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Title

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Journal

Bulletin of the American Meteorological Society, 94(4)

ISSN

0003-0007

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Publication Date

2013-04-01

DOI

10.1175/bams-d-11-00262.1

Peer reviewed



AMERICAN METEOROLOGICAL SOCIETY

Bulletin of the American Meteorological Society

EARLY ONLINE RELEASE

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The DOI for this manuscript is doi: [10.1175/BAMS-D-11-00262.1](https://doi.org/10.1175/BAMS-D-11-00262.1)

The final published version of this manuscript will replace the preliminary version at the above DOI once it is available.



1 **Monitoring and Understanding Trends in Extreme Storms: State of Knowledge**

2
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Abstract

The state of knowledge regarding trends and an understanding of their causes is presented for a specific subset of extreme weather and climate types. For severe convective storms (tornadoes, hail storms, and severe thunderstorms), differences in time and space of practices of collecting reports of events make the use of the reporting database to detect trends extremely difficult. Overall, changes in the frequency of environments favorable for severe thunderstorms have not been statistically significant. For extreme precipitation, there is strong evidence for a nationally-averaged upward trend in the frequency and intensity of events. The causes of the observed trends have not been determined with certainty, although there is evidence that increasing atmospheric water vapor may be one factor. For hurricanes and typhoons, robust detection of trends in Atlantic and western North Pacific tropical cyclone (TC) activity is significantly constrained by data heterogeneity and deficient quantification of internal variability. Attribution of past TC changes is further challenged by a lack of consensus on the physical linkages between climate forcing and TC activity. As a result, attribution of trends to anthropogenic forcing remains controversial. For severe snowstorms and ice storms, the number of severe regional snowstorms that occurred since 1960 was more than twice that of the preceding 60 years. There are no significant multi-decadal trends in the areal percentage of the contiguous U.S. impacted by extreme seasonal snowfall amounts since 1900. There is no distinguishable trend in the frequency of ice storms for the U.S. as a whole since 1950.

51

Capsule Summary

52 The state of knowledge regarding trends and an understanding of their causes is presented for

53 severe convective storms, extreme precipitation, hurricanes and typhoons, and severe

54 snowstorms and ice storms.

55

56 **1. Introduction**

57 The record for the number of weather and climate disasters that exceeded \$1 billion (U.S.)
58 or more in losses was set in 2011 (<http://www.ncdc.noaa.gov/oa/reports/billionz.html>). Twelve
59 of the fourteen events counted in this record were related to storms, including severe local
60 weather (tornadoes), storm related excessive precipitation, snowstorms/blizzards, and
61 hurricane/tropical storms¹. There is broad recognition that our climate is non-stationary and
62 changing (Global Climate Change Impacts in the US 2009), not only in mean conditions but in its
63 extremes as well (Katz 2010). However, there is less certainty in our ability to detect multi-
64 decadal changes in each of these phenomena, and to understand the causes for any changes
65 we can detect. This motivates our interest in a status report on our ability to detect, analyze,
66 and understand changes in the risk of weather and climate extremes. Due to the intense media
67 coverage of and great public interest in the 2011 disasters, we suspect that many BAMS readers
68 have received inquiries or have a personal interest about the nature of these events in the
69 context of long-term trends and potential climate change. This paper is meant to present a
70 clear record that can be used by meteorological professionals about what is known and
71 unknown and why.

72 This paper examines a specific subset of extreme weather and climate types affecting the
73 United States. For our purposes, storm-related extremes here refer to those short duration

¹ The observed changes in losses represent a combination of the effects of both physical climate and socio-economic variability (e.g., Pielke et al. 2008), and it is difficult to attribute any of these changes to climate (Bouwer 2011). Here we will concentrate on physical climate variability. The non-storm disasters were the Texas, Arizona, New Mexico wildfires and the Southern Plains/Southwest drought and heat wave.

74 events that have levels/types of wind and/or precipitation at local to regional scales that are
75 uncommon for a particular place and time of year (Peterson et al. 2008). The categories of
76 storms described herein were chosen because they often cause property damage and loss of
77 life, but the identification of an extreme occurrence is based on meteorological properties, not
78 on the destructiveness. Our primary purpose is to examine the scientific evidence for our
79 capability to detect trends and understand their causes for the following weather types: (1)
80 severe convective storms (tornadoes, hail storms, and severe thunderstorms), (2) extreme
81 precipitation, (3) hurricanes and typhoons, and (4) severe snowstorms and ice storms. These
82 storm categories are not independent. Extreme precipitation can occur in any of the other
83 three. Categories 1 and 4 are both typically associated with extratropical cyclones and
84 sometimes in the same one. Nevertheless, the particular impacts are distinct and thus a
85 separate examination of each of these is warranted.

86 The reason society ultimately cares about variability and change in the above physical
87 phenomena is that these translate into socio-economic and biophysical impacts (e.g. life,
88 property, ecosystems). The assessment of changes in the physical phenomena is just the first
89 step. It is essential that trends in the impacts also be assessed in a comprehensive manner. As
90 will be addressed later, this second step is quite challenging.

91 **2. Severe Convective Storms: Thunderstorms, Tornadoes, and Hail Storms**

92 Severe thunderstorms (hail of at least 2.5 cm or wind gusts of more than 95 km/h) and
93 tornadoes pose challenging problems in efforts to establish temporal trends. In general, reports
94 of such events in the US are collected to verify weather warnings and, as such, changes in

95 verification efforts and emphasis are likely to have led to most, if not all, of the reported
96 changes in frequency. The problems have been discussed by Doswell et al. (2005) and Verbout
97 et al. (2006). The occurrence of F1+ tornadoes shows no trend since 1954, the first year of near
98 real-time data collection, with all of the increase in tornado reports resulting from an increase
99 in the weakest tornadoes, F0 (Fig. 1). Stronger events may be more reliably reported than
100 weaker events, but changes in tornado damage assessment procedures still lead to problems in
101 trend identification (Doswell et al. 2009). Changnon and Changnon (2000) used reports from
102 first-order station observers for the 20th century to assess severe weather conditions and found
103 considerable regional variability in the incidence of hail—increasing trends in some areas,
104 decreasing trends elsewhere. The change from human observers to automated stations
105 beginning in the 1990s influences the comparability of observations from the past to the future.
106 Due to the changing practices and the nature of rare events, we have little confidence in the
107 accuracy of trends in the meteorological occurrence of severe thunderstorms (including hail
108 storms) and tornadoes.

109 Since raw reports are fraught with difficulties, attention has focused on examining the
110 environmental conditions associated with severe thunderstorms to estimate the frequency and
111 distribution of events (Brooks et al. 2003). This is guided by our understanding of the
112 ingredients for severe thunderstorm occurrence derived from studies of day-to-day weather
113 forecasting (Rasmussen and Blanchard 1998). The quality of severe thunderstorm forecasts
114 indicates that the understanding of the physical processes is relatively good (Moller 2001). For
115 example, using measures of the potential energy available for storms and the organizing

116 potential of tropospheric shear, discrimination between severe and non-severe thunderstorms
117 is possible (Fig. 2). Severe thunderstorms occur in an environment with large values of potential
118 energy and wind shear, and tornadoes, in particular, are favored in high shear environments.
119 Moist enthalpy, combining temperature and moisture content, near the earth's surface has
120 been increasing in recent decades (Peterson et al. 2011). By itself, this would lead to an
121 increase in thunderstorms, but changes above the Earth's surface could reduce or counteract
122 that effect with unknown impacts on the initiation of thunderstorms. Brooks and Dotzek (2008)
123 found long-term changes in the overall occurrence of favorable conditions for severe
124 thunderstorms, but the interannual variability in their study was so large as to make the results
125 statistically insignificant. Trapp et al. (2009) used an ensemble of global climate model
126 simulations for the second half of the 20th century and found qualitatively similar changes in the
127 severe thunderstorm environments; however, the large observed interannual variability implies
128 that statistical significance of trends may not be reached for several more decades. The use of
129 high-resolution models to dynamically downscale such climate data has the potential of
130 providing an alternative to the observation-based and storm-environment-based approaches
131 mentioned above (Trapp et al. 2011).

