nature climate change

LETTERS

PUBLISHED ONLINE: 17 MARCH 2013 | DOI: 10.1038/NCLIMATE1828

Trends in hourly rainfall statistics in the United States under a warming climate

T. Muschinski[1] and J. I. Katz[1,2]★

It is now widely accepted[1–5] that the mean world climate has warmed since the beginning of climatologically significant anthropogenic emission of greenhouse gases. Warming may be accompanied[6–8] by changes in the rate of extreme weather events such as severe storms and drought. Here we use hourly precipitation data from 13 stations in the 48 contiguous United States to determine trends in the frequency of such events, taking the normalized variance and a renormalized fourth moment of the precipitation measurements, averaged over decades, as objective measures of the frequency and severity of extreme weather. Using data mostly from the period 1940–1999 but also two longer data series, periods that include the rapid warming that seems to have begun at approximately 1970, we find a significant increase of $6.5 \pm 1.3\%(1\sigma)$ per decade in the normalized variance at a site on the Olympic Peninsula at which it is low. We place statistical limits on any trend at the remaining 12 sites, where the normalized variance and its uncertainty are larger. At most sites these limits are consistent with the same rate of linear increase as at the Olympic Peninsula site, but exclude the same rate of percentage increase.

Severe storms are usually accompanied by, and may even be defined by, short periods of intense rainfall. Events, such as tornadoes, that are not themselves sources of intense rain are produced by severe storms that are. Precipitation data are comparatively insensitive to changes in the metre-scale environment that must be considered in historical studies of temperature data[5].

Many studies[9–12] of the frequency of extreme weather events have been concerned with the largest one-day or few-day (often five-day) precipitation totals recorded over a year or other long interval. Other studies[13] have been concerned with the number of days in which total precipitation is above some high threshold or in some high range. These are the data of most value to civil engineers and planners, but do not describe well shorter-lived events such as thunderstorms.

For quantification of the storminess of precipitation, hourly data offer information and insights lost by averaging over entire days. In addition, extreme value statistics[9–11,14–18] and the statistics of infrequent events[13] discard the information present in lesser, but more frequent, events, lose the statistical advantage of averaging over more data and may depend on arbitrary choices of thresholds and criteria. Studies of hourly data[19–21] that use only extremes suffer from these disadvantages too. These factors also complicate combining information from multiple sites that may be in different climatic regimes in which different definitions of extreme weather events may be appropriate. Utilization of all available data has been a powerful tool for extracting climatic information from temperature variations that may be inconsistent among sites (see, for example, ref. 5). We therefore study metrics that combine information present in entire time series, including periods of lower intensity precipitation, using data with the finest available (hourly) temporal resolution.

Hourly precipitation data are available since 1940 (and at some sites since 1900) for many US locations from National Oceanic and Atmospheric Administration (NOAA) databases. We use the moments of these data to define objective measures of short-term severe weather events. Although it is known that changes in land use on large spatial scales affect mean rainfall in a manner analogous to the urban heat island effect[5], by normalizing the moments to the mean rainfall it is possible to separate (though necessarily arbitrarily) changes in the frequency of severe weather events from changes in mean precipitation[22]. This permits a test, within the limits of the available data, of the hypothesis[11,23] that the frequency and intensity of heavy rain and consequent flooding are increasing.

The normalized nth moment is defined:

$$M_{n,D} \equiv \frac{\sum_{i \in D} (p_i - \langle p_i \rangle_D)^n}{N \langle p_i \rangle_D^n}$$

where the p_i are the measured hourly data, i denotes the date and time of measurement, D denotes the decade over which the moment and data are averaged and N is the number of valid data included in the sum. This is generally less than the number of hours in a decade because some data are missing. The mean precipitation

$$\langle p_i \rangle_D \equiv \frac{1}{N} \sum_{i \in D} p_i$$

We also define a renormalized nth moment:

$$M'_{n,D} \equiv \frac{M_{n,D}}{M_{2,D}^{n-1}}$$

The second moment measures the dispersion of the rainfall data. A large value of the normalized second moment indicates, independent of the mean precipitation, how uniformly or episodically precipitation is distributed over the hours of the decades. Moments with $n > 2$ contain statistical information not contained in the second moment. Renormalization sets a natural scale for these higher moments: for example, if a distribution were to consist of a fraction f of data all with the same value C, and the remainder 0, then $M_n = f^{1-n}$ but $M'_{n,D} = 1$. The value of $M'_{n,D}$ (always ≥ 1) is a dimensionless statistic describing the spikiness of the rainfall

[1]Department of Physics, Washington University, Saint Louis, Missouri 63130, USA, [2]McDonnell Center for the Space Sciences, Washington University, Saint Louis, Missouri 63130, USA. *e-mail: katz@wuphys.wustl.edu.

NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE1828

Table 1 | Sites and results.

Site	NOAA Site	Location	Lat. (N)	Long. (W)	χ^2 (d.f.)	Slope
1	140620	Bazine 13 miles SSW, KS	38° 16′	99° 45′	1.02 (4)	−2.6±3.0
2	020080	Ajo, AZ	32° 22′	112° 52′	3.58 (4)	−9.8±4.3
3	366889	Philadelphia Airport, PA	39° 52′	75° 14′	13.01 (9)	−0.1±0.7
4	010008	Abbeville, AL	31° 25′	85° 17′	9.00 (4)	−6.6±2.4
5	081271	Canal Point Gate 5, FL	26° 52′	80° 38′	11.58 (4)	+1.4±2.2
6	241088	Bredette, MT	48° 33′	105° 16′	9.30 (5)	−2.1±2.4
7	450013	Aberdeen 20 miles NNE, WA	47° 16′	123° 42′	31.62 (4)	+6.5±1.3
8	047633	Sacramento, CA	38° 25′	121° 30′	4.79 (5)	−2.0±2.3
9	310301	Asheville, NC	35° 35′	82° 33′	16.74 (8)	+0.5±0.9
10	111577	Chicago Midway Airport, IL	41° 44′	87° 47′	8.50 (4)	−5.4±2.2
11	217294	Saint Cloud, MN	45° 33′	94° 03′	3.17 (4)	−3.8±3.1
12	431081	Burlington, VT	44° 28′	73° 09′	12.13 (4)	+3.4±1.9
13	045114	Los Angeles Int. Airport, CA	33° 56′	118° 24′	2.77 (4)	−7.8±4.8

The penultimate column gives χ^2 and degrees of freedom (d.f.) for an assumed constant M_2. The last column gives the best fit normalized (to the mean) trend of M_2 and its 1σ uncertainty in per cent per decade.

distribution; $M'_{n,D}$ can be unity even for distributions with large normalized second moments, such as this example with $f \ll 1$ for which $M_2 = 1/f$. Additional moments contain independent but qualitatively similar information.

We chose for study 13 sites (Table 1) in the 48 contiguous United States (all states other than Alaska and Hawaii) that have long runs of data in a NOAA database[24], represent a broad range of climates and are well-distributed (widely and not clustered) over this region. Figure 1 shows the normalized second moments of the hourly precipitation data, averaged over decades (decade 1 is 1900–1909, decade 2 is 1910–1919 and so on). The error bars indicate the standard deviations of the normalized decadal moments computed from the dispersion of the normalized annual moments within each decade. This indicates the uncertainty in the decadal moments resulting from annual and few-year climate variations such as El Niño and La Niña. Longer term (decadal) variability appears as decade-to-decade fluctuations about any smooth trend whereas shorter-term variations are effectively averaged over in the decadal means. Years in which fewer than half of the hourly data are in the record are excluded, as are decades in which fewer than half of the years are represented.

Figure 2 shows, in parallel to Fig. 1, the renormalized fourth moments. Most of the error bars are not shown because many of them are large (a consequence of the sensitivity of high moments to a few outlying data) and would make the figure difficult to read.

The moments M_2 and M'_4 provide a description of climate beyond wet versus dry or seasonal variations (that are averaged over in the decadal means). For example, the consistently low values of $M_{2,D}$ for site 7 (Aberdeen, Washington, in the Olympic Peninsula) describe a climate characterized by long periods of non-zero but low precipitation rate (drizzle), but few severe storms, whereas the large values for site 2 (Ajo, Arizona, in the desert southwest) describe a dry climate in which most of the rainfall occurs in brief intense storms. The drizzly site in the Olympic Peninsula has a large M'_4, in part because its small M_2 enters to the -3 power in the definition of M'_4. There is no simple qualitative interpretation of M'_4 (and other higher moments) but they contain independent information related to the kurtosis.

