When Will We Detect Changes in Short-Duration Precipitation Extremes?

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Supplemental Material

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Supporting Information

Observed data homogeneity

Assessment of trends in time series may be confounded by inhomogeneities due to changes in the observing system (e.g. appearing as abrupt discontinuities or gradual changes). Abrupt discontinuities may occur due to changes in gauge relocation, instrumentation or observing and recording practices, whilst gradual changes may be a consequence of a change in gauge surroundings or in the properties of rain gauge characteristics (WMO, 2008). Several statistical tests are available to identify such discontinuities. Here we apply three such tests, the Buishand range test (Buishand, 1982), Pettit test (Pettitt, 1979) and Standard Norman Homogeneity test (Alexandersson, 1986). We consider that a series has a potential break in where at least two tests identify a significant break where the estimated year of breaks are within 5 years of each other. Aguilar et al. (2003) recommend that homogeneity tests are best performed on a time series that is expressed relative to a reference time series, i.e. one experiencing the broad climatic influences of the candidate gauge (the gauge to be tested for inhomogeneity). They suggest that inhomogeneities may be detected by comparing time series of the ratios (in the case of precipitation) or differences (for temperature) as these should show neither sudden changes, nor trends, which may be identified in a number of ways e.g. inspection of time series plots or implementation of a statistical break point test. The above tests were therefore applied to annual time series of gauge mean wet hour intensity (MWHI) expressed relative to a neighbouring gauge but only where such gauges were located no more than 25km from the candidate gauge as Blenkinsop et al. (2017) demonstrated a low correlation between gauges at greater distances, particularly in summer. As some gauges did not have any qualifying neighbouring gauges these tests were therefore also applied to annual time series of the absolute MWHI for each gauge.

The application of these tests enabled the identification of a change in resolution of some tipping bucket raingauge (TBR) measurements but due to the lack of gauge metadata (e.g. information on gauge relocation or instrument changes) it was not possible to assess other potential causes. For example, detected change points for the gauge at Upper Black Laggan (UBL), NW Scotland, matched a change in measurement resolution from 0.5mm to 0.2mm in 2003 which accounted for a decrease in mean wet hour intensity. As such changes in the resolution of measurement could affect trend analyses we corrected changes in the precision of precipitation measurement through time following Groisman et al. (2012), converting the finer-resolution measurements to the most coarse measurement for each gauge throughout the entire period of record. Under this method, small precipitation amounts are gradually accumulated until they reach the coarse resolution for each gauge. The effect of effect the change in tip resolution and subsequent homogenisation on mean wet hour intensity is illustrated in Figure S1 which shows the (MWHI) for the gauge at UBL which is contrasted with a neighbouring
gauge located ~2km away. This indicates the reduction in mean intensities at UBL when the tip resolution increases from 0.5mm to 0.2mm resulting in a Sen’s statistic (i.e. trend) of -0.023, significant at the 0.01 level (panel a). After homogenisation to a consistent resolution of 0.5mm Sen’s statistics is lower (-0.008), still significant at the 1% level. The influence of tip resolution is further demonstrated by comparing the original time series for Lower Black Laggan (LBL; homogeneous at 0.2mm resolution) with the higher intensities when converted to the coarser resolution as the same total rainfall is distributed over fewer wet hours. In this instance, statistical tests did not identify a break point in the original time series but all three detected a break point at the year 2000 when the UBL time series is expressed relative to that of LBL (Figure S1b). Note that the break point detection time is not expected to exactly match that of a known homogeneity given noise in the time series but here the two are broadly consistent.

Most gauges contained changes in gauge resolution (mainly 0.5mm to 0.2mm or 0.1mm to 0.2mm) although not all of these produced significant change points but were identified by changes in the time series of minimum non-zero rainfall amounts. A small number of gauges were considered unreliable and excluded on the basis of having more than one change in tip resolution. After homogenisation gauges were individually consistent at either 0.1mm, 0.2mm, 0.4mm or 0.5mm.

Figure S1: Time series of a) annual mean wet hour intensity (MWHI) for gauges at Lower (LBL) and Upper Black Laggan (UBL), and b) the ratio between the annual values at the two locations (UBL/LBL). Data in a) for LBL are shown using tip resolution of 0.2mm and coarsened to 0.5mm, and for UBL before and after homogenisation at the 0.5mm
resolution. The ratio in b) is calculated using LBL at a resolution of 0.5mm. The vertical
time denotes the timing of the change in tip resolution at UBL.