132 **3. Extreme Precipitation**

133 The occurrence of extreme precipitation rates requires abundant atmospheric water vapor
134 and strong upward motion. Upward motion arises from three principal mechanisms: dynamical
135 forcing, release of convective instability, and orographic forcing. Depending on the situation, all
136 of these mechanisms can make a significant contribution to a specific event. In the U.S., the

137 principal meteorological phenomena associated with extreme precipitation events include
138 extratropical cyclones (ETCs), tropical cyclones (TCs), mesoscale convective systems, and the
139 North American Monsoon (Kunkel et al. 2011).

140 The U.S. observing network is better suited for the assessment of changes in very heavy
141 precipitation than for any other class of extreme storm. For instance, the NWS Cooperative
142 Observer Network (COOP) network has largely employed the same standard 8" nonrecording
143 precipitation gauge throughout its history (Yang et al. 1998), minimizing time-dependent biases
144 resulting from changes in instrumentation. Furthermore, the gauge itself exhibits only a minor
145 wind-driven bias in measuring large amounts of liquid precipitation (Groisman and Legates
146 1994). In addition, field experiments (Sevruk 1982) and theoretical results (Folland 1988) show
147 that gauge undercatch is not substantial in very heavy rainfall. From a spatial perspective, the
148 U.S. COOP network is of sufficient density for the detection of changes in very heavy
149 precipitation over most regions (Groisman et al. 2005), except for some high elevations in the
150 west. The COOP data do not distinguish between convective and non-convective precipitation.

151 There are a variety of extreme precipitation metrics, analysis methods, observing stations
152 sets, and time periods used in published trends studies, reflecting tradeoffs among these
153 choices. Statistical methodological approaches tend to fall into two basic categories: purely
154 empirically-based or those with a more theoretical basis. For the empirically-based methods,
155 thresholds are defined in terms of the data distribution, statistics such as the frequency of
156 threshold exceedance are calculated and aggregated across space, and trends fitted. For the
157 theoretically-based methods, distributions from the statistical theory of extreme values (e.g.,

158 Coles 2001) are fitted to extreme statistics including seasonal or annual maxima and excesses
159 over a high threshold, and with the provision for trends in the parameters of these extremal
160 distributions. The advantages of the purely empirical approach include being automatically
161 applied and relatively powerful in detecting any trends, and being relatively easy to explain to
162 non-specialists; its disadvantages include providing information only in aggregate terms for
163 large regions and only applicable to moderately extreme events. The advantages of methods
164 based on extreme value theory include providing information in a form useful to decision and
165 policy makers (i.e., in terms of return levels that apply locally and to the most extreme events
166 of greatest societal relevance); its disadvantages include difficulty in being routinely applied
167 (e.g., requiring a choice of threshold for the statistical theory to be a reasonable approximation)
168 and the lack of a straightforward way to account for the spatial dependence of extremes in
169 trend analyses. The choice of metrics often involves a tradeoff between the desire to examine
170 trends in the low probability events that are most societally-relevant and the need to minimize
171 sampling uncertainty by including less extreme, but more frequent events. The time period is
172 often chosen on the basis of the number of stations with relatively complete data. In this case,
173 there is a tradeoff between the desire to examine as long of a period as possible, but longer
174 periods reduce the number of stations, and the need to minimize sampling uncertainty by
175 including a minimum number of stations. The different choices that can be made are
176 represented in the following set of analyses that are described below.

177 Many studies have found a statistically significant increase in the number and intensity of
178 extreme precipitation events of durations ranging from hourly to a few days (Karl et al. 1996;

179 Karl and Knight 1998; Groisman et al. 2004; 2005; 2011; Kunkel et al. 2003, 2007; Global
180 Climate Change Impacts in the United States 2009; Alexander et al. 2006). Given that trends in
181 mean precipitation (+0.6% per decade; NOAA 2011) are less than extreme precipitation (2% per
182 decade in top 1% of events; Kunkel et al. 2008), this apparently reflects a change in the tails of
183 the distribution, rather than a shift in the entire distribution, over several decades compared to
184 previous decades of the 20th century. The consistency of the results from these analyses reflects
185 a degree of confidence in our ability to measure such changes in the U.S. For example, a set of
186 precipitation-observing COOP stations with records extending back to around the turn of the
187 20th Century has been used to examine the temporal and spatial variations in number of
188 extreme precipitation totals of 2-day duration exceeding a recurrence interval of 5 years. This
189 duration was used to minimize instances of a single extreme precipitation event straddling the
190 time of observation and the amount being split across the two days. Recurrence interval
191 thresholds are used extensively in design of runoff control structure, which motivates their use
192 as one component of a metric. Time series of station events were aggregated over decadal
193 periods into 7 regions² of the coterminous U.S. and expressed as a spatially-averaged index (Fig.
194 3). There is considerable decadal-scale variability whose behavior often varies spatially (e.g.
195 Mass et al. 2011). However, since 1991, all regions have experienced a greater than normal
196 occurrence of extreme events. In the eastern regions, the recent numbers are the largest since
197 reliable records begin (1895). For western regions, the recent decades are comparable to the
198 early part of the historical record. Using the non-parametric Kendall's tau test for trends, the

² These are the regions being used for the 2013 National Climate Assessment Report

199 increase is statistically significant for the U.S. as a whole and the individual regions of the
200 Midwest and Southeast (Table 1). Over the period 1957-2010, the Northeast region trend is
201 also statistically significant. An analysis of another metric, the total amount of precipitation
202 accumulated on days whose precipitation exceeds the 99th percentile for daily amounts,
203 indicates a highly statistically significant upward trend for the period of 1957-2010 for the same
204 set of regions (Midwest, Southeast, and Northeast) and the U.S. as a whole (Table 1); in this
205 case, the results are robust to the choice of metric. No significant extreme precipitation trends
206 are found in the western U.S. (see also Mass et al. 2011). Since the nature and magnitude of
207 some impacts is sensitive to the duration of excessive precipitation, the sensitivity of results to
208 the duration and return period has been studied (e.g. Kunkel et al. 2003, 2008) and qualitatively
209 similar results have been found for durations of 1 to 90 days and return periods of 1 to 20 years
210 in the definition of the metric.

211 The estimated change from 1948 to 2010 in the twenty year precipitation return value at
212 individual stations based on daily accumulated precipitation station data (Fig. 4) from the
213 Global Historical Climate Network-daily (Durre et al. 2008) were calculated using extreme value
214 analysis (Tomassini and Jacob 2009; Cooley and Sain 2010). (see Supplemental Online Material
215 for details). About 76% of all stations experience increases in extreme precipitation, with 15%
216 showing a statistically significant increase based on station-specific hypothesis testing. From the
217 central states to the north Atlantic these exhibit a high degree of spatial coherence. Regions
218 with greater numbers of stations with decreases are of smaller spatial extent; the largest are in
219 the northwest U.S. and the southern Appalachian Mountains. A field significance test was highly

220 statistically significant. The choice of a 20-year return period in Fig. 4 is solely for illustrative
221 purposes, with the estimated changes in return values for longer return periods being identical
222 for this simplified form of extreme value analysis (see Supplementary Online Materials).

223 Figs. 3 and 4 and Table 1 display results for 3 different metrics. They are in best agreement
224 over roughly the eastern half of the U.S., all indicating general upward trends. For the western
225 half, the agreement is not as good; over the Great Plains and Southwest, the 20-yr return
226 period threshold exhibits general upward trends in contrast to the lack of trends exhibited by
227 the other two metrics.