Table 1 gives the χ^2 of a fit to a constant value (the uncertainty-weighted mean) of $M_{2,D}$ at each site. The deviations from a constant are nominally statistically significant at the $P < 0.05$ level for sites

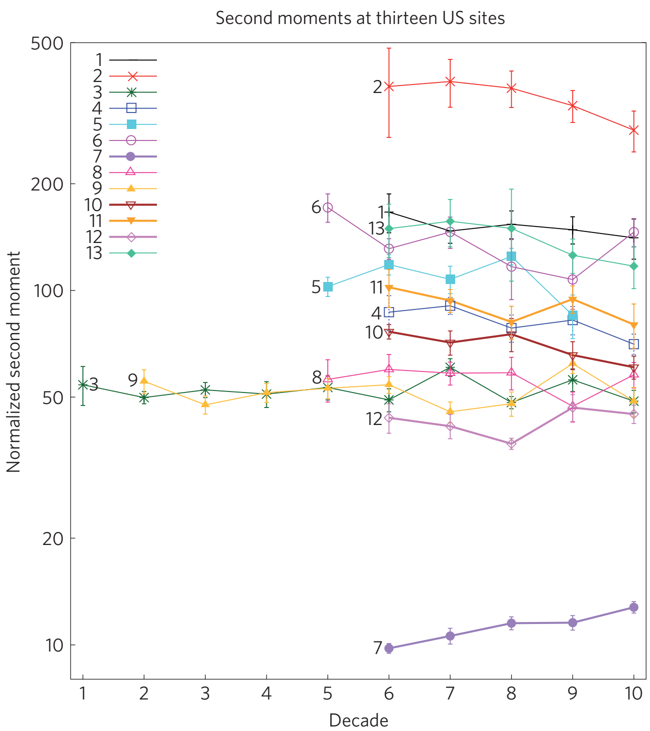

Figure 1 | Second moments. Decadal-mean-normalized second moments of hourly precipitation data at thirteen sites in the 48 contiguous United States. Decade 1 is 1900–1909 and so on. Error bars indicate standard deviations of decadal means of annual mean moments. Data are from ref. 24.

5, 7, 9 and 12 (the decadal averages from site 2 show a smooth trend, but are also consistent with a constant because of their large uncertainties). We fitted slopes in percentage per decade, normalized to the mean values for the decades for which we have data; the differences between linear and exponential fits over the span of data are small. The fitted slopes at sites 5, 9 and 12 are not significant at the 2σ level; the significant χ^2 test of the constant model may indicate fluctuations (such as those produced by decadal

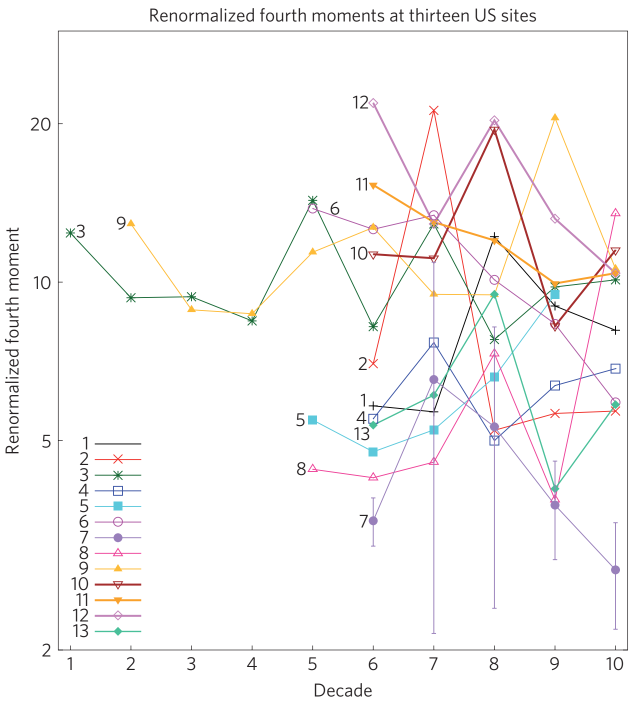

Figure 2 | Fourth moments. Decadal-mean-renormalized fourth moments of hourly precipitation data at thirteen sites in the 48 contiguous United States. Decade 1 is 1900–1909 and so on. Error bars (shown only for site 7 to minimize clutter) indicate standard deviations of decadal means of annual mean moments. Data are from ref. 24.

