Merged Analysis of Precipitation or CMAP) based on precipitation observations using rain gauges, satellite estimates and numerical model outputs (Xie and Arkin, 1997). A second dataset obtained using similar methods was found by the Global Precipitation Climatology Project (GPCP) for the period 1979–2005 (Adler et al., 2003; Huffman et al., 2009). A third data reanalysis has been developed by the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) (Kistler et al., 2001). The three datasets generate time series having significant differences (Li et al., 2014; Gu et al., 2007). For the period 1979–2008, the CMAP model shows a decreasing trend of −1 mm/year. In contrast, the GPCP trend shows a nearly flat trend of 0.1 mm/year while the NCEP/NCAR model shows an increasing trend of 3.5 mm/year.

These differences are not entirely surprising given that precipitation varies considerably over time scales of decades (van

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**Fig. 1.** Locations of stations examined in this study. Red dots show the 776 stations having 100–149 years of data, green dots the 184 stations having 150–199 years of data and blue dots the 24 stations having more than 200 years of data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

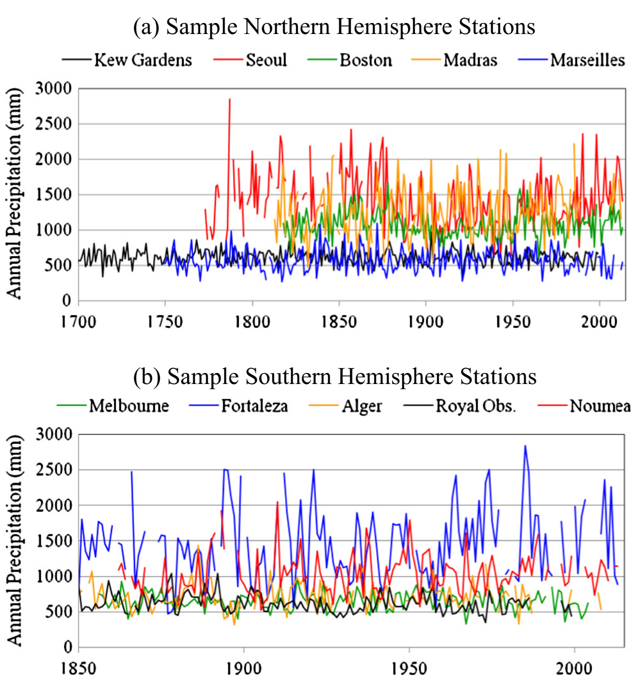



**Fig. 2.** Examples of annual precipitation for stations located in (a) Northern Hemisphere and (b) Southern Hemisphere. Stations in (a) are: Kew Gardens, United Kingdom; Seoul, South Korea; Boston, United States; Madras, India and Marseilles, France. Stations in (b) are: Melbourne, Australia; Fortaleza, Brazil; Alger, Algeria; Royal Observatory, South Africa and Noumea, New Caledonia.

Wijngaarden, 2013). Hence, the resulting trends frequently are not statistically significant. This study examined monthly precipitation measurements taken at over 1000 stations, each having a record of at least 100 years of observations to detect long term changes in precipitation. Data for some stations was recorded in the 1700s. This enables examination of possible precipitation changes occurring over much longer time scales than was considered by the previous studies. This is important as it facilitates detection of a long term trend due to anthropogenic climate change as opposed to natural decadal variations.

## 2. Methodology

This study retrieved monthly precipitation totals available through the Royal Dutch Archive (KNMI, 2014) and the Australian Bureau of Meteorology (BOM, 2014). Data from over 1600 stations having at least 100 years of data observation were considered. Most of the data was available beginning after 1850. Data was not available for many stations after 2000 when a number of stations were closed or data was not forwarded to the KNMI archive. A disproportionate number of stations were located in Australia and the U.S. Therefore, the selection criteria for Australia and the U.S. were minimum observation periods of 115 and 125 years, respectively. This reduced the dataset to 1019 stations. The annual total precipitation was only computed for years in which no month had missing data.