228 Identification of the causes of long-term trends in extreme precipitation remains an area of
229 active research, but some cogent work has already been completed. Globally, Min et al. (2009,
230 2011) have linked changes in extreme precipitation during the past several decades to human-
231 caused changes in atmospheric composition. Karl and Trenberth (2003) have empirically
232 demonstrated that for the same annual or seasonal precipitation totals, warmer climates
233 generate more extreme precipitation events compared to cooler climates. This is consistent
234 with water vapor being a critical limiting factor for the most extreme precipitation events. A
235 number of analyses have documented significant positive trends in water vapor concentration
236 and have linked these trends to human fingerprints in both changes of surface (Willett et al.
237 2007) and atmospheric moisture (Santer et al. 2007).

238 It is logical therefore to explore the connection. The evidence in Table 2 from a pilot study
239 (see Supplementary online material for details) depicts significant increases in the water vapor
240 associated with extreme precipitation events, particularly east of the Rockies, and is suggestive

241 that increases in water vapor in the environment of precipitation-producing systems may be a
242 physical cause for the increase in intense precipitation events over the U.S.³ In addition to the
243 amount of water available for the generation of extreme precipitation events, dynamical
244 factors must also be important. Even though there is no trend in U.S. landfalling Tropical
245 Cyclones (TCs) (Global Climate Change Impacts in the United States, 2009), two studies found
246 an upward trend in the number of extreme precipitation events associated with TCs (Knight and
247 Davis 2009; Kunkel et al. 2010) while a third (Groisman et al. 2011) did not. There is also an
248 upward trend in the number of extreme precipitation events in the vicinity of fronts associated
249 with extra-tropical cyclones (Kunkel et al. 2011). However, there is no research indicating
250 whether there has been a trend in the number and/or intensity of fronts. Gutowski et al. (2008)
251 stated that the observed increases in extreme precipitation are “consistent with the observed
252 increases in atmospheric water vapor, which have been associated with human-induced
253 increases in greenhouse gases”. While the role of water vapor as a primary cause for the
254 increase in extreme precipitation events is compelling, the possibility of changes in the
255 characteristics of meteorological systems cannot be ruled out. There may also be regional
256 influences from the temporal redistribution of the number of El Nino events versus La Nina
257 events and from land use changes such as the 20th Century increase in irrigation over the Great
258 Plains and the post-World War II increase of corn and soybean acreage and planting density
259 over the Midwest (DeAngelis et al. 2010; Groisman et al. 2011).

³ In this analysis, each extreme precipitation event was assigned a precipitable water value, which was the maximum value from any radiosonde station within 300 km of the event location and within 24 hours of the observation time of the precipitation value.

260 **4. Hurricanes and Typhoons**

261 Detection of long-term changes in tropical cyclone (TC) activity has been hindered by a
262 number of issues with the historical records. Heterogeneity introduced by changing technology
263 and methodology is the major issue (e.g., Landsea et al. 2004). Data used to construct the
264 historic “best track” archives are often initially collected and analyzed to support short-term
265 forecasting needs using the best information, technology, and models of the day with no
266 mandates in place to maintain heterogeneity. Improvements are generally implemented
267 without any overlap or calibration against existing methods to document the impact of the
268 changes on the longer-term climate record. The introduction of aircraft reconnaissance in some
269 basins in the 1940s and satellite data in the 1960s had an important effect on our ability to
270 identify and estimate the intensity of tropical cyclones, particularly those that never
271 encountered land or a ship. The cessation in 1987 of regular aircraft reconnaissance into
272 western North Pacific typhoons created a void in available *in situ* intensity measurements and
273 our ability to calibrate satellite estimates against ground-truth, which adds further uncertainty
274 to the records there. Efforts towards mitigation of these issues are ongoing, typically in the
275 form of estimating storm frequency undercounts in the earlier parts of the Atlantic record (e.g.,
276 Vecchi and Knutson 2011), and using satellite data to construct less heterogeneous global
277 records of storm intensity (e.g., Kossin et al. 2007). The latter efforts can be effective but at
278 best are limited to the meteorological satellite era that began in the 1960’s, which limits their
279 influence on trend detection on multi-decadal or longer time-scales. For example, comparisons
280 between an index of tropical cyclone power dissipation (Emanuel 2005) derived from best track

281 data versus a more homogeneous satellite reconstruction indicate high temporal consistency
282 for the North Atlantic and somewhat less consistency for the western North Pacific since
283 around 1980 (Fig. 5). The observed upward trend in the North Atlantic best track is robust to
284 reanalysis, while the upward trend in the Pacific best track appears to be inflated by data
285 heterogeneity issues.

286 Attempts to detect trends in intra-basin regions such as those defined by islands and
287 archipelagos, or along coastlines are further constrained by the reduced data sample size
288 associated with sub-setting the data. Intra-basin regional trend detection is also substantially
289 challenged by variability in tropical cyclone tracks (e.g., Kossin et al. 2010; Holland 2007; Elsner
290 1998), which is driven largely by random fluctuations in atmospheric steering currents, but also
291 is observed in response to more systematic climatic forcings such as El Niño / Southern
292 Oscillation (ENSO). Landfalling tropical cyclone activity in the US, as well as East Asia, shows no
293 significant long-term trends (e.g., Landsea 2005).

294 While data issues confound robust long-term (i.e., ~40-years or more) trend detection,
295 trends in Atlantic TC frequency are robustly observed in the modern satellite period from
296 around 1970 to present. In this case, the main challenge lies in attribution of these trends. A
297 number of linkages between climate variability and TC activity have been well documented. In
298 the tropical North Atlantic (tNA), observed climate variability and trends have been attributed
299 using global climate models (e.g. Santer et al. 2006; Zhang 2007; Gillett et al. 2008; Ting et al.
300 2009; Zhang and Delworth 2009; Chang et al. 2011; Booth et al. 2012) or speculatively linked
301 (e.g., Mann and Emanuel 2006; Evan et al. 2009) to a number of natural and anthropogenic

302 factors. Natural multi-decadal internal variability of the North Atlantic is often referred to
303 generically as the Atlantic Multi-decadal Oscillation (AMO) and has been linked, in modeling
304 studies, to ocean thermohaline circulation variability (Delworth and Mann 2000). This variability
305 is thought to contribute to the observed decadal variability of the tNA, but the robustness of
306 evidence for this is presently a matter of debate. Natural tNA variability on shorter time-scales
307 is also introduced by the North Atlantic Oscillation and remotely by ENSO via teleconnections.
308 Uncertainties in the contribution of internal climate variability remain an important
309 confounding factor (Hegerl et al. 2010) in the detection and attribution of climate trends in the
310 tNA region. Owing to pronounced multidecadal variability evident in longer term records of
311 Atlantic basin-wide or U.S. landfalling tropical cyclone frequency (e.g., Vecchi and Knutson
312 2011, see their Fig. 5), the period since around 1970 (e.g., Fig. 5) appears to be too short to
313 draw confident inferences about longer term (e.g., century scale) trends in Atlantic tropical
314 cyclone activity.

315 External forcing of the tropical climate can be natural or anthropogenic. Volcanoes are an
316 important natural forcing agent, while greenhouse gas forcing has predominantly
317 anthropogenic underpinnings. Attribution of forcing via aerosols is generally less clear. For
318 example, sulfate aerosols occur naturally and are also a constituent of human-induced
319 pollution. Sulfate aerosol concentration is associated with atmospheric dimming effects (e.g.,
320 Mann and Emanuel 2006) as well as changes in cloud albedo (e.g., Booth et al. 2012), both of
321 which affect local external forcing. Concentrations of these and other aerosols have been
322 reduced in the tNA subsequent to the US Clean Air Act amendments of the 1970s, but

323 development in Asia has led to increased emissions in regions of the Indian and Pacific oceans,
324 and one study has proposed a link between black carbon aerosol pollution and increased
325 tropical cyclone intensity in the Arabian Sea (Evan et al. 2011). Mineral aerosols, such as dust
326 transported westward over the tNA from the Sahara, are of natural origin, but may be at least
327 partly modulated by human-induced land-use change. All of these forcings have been linked to
328 tNA sea surface temperature (SST) variability, but significant questions remain about their
329 relative contributions to the overall observed Atlantic hurricane variability. In terms of century-
330 scale variability, only anthropogenic forcing has a *prima facie* expectation of introducing a
331 significant trend on such time-scales, while inter-annual tropical variability can be largely
332 attributed to natural fluctuations such as ENSO. Comparatively, attribution of the observed
333 multi-decadal tNA variability is particularly uncertain and hypotheses span the range from
334 mostly natural internal variability (e.g., Zhang and Delworth's (2009) attribution study for tNA
335 vertical wind shear changes) to mostly external anthropogenic forcing (e.g., Mann and Emanuel
336 2006).