Results from observed change analysis

Additional results supporting the main text and referred to therein are provided below. The
confidence intervals (CI) for the trend estimations in Figures 5 and 6 and Figures S5 and S10 are
calculated using the Student’s t distribution where:

\[ CI = \bar{x} \pm t_{a/2, df} \cdot \frac{s}{\sqrt{n}} \]

where \( \bar{x} \) is the sample mean and \( t_{a/2, df} \) is the t value associated with the required confidence level
and sample size. The sample standard deviation is denoted by \( s \), and the sample size by \( n \).
Figure S2: Percentage change in mean precipitation intensity ($\Delta$mean) for the period 2002-2014 relative to successive rolling 13-year periods in the observations (top row 1h, middle row 24h). Change is plotted at the midpoint of the earlier 13-year period. The solid line denotes the median of the change across all available gauges, the shading denotes the range bounded by the 10th and 90th percentile ranges where at least 15 gauges are available. The horizontal lines indicate the periods used to resample the observed time series to evaluate normalised change. The bar plots (bottom row) denote the number of gauges available for each period.
Figure S3: Distribution of normalised change in mean precipitation intensity (mean, $D_x$) for 1h and 24h accumulations for the period 2002-2014 relative to three 13-year periods in the observations. The black triangles denote the median of the corresponding 1.5km model results for a 25-year change (scaled linearly from the 100-year change). The value $n$ denotes the number of gauges available for each period used to calculate change.
Figure S4: Distribution of normalised change in heavy precipitation ($p_{99_{ALL}}, D_x$) for 1h and 24h accumulations for the period 2002-2014 relative to three 13-year periods in the observations. The black triangles denote the median of the corresponding 1.5km model results for a 25-year change (scaled linearly from the 100-year change). The value $n$ denotes the number of gauges available for each period used to calculate change.
Figure S5: Distribution of normalised change in heavy precipitation intensity ($p_{95}, D_x$) for 1h and 24h accumulations for the period 2002-2014 relative to three 13-year periods in the observations. Here, only those gauges in the climate model domain (southern UK, see Figure 1) are used. The black triangles denote the median of the corresponding 1.5km model results for a 25-year change (scaled linearly from the 100-year change). The value $n$ denotes the number of gauges available for each period used to calculate change.
Figure S6: Spatial distribution of normalised change in heavy precipitation intensity ($p_{95}, D_x$) for 1h accumulations for the period 2002-2014 relative to 1989-2001 for a) DJF and b) JJA.
Figure S7: Relative Sen’s slope (unitless) for winter (DJF) hourly and daily mean rainfall intensity for a) successive periods ending in 2014 (long trends) and b) successive 30y periods (running trends). Points show mean slope of all gauges whilst ranges show the 95% confidence interval estimated using the Student’s t distribution when the number of gauges $n \geq 15$. Lower plots shows the number of gauges used for each period. See main paper for a description of the relative Sen’s slope.
Figure S8: Sen’s slope statistics (absolute) for 1h \( p_{95} \) for the period 1985-2014. Each row represents a different gauge, outlined boxes denote significance at the 95% level using the Mann-Kendall test. White areas denote gauges that do not meet completeness criteria for that season.
Figure S9: As in Figure S8 but for 24h $p_{95}$. 
Figure S10: Sen’s slope statistics for 1h $p_{95}$ for the period 1970-2014. Each row represents a different gauge, outlined boxes denote significance at the 95% level using the Mann-Kendall test. White areas denote gauges that do not meet completeness criteria for that season.
Figure S11: As in Figure S10 but for 24h $p_{95}$. 
Figure S12: As in Figure S7 but for summer (JJA) hourly and daily mean rainfall intensity.
Figure S13: Relative Sen’s slope (unitless) for a) winter (DJF) and b) summer (JJA) hourly and daily heavy precipitation intensity ($p_{95}$) for successive periods ending in 2014 (long trends). Points show mean slope using only those gauges for which trends may be calculated for all periods from 1955, $n$ denotes the number of gauges. See main paper for a description of the relative Sen’s slope.