It is important to examine precipitation data for inhomogeneities that may affect calculated trends. Inhomogeneities in precipitation data have been found to occur most frequently during cold winter months (Groisman and Legates, 1994). It has been found that instrumental discontinuities can be large for high-latitude station records but globally are not significant (Dai et al., 1997). The present analysis examined the annual total precipitation time series for each station using established techniques for detecting discontinuities as well as for gaps as long as decades. Step discontinuities can be found using a statistical *F*-test to determine whether the data is better fitted by a straight line or a model which adds an abrupt change at some point in the time series (van Wijngaarden, 2013; van Wijngaarden and Vincent, 2005). The resulting analysis removed 35 stations yielding a dataset consist-

(a) 1800-2000

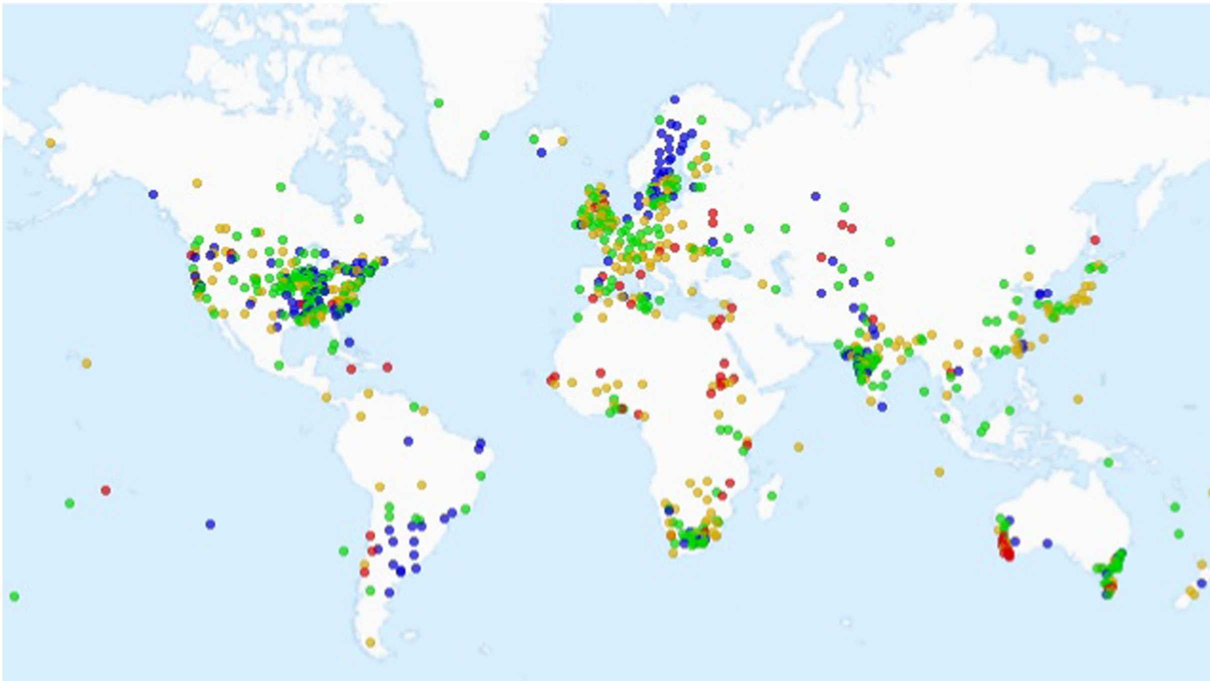
(b) 1850-2000

**Fig. 3.** Maps of Station Precipitation Trends for the periods of (a) 1800–2000, (b) 1850–2000, (c) 1900–2000 and (d) 1950–2000. Blue (green) indicates an increasing trend that is (not) statistically significant while red (yellow) indicates a decreasing trend that is (not) statistically significant. Trends are plotted for stations having at least 80% of observations for all years during the period in question as is discussed in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ing of 984 stations located in 114 different countries as shown in Fig. 1.