337 In addition to uncertainty about the relative contributions of the above forcings to the
338 observed tNA variability, there is also uncertainty about how TCs respond to the
339 ocean/atmosphere variability attributed to each individual forcing. Aerosol concentrations
340 emanating from source regions are generally more spatially heterogeneous than greenhouse
341 gas concentrations, and the AMO is generally associated with larger amplitude SST variations in
342 the North Atlantic than in other basins. The nature of the forcing is important, because the
343 response of tropical cyclone activity can be quite different for a given change in SST depending

344 on the type of forcing. Thus, for example, reduced surface wind speeds will increase SSTs and
345 also increase the thermodynamic potential for tropical cyclones, but the rate of increase in
346 thermodynamic potential with SST will, in general, be much larger than if the same SST increase
347 is brought about by increasing greenhouse gases (Emanuel 2007). This is because the degree of
348 thermodynamic disequilibrium between the oceans and atmosphere depends directly on the
349 net surface radiative flux, but inversely on surface wind speed. Thus SST is an imperfect proxy
350 for the thermodynamic environment of tropical cyclones and it should not be used as the sole
351 thermodynamic predictor of changing tropical cyclone activity. Nonetheless, analyses of
352 potential intensity projections for the 21st century from CMIP3 climate models demonstrate
353 that these modeled potential intensity changes are well correlated with changes in relative SST
354 (i.e., the local SST relative to the tropical mean SST; Vecchi and Soden 2007).

355 In summary, robust detection of trends in Atlantic and western North Pacific TC activity is
356 significantly constrained by data heterogeneity and deficient quantification of internal
357 variability. Attribution of past TC changes is further challenged by a lack of consensus on the
358 physical linkages between climate forcing and TC activity. As a result, attribution of any
359 observed trends in TC activity in these basins to anthropogenic forcing remains controversial.

360 **5. Severe Snow Storms and Ice Storms**

361 Quantifying changes in the frequency, duration, and severity of winter storms requires the
362 ability to accurately and consistently measure the amount of snow that falls and ice that
363 accumulates during individual storms and throughout entire seasons. Changes in observing
364 practices, reporting procedures, and observing technologies through time complicate these

365 analyses. These include a transition from primarily afternoon to morning observation times, a
366 gradual move to direct measurement from previous estimation of precipitation by “ten to one”
367 snow to water ratio, and periodic changes in observer training practices. Although resulting
368 artifacts in the climate record make analyses more difficult to accomplish, robust conclusions
369 can be reached by selecting a subset of stations for which the snowfall record is of highest
370 quality and which appear to have been minimally affected by non-climatic influences (Kunkel et
371 al. 2009a, 2009b, 2009c). In addition, identification of extreme events such as severe regional
372 snowstorms included here is likely less affected by changes in observing practices and
373 procedures than the analysis of mean conditions.

374 The two most dominant factors that influence U.S. winter storm characteristics (trajectory,
375 frequency, intensity) are the El Niño/Southern Oscillation (ENSO) and the North Atlantic
376 Oscillation/Arctic Oscillation (N)AO phenomena. La Niña favors a more northerly storm track,
377 bringing enhanced snow to the northern and central Rockies, while El Niño favors a more
378 southerly storm track and potentially heavy precipitation in the southern states (e.g., Redmond
379 and Koch 1991; Smith and O’Brien 2001). Over the last 110 years, ENSO behavior has varied
380 greatly, with a period of low activity from the early 1930s into the late 1940s. During the most
381 active periods, El Niño was favored early in the 20th century and from the mid-1970s to the late
382 1990s, while La Niña was most prominent from the 1950s to the mid-70s (Wolter and Timlin
383 2011).

384 The (N)AO, a dominant influence on eastern U.S. weather patterns also has undergone
385 similar ‘regime changes’, favoring its positive phase in the early part and latter decades of the

386 20th century. More prominent spells of its negative phase occurred from the middle of the 20th
387 century into the late 1960s. The last 15 to 20 years have seen a more even distribution of both
388 phases, favoring the negative phase in the recent winters of 2009-2010 and 2010-2011 (Hurrell
389 et al. 2003; Seager et al. 2010). Contributing factors to these regime changes are under
390 investigation (e.g., L'Heureux et al. 2008; Allen and Zender 2011). The decadal scale variability
391 of storm properties associated with each phenomenon can appear in observed records as a
392 "trend," illustrating a need for caution before attribution to anthropogenic climate change.

393 The characteristics of what constitutes a severe winter storm vary regionally. Snowfall
394 greater than 10 inches is common in many parts of the Northeast, and thus often only a short-
395 term inconvenience. However, the same snowfall across the Southeast might cripple the region
396 for a week or longer. A Regional Snowfall Index (RSI, Squires et al. 2009) has been formulated
397 that takes into account the typical frequency and magnitude of snowstorms in each region of
398 the eastern two-thirds of the U.S., providing perspectives on decadal changes in extreme
399 snowstorms since 1900. An analysis based on the area receiving snowfall of various amounts
400 shows there were more than twice the number of extreme regional snowstorms from 1961-
401 2010 (21) as there were in the previous 60 years (9) (Figure 6). The greater number of extreme
402 storms in recent decades is consistent with other findings of recent increases in heavier and
403 more widespread snowstorms (Kocin and Uccellini 2004).

404 These extreme storms occurred more frequently in snow seasons that were colder and
405 wetter than average (Fig. 6), but not exclusively. Approximately 35% of the snow seasons in
406 which these events occurred were warmer than average and 30% drier than average. The

407 implications are that even if temperatures continue to warm as they have over the past several
408 decades, for the next few decades, at least, such record storms are possible as they have been
409 observed during otherwise warmer- and drier-than-average seasons.

410 The impact of individual snowstorms is often immediate and dramatic, but the cumulative
411 effects of all snowstorms in a season can also be costly and disruptive. Snowfall measured at
412 approximately 425 high quality stations was used to assess variation and change in the
413 percentage of the contiguous U.S. affected by extreme high or low seasonal snowfall since 1900
414 (Kunkel et al. 2009c). Observations do not show significant century-scale trends in either high or
415 low seasonal totals. The areal percentage of the U.S. experiencing seasons with the heaviest
416 accumulated snowfall (top 10%) was greatest in the 1910s, the 1960s and 1970s (Figure 7a).
417 The areal percentage of the contiguous U.S. with unusually light seasonal snowfall totals (those
418 in the lowest 10%) decreased from 1940 through the mid-1970s (Figure 7b). Areal coverage of
419 extremely low seasonal snowfall has been steady or slightly increasing since that time.

420 It may appear contradictory that the number of extreme snowstorms could increase in the
421 latter half of the 20th century (Fig. 6) without a coinciding decrease in areal coverage of
422 extremely low seasonal snowfall totals (Fig. 7b). However, there should be no expectation that
423 changes in the frequency of such extreme short-duration events, which can occur during
424 otherwise unusually warm and snow-free seasons, would be correlated with trends in low
425 seasonal snowfall totals. This is especially true in northern areas of the U.S. where seasonal
426 snowfall totals can be lower than average even during years when an extreme snowstorm has
427 occurred.