**Variance estimates from model and observations**

Variance in 13-year heavy precipitation intensity ($p_{95}$) obtained by bootstrap resampling the 13 years of data in the control (future) period $\sigma_c^2 (\sigma_f^2)$ for the model are shown below in Tables S1 and S2. Also shown are variance estimates for the observations, for the 2002-2014 period, again estimated by bootstrap resampling the 13 years of data. It can be seen that the variance estimates agree well between the observations and the model control simulation, for precipitation accumulated on both the daily and hourly timescale, which gives credibility to the noise estimation that goes into the model detection time estimates.
<table>
<thead>
<tr>
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<th>1.5km</th>
<th>5km</th>
<th>12km</th>
<th>50km</th>
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<tbody>
<tr>
<td>Daily (Control)</td>
<td>1.676 (0.700,4.449)</td>
<td>1.662 (0.693,4.235)</td>
<td>1.461 (0.621,3.842)</td>
<td>1.060 (0.558,2.575)</td>
</tr>
<tr>
<td>Daily (Future)</td>
<td>6.647 (2.620,21.115)</td>
<td>6.697 (2.532,20.740)</td>
<td>5.957 (2.567,19.000)</td>
<td>4.984 (2.229,16.218)</td>
</tr>
<tr>
<td>Hrly (Control)</td>
<td>0.038 (0.018,0.085)</td>
<td>0.035 (0.016,0.078)</td>
<td>0.028 (0.013,0.065)</td>
<td>0.016 (0.009,0.030)</td>
</tr>
<tr>
<td>Hrly (Future)</td>
<td>0.088 (0.036,0.258)</td>
<td>0.082 (0.034,0.236)</td>
<td>0.072 (0.028,0.196)</td>
<td>0.048 (0.016,0.107)</td>
</tr>
<tr>
<td>Daily (Observations)</td>
<td>1.554 (0.663,4.130)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hrly (Observations)</td>
<td>0.043 (0.020,0.095)</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

Table S1: Variance in 13-year heavy precipitation intensity ($p_{95}$) in winter (mm$^2$), for the control (blue) and future (red) periods, for precipitation accumulated across a range of space (1.5km-50km) and time (hrly-daily) scales. Comparable results are shown for observations (green) calculated over the period 2002-2014 but at the point scale. Shown is the median of the variance across southern UK land points, and in brackets are the 10th and 90th percentiles of the spatially varying variance estimates. Variance is calculated across 100 estimates of $p_{95}$ obtained by bootstrap resampling the observed or model simulated precipitation time series.
<table>
<thead>
<tr>
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<th>1.5km</th>
<th>5km</th>
<th>12km</th>
<th>50km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily (future)</td>
<td>24.245 (8.799,63.433)</td>
<td>21.355 (7.951,56.065)</td>
<td>18.272 (7.121,47.927)</td>
<td>11.051 (3.887,33.724)</td>
</tr>
<tr>
<td>Hrly (control)</td>
<td>0.364 (0.162,0.791)</td>
<td>0.301 (0.131,0.663)</td>
<td>0.220 (0.091,0.512)</td>
<td>0.095 (0.041,0.212)</td>
</tr>
<tr>
<td>Hrly (future)</td>
<td>1.528 (0.588,3.854)</td>
<td>1.090 (0.443,2.601)</td>
<td>0.665 (0.277,1.468)</td>
<td>0.210 (0.082,0.499)</td>
</tr>
<tr>
<td>10min (control)</td>
<td>0.040 (0.019,0.083)</td>
<td>0.028 (0.013,0.056)</td>
<td>0.018 (0.007,0.037)</td>
<td>0.008 (0.003,0.019)</td>
</tr>
<tr>
<td>10min (future)</td>
<td>0.172 (0.071,0.444)</td>
<td>0.093 (0.042,0.219)</td>
<td>0.046 (0.020,0.115)</td>
<td>0.013 (0.005,0.039)</td>
</tr>
<tr>
<td>Daily (Observations)</td>
<td>5.454 (2.539,13.444)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hrly (Observations)</td>
<td>0.244 (0.108,0.655)</td>
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</table>

Table S2: As Table S1 but for variance in 13-year heavy precipitation intensity ($p_{95}$) in summer (mm²).
References