The number of years for which the annual precipitation could be computed was 116 years when averaged over all stations. The longest station record of 303 years was available for Kew Gardens, United Kingdom. Fig. 2 shows some sample annual precipitation data. In general, stations in the northern hemisphere had a longer data record than those located in the southern hemisphere. The year to year variability of precipitation varied considerably from station to station.

(c) 1900-2000



(d) 1950-2000

**Fig. 3** (*continued*)

## 3. Results

The percentage precipitation change relative to the average annual precipitation occurring during 1961–90 was computed for each station. The reference period of 1961–90 is commonly used (Zhang et al., 2007). The results of this study change minimally if the reference period is shifted one or two decades. Fig. 3 shows the location of stations experiencing either increasing or decreasing precipitation. Trends found using linear regression were only found for stations having observations for at least 80% of the years for the period in question. Table 1 lists the number of stations experiencing increasing/decreasing precipitation trends for the periods 1800–2000, 1850–2000, 1900–2000 and 1950–2000. The significance of the trends was assessed using the statistical *t*-test at the 5% level. Most trends were not statistically significant during any of the four time periods considered. Many stations experienced increased precipitation during one period but decreased precipitation during another time period. Only 39% of the 44 stations for

**Table 1**
Number of stations having decreasing/increasing precipitation trends for different time periods. The number of stations having statistically significant trends is in brackets. Trends were only found for stations having data for 80% of all years in the time period as is discussed in the text.

| Time period | Number stations with decreasing precipitation trend | Number stations with increasing precipitation trend |
|---|---|---|
| 1800–2000 | 21 (9) | 32 (12) |
| 1850–2000 | 113 (28) | 179 (67) |
| 1900–2000 | 323 (71) | 530 (162) |
| 1950–2000 | 328 (66) | 388 (68) |