428 Severe winter conditions are not limited to heavy snowfall. Ice storms can disrupt
429 transportation, and those exceeding certain threshold accumulations can cause catastrophic
430 damage to ecosystems and infrastructure. Most freezing rain events occur east of the Rocky
431 Mountains (Changnon and Creech 2003), and generally with less frequency than snow,
432 particularly outside the South. Freezing rain climatologies typically begin in the mid-20th
433 century, are generally limited to daily (“days with”) values for a subset of stations, and at best
434 only coarsely distinguish between different magnitudes. National and regional trends in the
435 number of freezing rain days show no systematic trends since about 1960, after some regions
436 experienced a relative maximum during the 1950s (Gay and Davis 1993; Changnon and Karl
437 2003).

438 Frozen precipitation and associated impacts will not disappear in a warmer world (Kodra et
439 al. 2011), and means and extreme events may even increase, for example at elevations and
440 latitudes where warmer conditions still remain below freezing. Snow measurements are
441 among the most challenging of all climate elements (Doesken and Judson 1996; Yang et al.
442 1998; Yang et al.2001), and climate analysis depends on a robust national system of reference
443 stations, spanning all elevations, designed to track snow properties through time and to
444 develop relations to other sensing technologies. Such a national system is especially important
445 in measuring and assessing variations and trends in smaller amounts of snow and water
446 content typical of low elevations (e.g., many cities and airports).

447 **6. Discussion and Conclusions**

448 The main conclusions of this scientific assessment are:

449 • Severe convective storms: thunderstorms, tornadoes, and hail storms- Differences in
450 time and space of practices of collecting reports of events make the use of the reporting
451 database to detect trends extremely difficult. Although some ingredients that are favorable for
452 severe thunderstorms have increased over the years others have not, so that, overall, changes
453 in the frequency of environments favorable for severe thunderstorms have not been
454 statistically significant.

455 • Extreme precipitation-There is strong evidence for a nationally-averaged upward trend
456 in the frequency and intensity of extreme precipitation events. The COOP network is
457 considered adequate to detect such trends. The causes of the observed trends have not been
458 determined with certainty, although there is evidence that increasing atmospheric water vapor
459 may be one factor.

460 • Hurricanes and typhoons- Robust detection of trends in Atlantic and western North
461 Pacific TC activity is significantly constrained by data heterogeneity and deficient quantification
462 of internal variability. Attribution of past TC changes is further challenged by a lack of
463 consensus on the physical linkages between climate forcing and TC activity. As a result,
464 attribution of any observed trends in TC activity in these basins to anthropogenic forcing
465 remains controversial.

466 • Severe snowstorms and ice storms-The number of severe regional snowstorms that
467 occurred since 1960 was more than twice the number that occurred during the preceding 60
468 years. There are no significant multi-decadal trends in the areal percentage of the contiguous

469 U.S. impacted by extreme seasonal snowfall amounts since 1900. There is no distinguishable
470 trend in the frequency of ice storms for the U.S. as a whole since 1950.

471 Figure 8 summarizes our scientific assessment of the current ability to detect multi-
472 decadal changes and understand the causes of any changes, putting each phenomenon into
473 one of three categories of knowledge from less to more. The position of each storm type was
474 determined through extensive verbal discussion at a meeting of the author team to reach a
475 group consensus. In terms of detection, the existing data for thunderstorm phenomena (hail,
476 tornadoes, thunderstorm winds) are not considered adequate to detect trends with confidence.
477 This is also the case with ice storms. The data adequacy for hurricanes and snow storms was
478 judged to be of intermediate quality; although trends have been studied, there are a number of
479 quality issues that add uncertainty to the results of such studies. The data adequacy for
480 precipitation is of higher quality than the rest of the types, leading to higher confidence in the
481 results of trend studies.

482 Knowledge of the potential physical causes of trends is higher for extreme precipitation
483 than for other storm types while knowledge of causes for hail, tornadoes, hurricanes, and snow
484 storms is intermediate among the types. The adequacy of knowledge is quite low for
485 thunderstorm winds and ice storms.

486 Improving the status of the data and understanding can be advanced through the
487 following steps:

- 488 • Severe convective storms- Consistent collection of severe thunderstorm and tornado
489 reports that does not depend upon the severe weather warning process would be necessary

490 to make the time series of reports useful for climate-scale purposes. Alternatively,
491 development of objective remotely-sensed observations, most likely based upon radar, that
492 serve as proxies for actual severe weather events could address issues, although challenges
493 will exist as radar technology changes.

- 494 • Extreme precipitation-It is essential that the high quality data network be maintained so
495 that future variations and trends can be detected. The role of water vapor trends as
496 possible cause of extreme precipitation trends should be more thoroughly explored.
- 497 • Hurricanes and typhoons-Better understanding of factors controlling tropical cyclone
498 variability will be realized through the development of improved theoretical frameworks,
499 numerical and statistical modeling, and observations. Improved observations will most likely
500 result from additional observing platforms, both in situ (e.g., expanded manned or
501 unmanned aircraft reconnaissance and/or tethered blimps such as the Aeroclipper) and
502 remote (e.g., better microwave and scatterometer coverage). Consistency of the data is
503 essential, and calibration periods are needed when new instruments or protocols are
504 introduced so that biases can be quantified and data heterogeneity can be minimized.
- 505 • Severe snow storms and ice storms-A high priority is reducing uncertainties in the historical
506 record through the incorporation of new sources of data and development and application
507 of techniques that properly account for changing technologies and observing practices that
508 have occurred through time. This should be done while also creating a robust national
509 system of observing stations with sufficient density spanning all elevations, integrating new

510 technologies, and employing well documented and consistent observing and reporting
511 practices

512 The identification and understanding of trends in impacts shares many of the same
513 difficulties, such as data quality and attribution of impacts, found for trends in the
514 meteorological phenomena discussed here. For example, temporal and spatial changes in social
515 vulnerability (Cutter and Finch 2008) make detection of robust trends on outcomes of small-
516 scale meteorological events very challenging. As with the physical climate extreme data,
517 changes in practices of economic loss reporting and attribution over time have occurred.
518 Different datasets record information on different classes of events, not all parameters are
519 collected, and the duration of the record is variable as well (Gall et al. 2009). Metrics that are
520 recorded vary in precision and, in some cases, techniques attempting to adjust for population,
521 wealth, mortality, or type of loss (insured/uninsured; direct/indirect) are inconsistent making
522 cross-database comparisons very difficult.

523 **7. Acknowledgements**

524 We thank Isaac Held for helpful comments on the Hurricane section. We also thank Imke
525 Durre, Xungang Yin, Jared Rennie, Michael Palecki, and David Wuertz of NCDG for analytical
526 assistance. The four reviewers provided valuable suggestions. This work was partially supported
527 by National Oceanic and Atmospheric Administration Climate Program Office award
528 NA07OAR4310063. Any opinions, findings, and conclusions are those of the authors and do not
529 necessarily reflect the views of NOAA or the institutions for which they work. Christopher

530 Paciorek and Michael Wehner were supported by the *Office of Biological and Environmental*
531 *Research* of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Figure Captions

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781 dots are F1 and stronger tornadoes.

782 Figure 2. Convective parameters from 0000 UTC soundings in US 1997-9. "Wmax" is vertical
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784 potential energy. "Shear" is magnitude of vector wind difference between surface winds and 6
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787 of hurricane force), grey dots are non-severe thunderstorms. Data from Craven and Brooks
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789 Figure 3. Time series of decadal values of an index (standardized to 1) of the number of 2-day
790 precipitation totals exceeding a threshold for a 1 in 5-yr occurrence for 7 regions and the U.S. as
791 a whole. This was based on an individual analysis of 930 long-term stations. Station time series
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793 by averaging grid points within the region. Finally, the results were averaged over decadal
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795 Figure 4. Changes in observed twenty year return value of the daily accumulated precipitation
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806 homogeneous satellite-based intensity reconstructions. Thin lines show the raw values, thick
807 lines show the smoothed time series, and least-squares linear trend lines calculated from the
808 raw series are shown. The data are updated and adapted from Kossin et al. (2007).