and longer term oscillations[25–29]) rather than a long-term steady trend such as that of global warming. Sites 2, 4 and 10 have negative trends of significance between 2.3σ and 2.7σ but χ^2 tests consistent ($P > 0.05$) with the constant model.

In contrast, at site 7 (where strong storms are rare and M_2 is small) the hypothesis of constant $M_{2,D}$ is rejected with much higher confidence ($P < 0.001$). Data from this site are well fitted ($\chi^2 = 0.94$ with 3 d.f.) by a very significant increase of 6.5 ± 1.3 (1σ)% per decade. As our other sites are in different climate regimes, this trend at one site does not imply significant trends elsewhere. We test the hypothesis of a steady increase at other sites of 6.5% per decade and find that it is rejected with $P < 0.001$ at five of the remaining sites and with $0.001 < P < 0.01$ at another two sites.

The strictest upper bounds on a multiplicative trend in M_2 are found at sites 3 and 9 (with long data runs of ten and nine decades); even the 3σ upper bounds are only 2.0% per decade and 3.2% per decade, respectively, less than the trend at site 7. As M_2 describes intense short-term events, the considerations of ref. 30 derived from the temperature dependence of the water vapour pressure may not be applicable; a naive use of an empirical ≈ 0.1 K per decade warming would suggest a trend in M_2 of +0.6% per decade, consistent with our limits at all sites other than site 7.

The 2σ upper bounds on additive trends in M_2 at sites 3 and 9 are 0.61 per decade and 1.11 per decade, respectively, consistent with the value at site 7 of 0.71 ± 0.14 per decade. The same rate of additive increase would be unobservably small and consistent with the data at any site other than 7.

The χ^2 test of the hypothesis of constant $M'_{4,D}$ indicates $P > 0.05$ at each site, perhaps because of the large uncertainties resulting from large year-to-year variability. No site has a fitted slope differing from zero by more than 2.6σ. At site 3 the fitted slope is (-1.2 ± 2.3)% per decade (1σ), setting a 3σ upper limit of 5.7% per decade. At all other sites (including site 7, where the uncertainties in $M_{2,D}$ are small) the 1σ uncertainties of the fitted slopes of $M'_{4,D}$ are 15% per decade or greater.

We conclude that the increasing trend of M_2 at site 7 is real and reflects a changing climatic regime at this site, where storms are rare but slow steady precipitation is frequent. We find no compelling evidence for a non-zero trend at other sites, at which storms are more frequent and M_2 is larger. However, because of their intrinsically stormier and more variable weather, slow additive trends would be more difficult to detect at these other sites. For example, the increase of 0.7 per decade at site 7 would be only 0.7% per decade, undetectably small, at a representative site at which $M_2 = 100$.

Our results are consistent with trends seen[9–13] in daily data, but no quantitative comparison is possible. Hourly data from a much larger number of sites might be regionally averaged to reveal trends too slow to be significant for a single site. Such a study involves issues of algorithmic assessment of data validity that we are now investigating.

Received 10 September 2012; accepted 21 January 2013; published online 17 March 2013