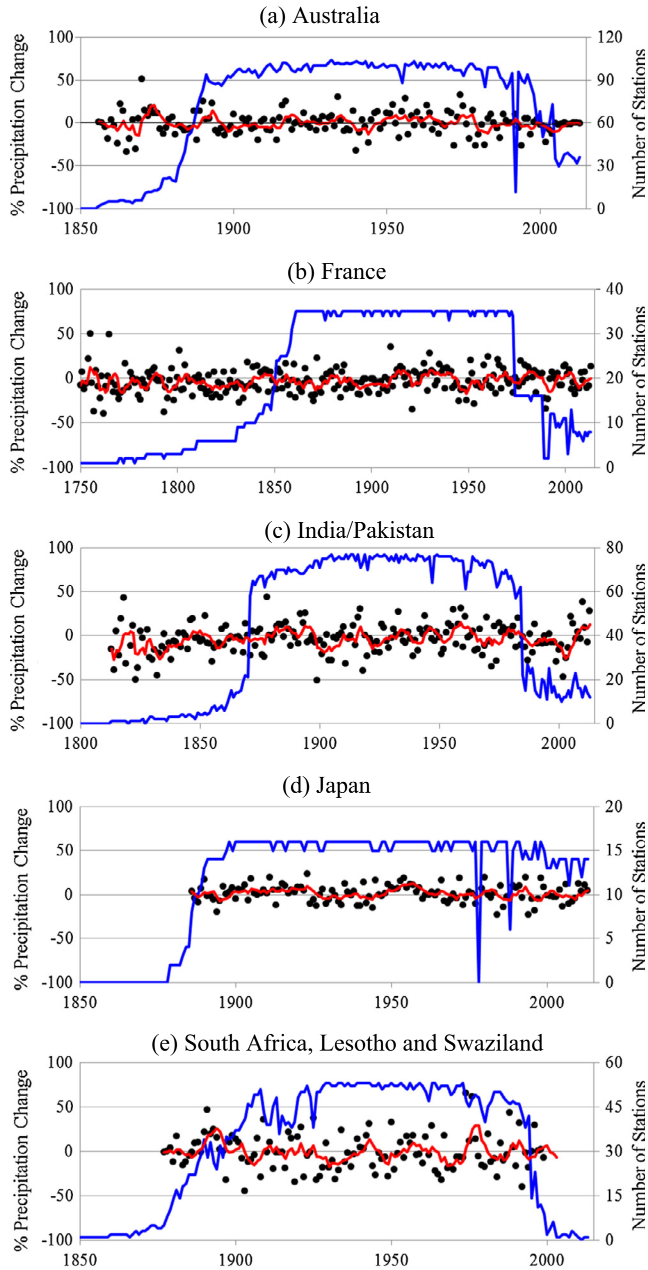



**Fig. 4.** Percentage precipitation change relative to 1961–90 for various countries. The red curve is the moving 5 year average while the blue curve shows the number of stations. Considering only years having at least 5 stations reporting data, the trends in units of % per century are: (a) Australia −1.0 ± 4.8, (b) France 0.3 ± 2.8, (c) India/Pakistan 0.5 ± 5.3, (d) Japan −1.5 ± 4.5, (e) South Africa, Lesotho and Swaziland −1.4 ± 10, (f) Africa North of Equator −10 ± 5.2, (g) Sweden 9.0 ± 4.3, (h) United Kingdom 0.6 ± 2.4 and (i) U.S. (Lower 48 States) 2.2 ± 2.0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

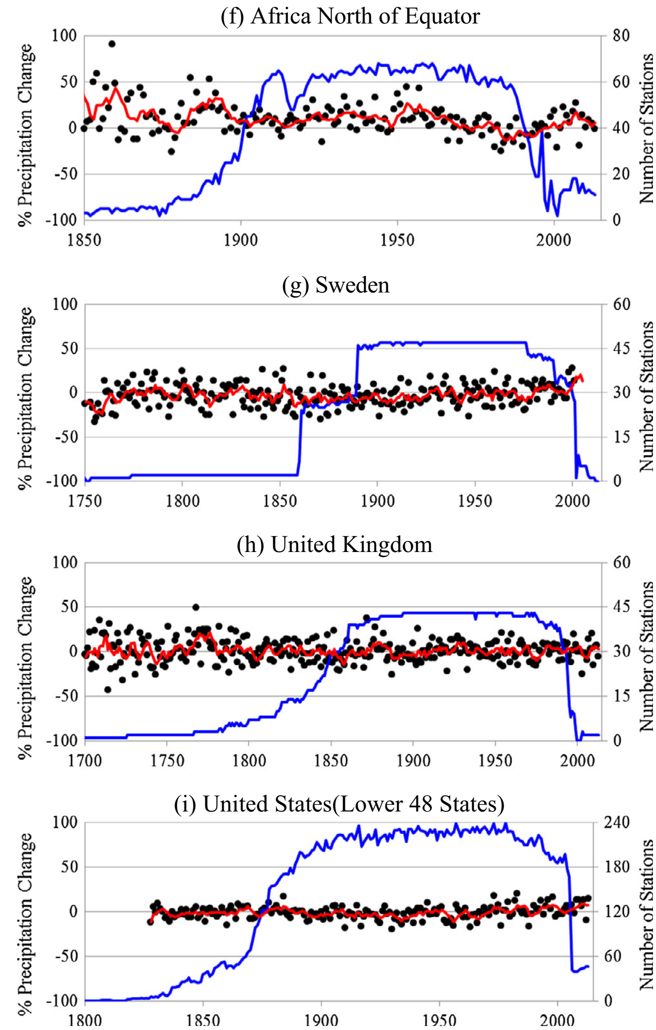



**Fig. 4** (*continued*)

which trends were found for all 4 intervals, experienced trends that either all increased or all decreased. Half of the 256 stations for which trends were found for the last 3 intervals, experienced trends that either all increased or all decreased. About one third of the 684 stations had opposite trends during 1900–2000 and 1950–2000. The average trends in units of % per century were 1.3 ± 1.5, 2.3 ± 1.3, 3.6 ± 1.1 and −1.9 ± 3.3 during the periods 1800–2000, 1850–2000, 1900–2000 and 1950–2000, respectively where the uncertainty represents the 95% confidence interval.