809 Figure 6. Number of extreme snowstorms (upper 10 percentile) occurring each decade within
810 the six U.S. climate regions in the eastern two-thirds of the contiguous U.S. (Based on an
811 analysis of the 50 strongest storms for each of the six climate regions from October 1900-April
812 2010). The inset map shows the boundaries of each climate region. These regions were selected
813 for consistency with NOAA's monthly to annual operational climate monitoring activities. The
814 map includes standardized temperature anomalies and precipitation departures from the 20th
815 century mean calculated across all snow seasons in which each storm occurred. The snow
816 season is defined as December-March for the South and Southeast regions and November-April
817 for the other four regions.

818 Figure 7. (a). Area weighted annual percentage of U.S. homogenous snowfall stations exceeding
819 their own 90th percentile seasonal totals, 1900-01 to 2010-11. Reference period is 1937-38 to
820 2006-07. Adapted from Kunkel et al. (2009c). Thick blue line: 11-year running mean of the

821 percentages. Dashed line: Number of grid cells with active stations each year. (b) as (a) but for
822 the percentage of the contiguous U.S. snowfall data below the 10th percentile.

823 Figure 8. Authors' assessments of the adequacy of data and physical understanding to detect
824 and attribute trends. Phenomena are put into one of three categories of knowledge from less to more.
825 The dashed lines on the top and right sides denote that knowledge about phenomena in the top
826 category is not complete.

827 Table 1. Nonparametric test for trend in extreme precipitation based on Kendall's τ for the
 828 number of occurrences of 2-day precipitation exceeding a threshold for a 1-in-5yr return period
 829 over the period of 1895-2010 and over the period of 1957-2010, as well as the total precipitation
 830 exceeding the 99 percentile for daily amounts over the period of 1957-2010.

831

Region	Kendall's τ (2-dy,5-yr) 1895-2010	Kendall's τ (2-dy,5-yr) 1957-2010	Kendall's τ (99%ile) 1957-2010
United States	0.240***	0.388***	0.340***
Northeast	0.065	0.266***	0.360***
Southeast	0.242***	0.192**	0.188**
Midwest	0.206***	0.224**	0.301***
N. Great Plains	0.032	0.146	0.085#
S. Great Plains	0.097	0.053	-----
Northwest	-0.006	0.063	0.062
Southwest	0.012	0.121	0.048

832

833 *Significant at 0.10 level

834 **Significant at 0.05 level

835 ***Significant at 0.01 level

836 #Results for combined Northern and Southern Great Plains

837 *Notes on Table 1:* Kendall's τ can be used to perform a nonparametric test for trend (Chapter 8,

838 Hollander and Wolfe 1973). The statistic τ is a measure of association between the variable and

839 time, ranging between -1 and 1 like an ordinary correlation coefficient. The P -value is based on
840 the null hypothesis of no trend (i.e., the time series is uncorrelated with time). Positive values of
841 τ indicate indices increasing with time, but not necessarily linearly. Kendall's τ is commonly
842 used to test for trends in hydrologic time series (Chapter 8, Helsel and Hirsch 1993; Villarini et
843 al. 2009).

844

845 Table 2. Differences between two periods (1990-2009 minus 1971-1989) for daily, 1-in-5yr
846 extreme events and maximum precipitable water values measured in the spatial vicinity of the
847 extreme event location and within 24 hours of the event time.

Region	Extreme Precipitation Frequency index Difference (%)	Precipitable Water Difference (%)
Northeast	+55**	+2
Southeast	+11*	+9***
Midwest	+21**	+6**
North Great Plains	+18*	+16***
South Great Plains	+15	+8***
Northwest	+36*	+4
Southwest	+36*	-4

848

849 *Significant at 0.10 level

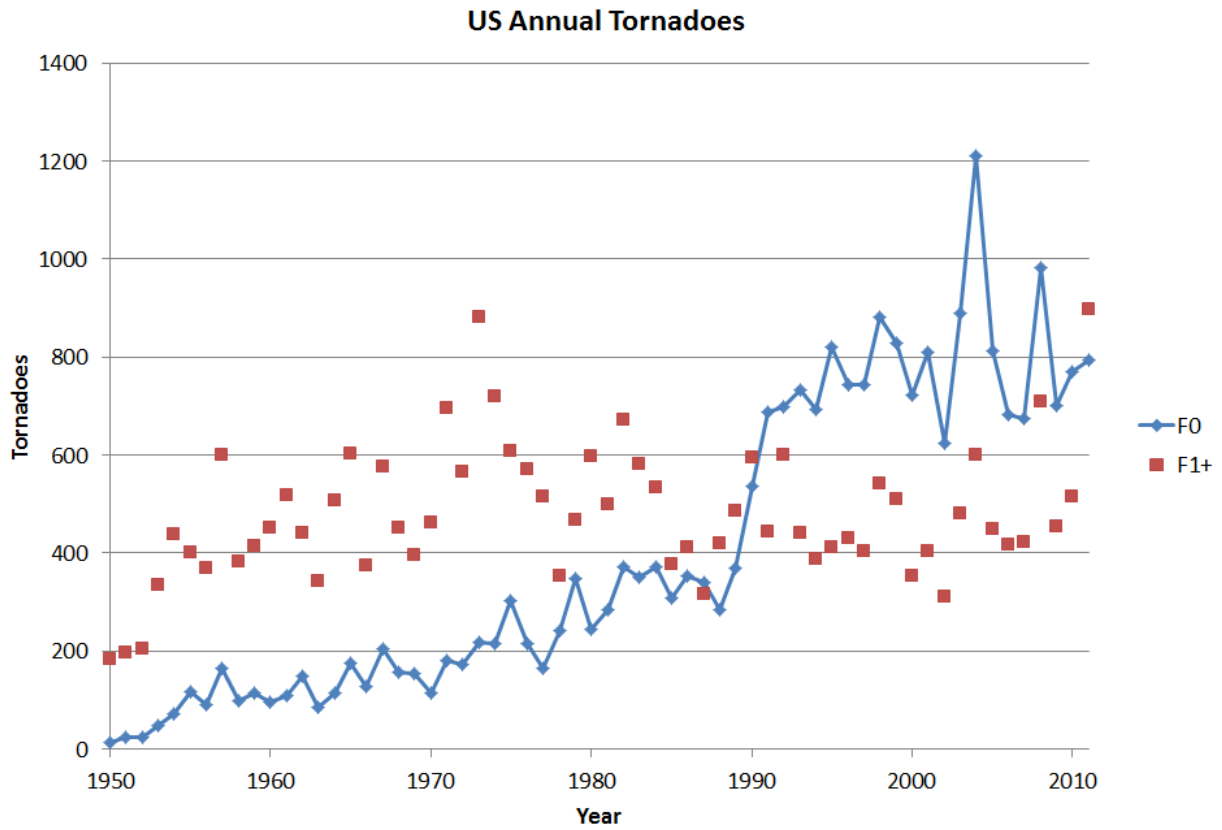
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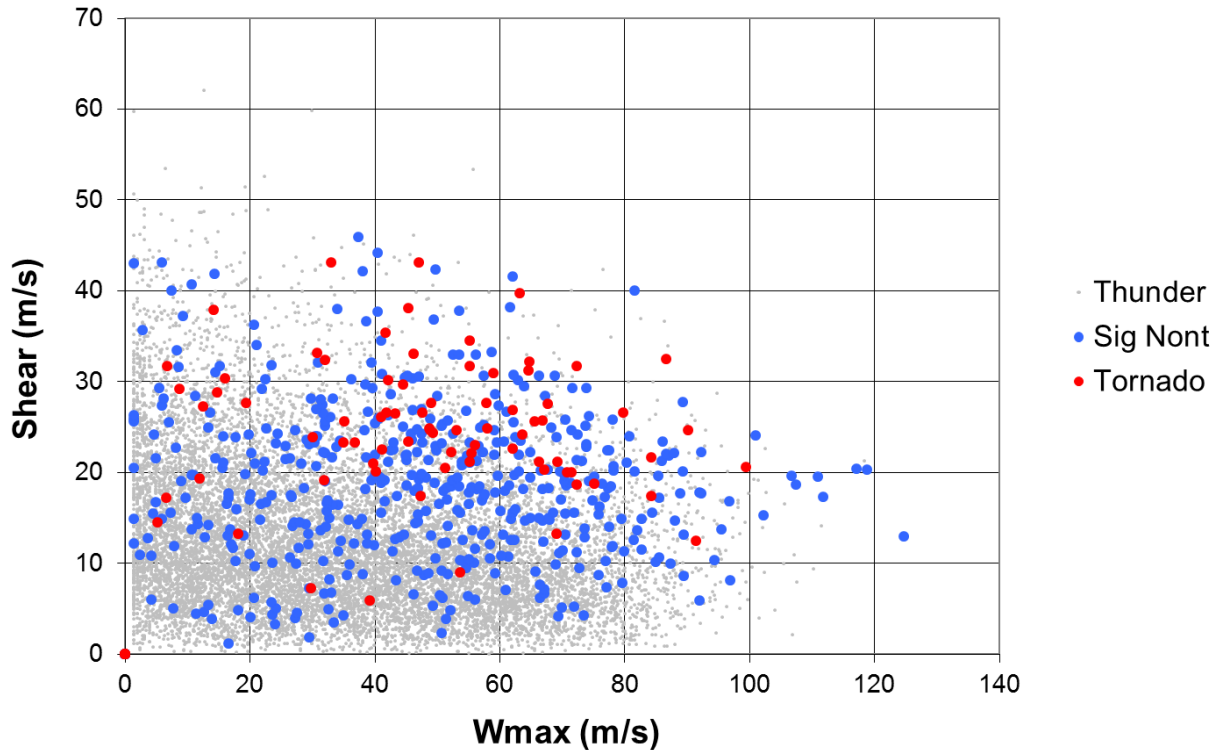