References

1. Jones, P. D. & Moberg, A. Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J. Clim.* **16,** 206–223 (2003).
2. Menne, M. J. & Williams, C. N. Detection of undocumented change points using multiple test statistics and reference series. *J. Clim.* **18,** 4271–4286 (2005).
3. Trenberth, K. E. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon, S *et al.*) 235–336 (Cambridge Univ. Press, 2007).
4. Hansen, J., Ruedy, R., Sato, S. & Lo, K. Global surface temperature change. *Rev. Geophys.* **48,** RG4004 (2010).
5. Rohde, R. *et al.* A new estimate of the average Earth surface land temperature spanning 1753 to 2011. *Geoinfor. Geostat.: An Overview* **1,** http://dx.doi.org/10.4172/gigs.1000101 (2012).
6. IPCC *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., Hanson, C. E.) (Cambridge Univ. Press 2007).
7. IPCC *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds Field, C. B. *et al.*) (Cambridge Univ. Press, 2007).
8. Coumou, D. & Rahmstorf, S. A decade of weather extremes. *Nature Clim. Change* **2,** 491–496 (2012).
9. Groisman, P. Ya. *et al.* Trends in intense precipitation in the climate record. *J. Clim.* **18,** 1326–1350 (2005).
10. Alexander, L. V. *et al.* Global observed changes in daily climatic extremes of temperature and precipitation. *J. Geophys. Res.* **111,** D05109 (2006).
11. Min, S. K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. Human contribution to more-intense precipitation extremes. *Nature* **470,** 378–381 (2011).
12. Utsumi, N., Seto, S., Kanae, S., Maeda, E. E. & Oki, T. Does higher surface temperature intensify extreme precipitation? *Geophys. Res. Lett.* **38,** L16708 (2011).
13. Groisman, P. Ya., Knight, R. W. & Karl, T. R. Changes in intense precipitation over the Central US. *J. Hydrometeorol.* **13,** 47–66 (2012).
14. Epstein, B. Statistical aspects of fracture problems. *J. Appl. Phys.* **19,** 140–147 (1948).
15. Johnson, L. G. *The Statistical Treatment of Fatigue Experiments* (Elsevier, 1964).
16. Doremus, R. H. Fracture statistics: A comparison of the normal, Weibull and Type I extreme value distributions. *J. Appl. Phys.* **54,** 193–198 (1983).
17. Katz, J. I. Statistics and microphysics of the fracture of glass. *J. Appl. Phys.* **84,** 1928–1931 (1998).
18. Katz, J. I. Atomistics of tensile failure in fused silica: Weakest link models revisited. *SPIE* **3848,** 2–10 (1999).
19. Lenderink, G. & van Meijgaard, E. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geosci.* **1,** 511–515 (2008).
20. Wong, M. C., Mok, H. Y. & Lee, T. C. Observed changes in extreme weather indices in Hong Kong. *Int. J. Climatol.* **31,** 2300–2311 (2010).
21. Lenderink, G., Mok, H. Y., Lee, T. C. & van Oldenborgh, G. J. Scaling and trends of hourly precipitation extremes in two different climate zones—Hong Kong and the Netherlands. *Hydrol. Earth Syst. Sci.* **15,** 3033–3041 (2011).
22. Von Storch, H. & Zwiers, F. W. *Statistical Analysis in Climate Research* (Cambridge Univ. Press, 1999).

23. Pali, P. *et al.* Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* **470,** 382–385 (2011).
24. NOAA US Hourly Precipitation Data http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=5008 (2011).
25. Mandelbrot, B. B. & Wallis, J. R. Some long-run properties of geophysical records. *Water Resour. Res.* **5,** 321–340 (1969).
26. Hasselmann, K. Stochastic climate models Part I. Theory. *Tellus* **28,** 473–485 (1976).
27. Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M. & Francis, R. C. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.* **78,** 1069–1079 (1997).
28. Pelletier, J. D. The power spectral density of atmospheric temperature from time scales of 10^{-2} to 10^{6} yr. *Earth Planet. Sci. Lett.* **158,** 157–164 (1998).
29. Manuta, N. J. & Hare, S. R. The Pacific decadal oscillation. *J. Oceanogr.* **58,** 35–44 (2002).
30. Allen, M. R. & Ingram, W. J. Constraints on future changes in climate and the hydrological cycle. *Nature* **419,** 224–232 (2002); erratum *Nature* **489,** 590 (2012) .

Acknowledgements
We thank L. Canel-Katz, J. Hoffman and J. G. Miller for comments on the manuscript, P. Ya. Groisman for assistance with the NOAA precipitation databases and Novim for support.

Author contributions
J.I.K. conceived and designed the study and wrote the paper. T.M. contributed to the study design and writing the paper, carried out the calculations, and analysed the results.

Additional information
Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.I.K.

Competing financial interests
The authors declare no competing financial interests.