The percentage precipitation change was averaged over all stations in a given country or region as shown in Fig. 4. These results are consistent with those shown in Fig. 3 but large fluctuations of precipitation on time scales of years to decades are evident. Notably, countries such as India/Pakistan and South Africa as well as Africa north of the equator experience greater interannual variability than do France, Japan and the United Kingdom. There are notable outlier points. For example, 1900 was an exceptionally dry year in India/Pakistan. This drought occurred when the monsoons failed to arrive and caused widespread starvation. Estimates of the number of deaths range as high as a few million (Fieldhouse, 1996). For each time series, the data points lie close to the horizontal line showing zero precipitation change. The trends were computed for the years in which there were at least 5 stations reporting data. The stated uncertainty of each trend found in this study is the 95% confidence interval resulting from applying a statistical *t*-test. Most of the resulting trends were consistent with little precipitation

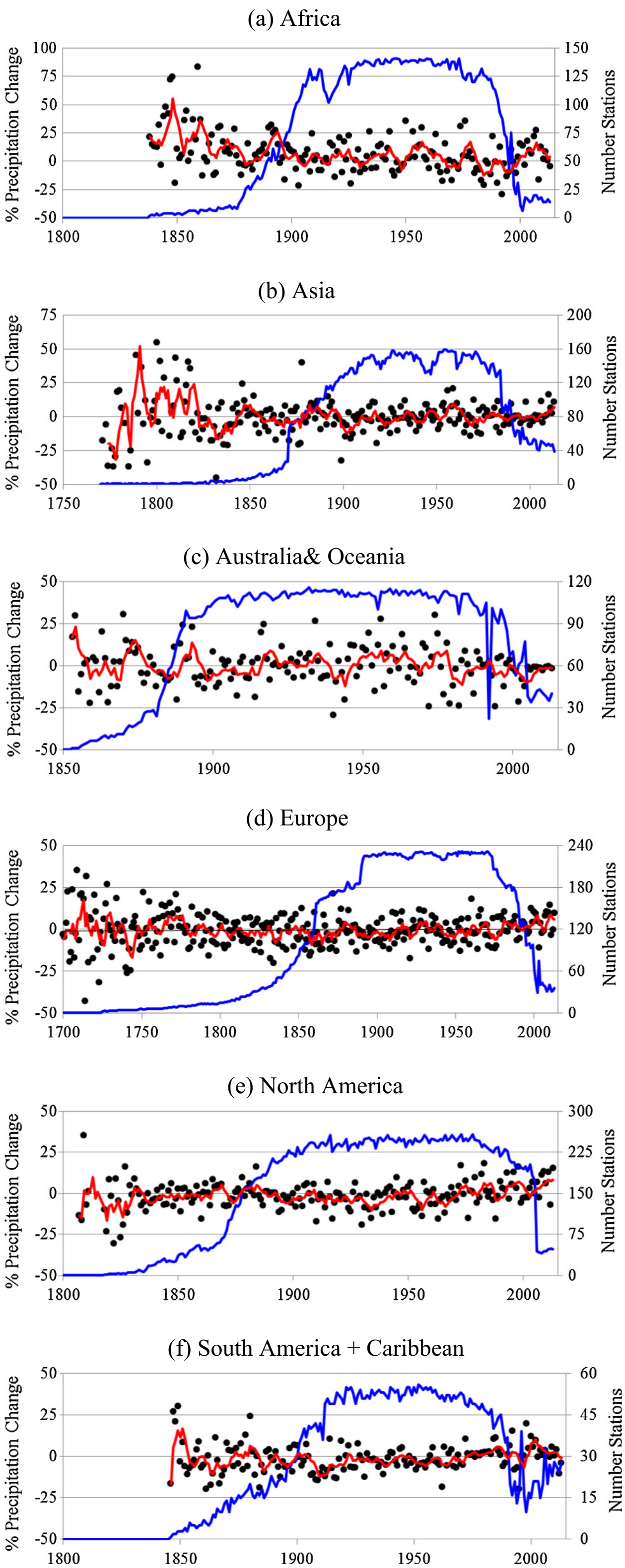



**Fig. 5.** Percentage precipitation change relative to 1961–90 for the various continents. The red curve is the moving 5 year average while the blue curve shows the number of stations. Considering only years having at least 10 stations reporting data, the trends in units of % per century are: (a) Africa −3.6 ± 5.5 during 1873–2013, (b) Asia 2.5 ± 2.9 during 1854–2013, (c) Australia/Oceania −2.2 ± 4.3 during 1864–2004, (d) Europe 1.7 ± 1.4 during 1774–2013, (e) North America 2.5 ± 2.0 during 1833–2013 and (f) South America + Caribbean 3.2 ± 2.7 during 1866–2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

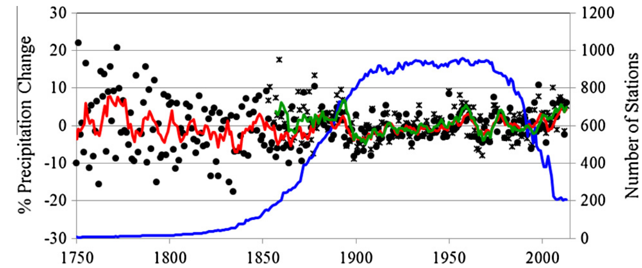