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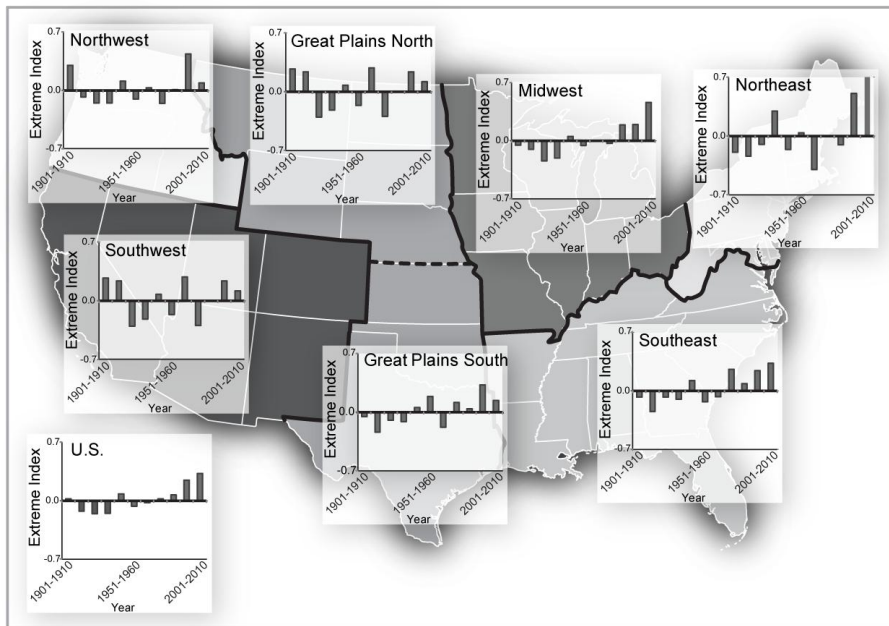
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Wmax/6 km Shear Proximity Values