**Fig. 6.** Percentage precipitation change relative to 1961–90 for all stations. The black dots represent data found by averaging the data over all stations while the crosses were found by weighting the various continental time series by the continental area. The red (green) curves are the 5 year moving averages while the blue curve indicates the number of stations. The green curve was only found for years where data exists for all 6 continents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Trends for global percentage precipitation change. The results for continental area weighting are only tabulated after 1850 when data is available for the 6 continents as is described in the text.

| Time period start | Precipitation change trend (%/century) | | | |
|---|---|---|---|---|
| | Station average | | Continental area weighting | |
| | Time period end 2000 | Time period end 2013 | Time period end 2000 | Time period end 2013 |
| 1700 | −0.2 ± 1.1 | 0.01 ± 1.1 | | |
| 1750 | −0.3 ± 1.0 | 0.02 ± 0.9 | | |
| 1800 | 1.2 ± 1.1 | 1.5 ± 1.0 | | |
| 1850 | 1.7 ± 1.4 | 2.1 ± 1.2 | −1.2 ± 1.7 | −0.3 ± 1.5 |
| 1900 | 3.1 ± 2.2 | 3.5 ± 1.8 | 2.6 ± 2.5 | 3.9 ± 2.1 |
| 1950 | −1.1 ± 6.8 | 2.2 ± 4.8 | −5.4 ± 8.1 | 2.0 ± 5.8 |

change. Similar results were also found for regions of large continents/countries such as California in the United States. Only the results for Sweden and Northern Africa show evidence of nonzero trends.

Fig. 5 shows the percentage precipitation change occurring for six continents. Here, the Caribbean stations have been grouped with South America which has relatively few stations compared to the U.S. Stations located on Pacific islands have been included in the plot labelled Australia & Oceania. Africa, Asia and Australia & Oceania exhibit greater year to year variation than do Europe, North and Latin America. The trends were computed for the years in which there were at least 10 stations reporting data. The resulting trends together with their uncertainties are consistent with minimal precipitation change for all of the continents.

Fig. 6 shows the global percentage precipitation change. This was computed in two ways. First, an average of the station data was taken. This preferentially weights North America and Europe where about half of the stations are located. An alternative was to combine the time series for the 6 continents using weighting factors proportional to the continental areas. The resulting two curves do not differ significantly. Table 2 shows the trends depend strongly on the time period considered illustrating the effect of decadal variations. Most of the trends have 95% confidence intervals that overlap with no change in precipitation.

Fig. 7 compares the percentage precipitation change for stations located north of 20°N latitude, within ±20° of the equator and south of −20°N latitude. There is no substantial trend difference between the three curves. Data were also considered using smaller 10° latitude increments. Such figures do not show dramatically different trends although the year to year fluctuation increases because of the reduced number of stations. Similarly, Fig. 8 compares the percentage precipitation change for dry stations (total

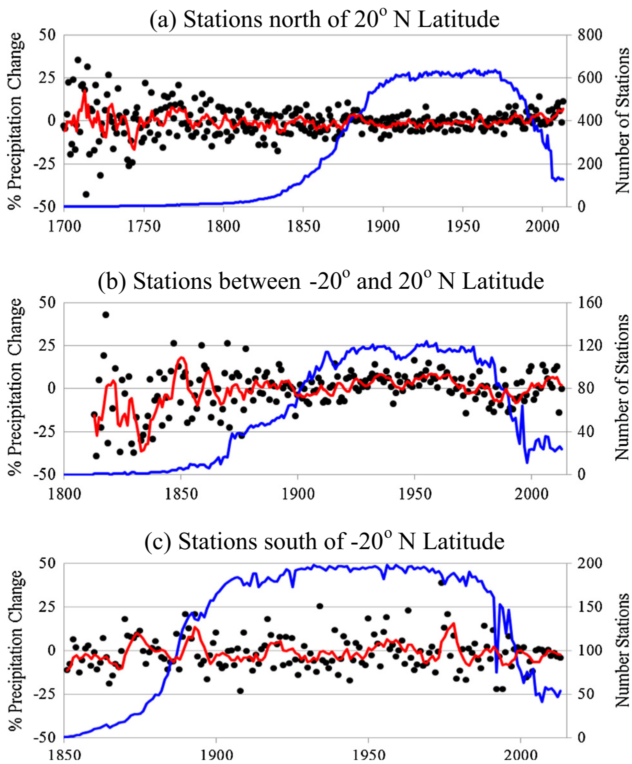



**Fig. 7.** Effect of latitude on percentage precipitation change relative to 1961–90 for stations having latitude (a) north of 20° latitude, (b) between −20° and 20° and (c) south of −20°. The red curve is the moving 5 year average while the blue curve shows the number of stations. Considering only years having at least 10 stations reporting data, the trends in units of % per century are: (a) 1.2 ± 1.0 during 1771–2013, (b) 1.4 ± 3.1 during 1854–2013 and (c) −0.7 ± 3.6 during 1860–2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

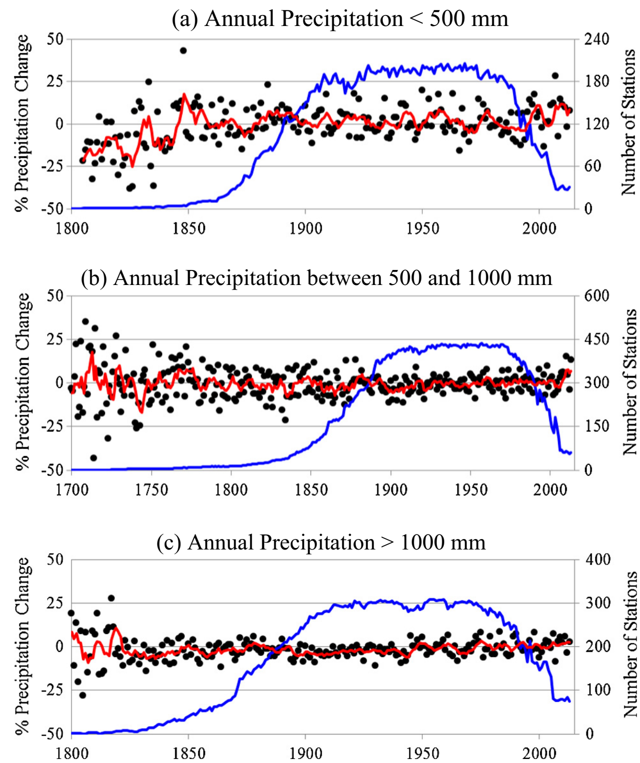



**Fig. 8.** Effect of total precipitation on percentage precipitation change relative to 1961–90 for stations having total annual precipitation (a) <500 mm, (b) between 500 and 1000 mm and (c) >1000 mm. The red curve is the moving 5 year average while the blue curve shows the number of stations. Considering only years having at least 10 stations reporting data, the trends in units of % per century are: (a) 1.4 ± 2.8 during 1854–2013, (b) 0.9 ± 1.1 during 1774–2013 and (c) 2.4 ± 1.2 during 1832–2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

precipitation <500 mm), stations experiencing moderate rainfall (between 500 and 1000 mm) and wet stations (total precipitation >1000 mm). There is no dramatic difference. Hence, one cannot conclude that dry areas are becoming drier nor wet areas wetter.

## 4. Conclusions

This study examined the percentage change of nearly 1000 stations each having monthly totals of daily precipitation measurements for over a century. The data extended from 1700 to 2013, although most stations only had observations available beginning after 1850. The percentage change in precipitation relative to that occurring during 1961–90 was plotted for various countries as well as the continents excluding Antarctica. There are year to year as well as decadal fluctuations of precipitation that are undoubtedly influenced by effects such as the El Nino Southern Oscillation (ENSO) (Davey et al., 2014) and the North Atlantic Oscillation (NAO) (Lopez-Moreno et al., 2011). However, most trends over a prolonged period of a century or longer are consistent with little precipitation change. Similarly, data plotted for a number of countries and or regions thereof that each have a substantial number of stations, show few statistically significant trends. The number of statistically significant trends is likely to be even less if the time series slope is found using methods that are less influenced by outliers points (Sen, 1968). The annual precipitation averaged over all stations was 850 mm. Therefore, a change of 1% per century corresponds to a change of 0.09 mm per year. This is consistent with the results obtained by the Global Precipitation Climatology Project for the period 1979–2005.

A significant finding of Zhang et al. (2007) was evidence for a possible shift of global precipitation patterns. Precipitation during the twentieth-century appeared to have decreased in regions near the equator while a small increase was found in the Northern Hemisphere mid-latitudes as well as in the Southern Hemisphere. This study found precipitation has decreased in Northern Africa since 1850 but there is no clear change in places such as the Indian subcontinent. Northern Africa contains the Sahara desert which experiences very low rainfall and very few rainfall events in a year can strongly affect the percentage precipitation change causing relatively large year to year fluctuations. This study also found some indications that precipitation increased slightly in regions of the Northern Hemisphere such as the U.S. and in parts of Europe such as Sweden. Fig. 3 also shows indications of increased precipitation at a number of stations in South America. However, many of the trends are small and most of the confidence intervals overlap with zero precipitation change.

Stations experiencing low, moderate and heavy annual precipitation did not show very different precipitation trends. This indicates deserts/jungles are neither expanding nor shrinking due to changes in precipitation patterns. It is therefore reasonable to conclude that some caution is warranted about claiming that large changes to global precipitation have occurred during the last 150 years.

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