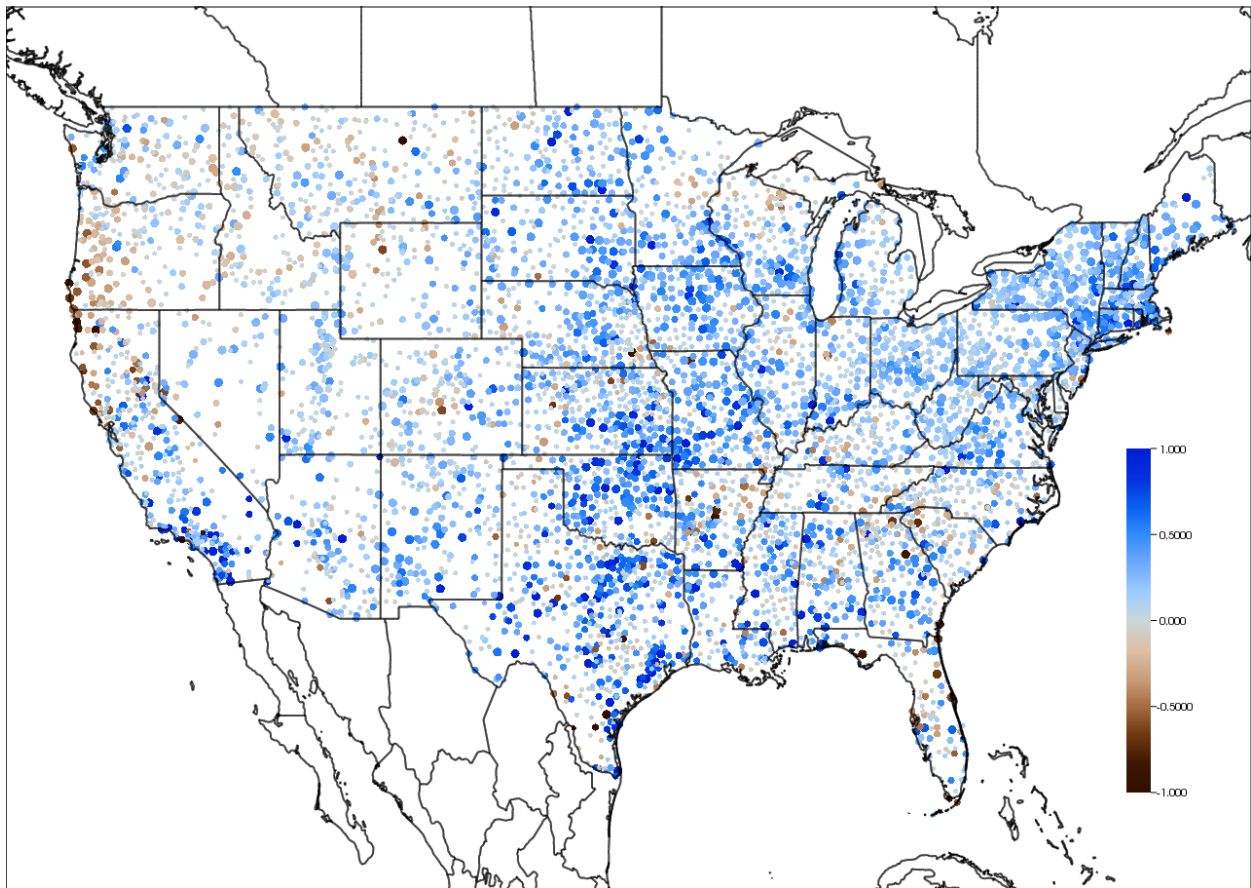
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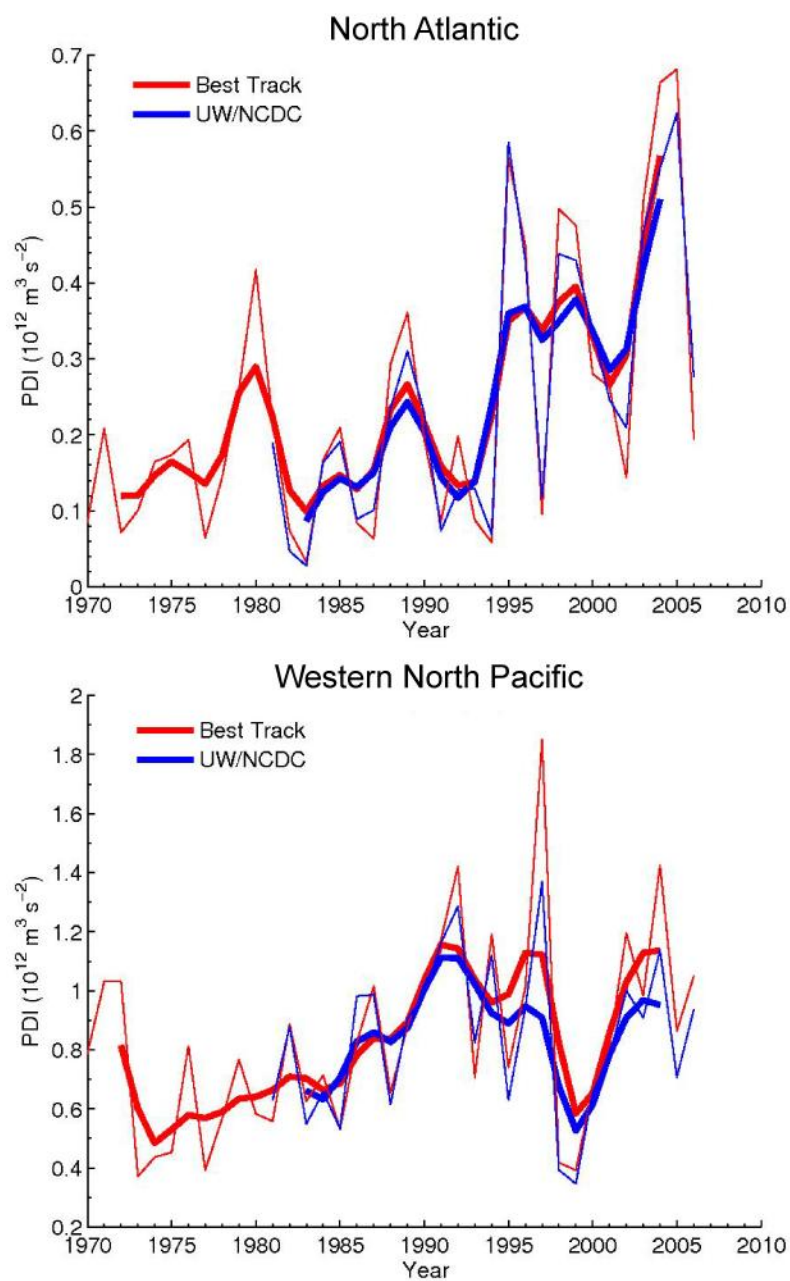
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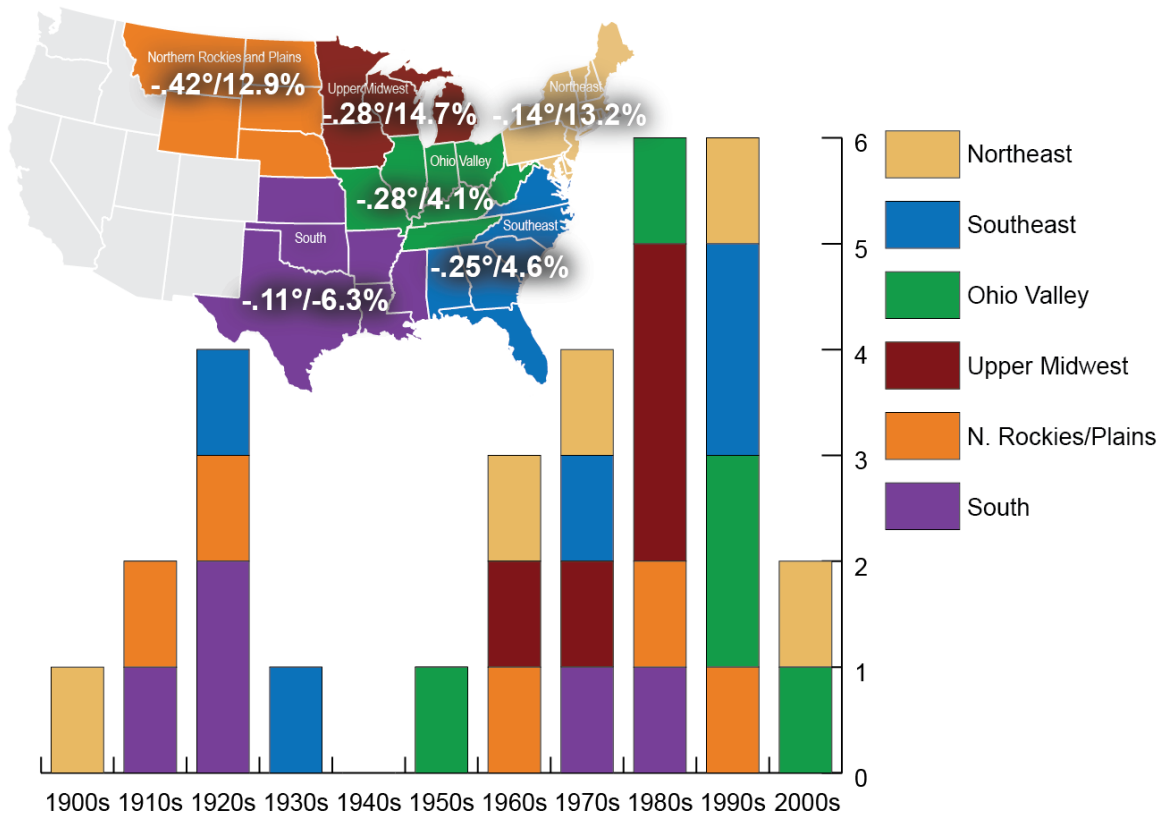


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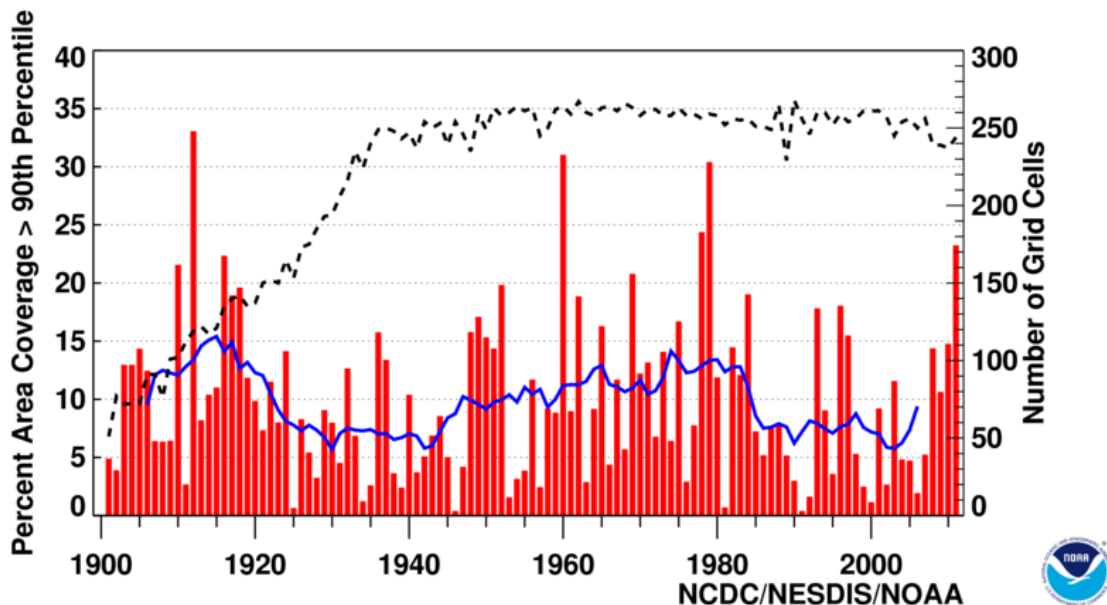


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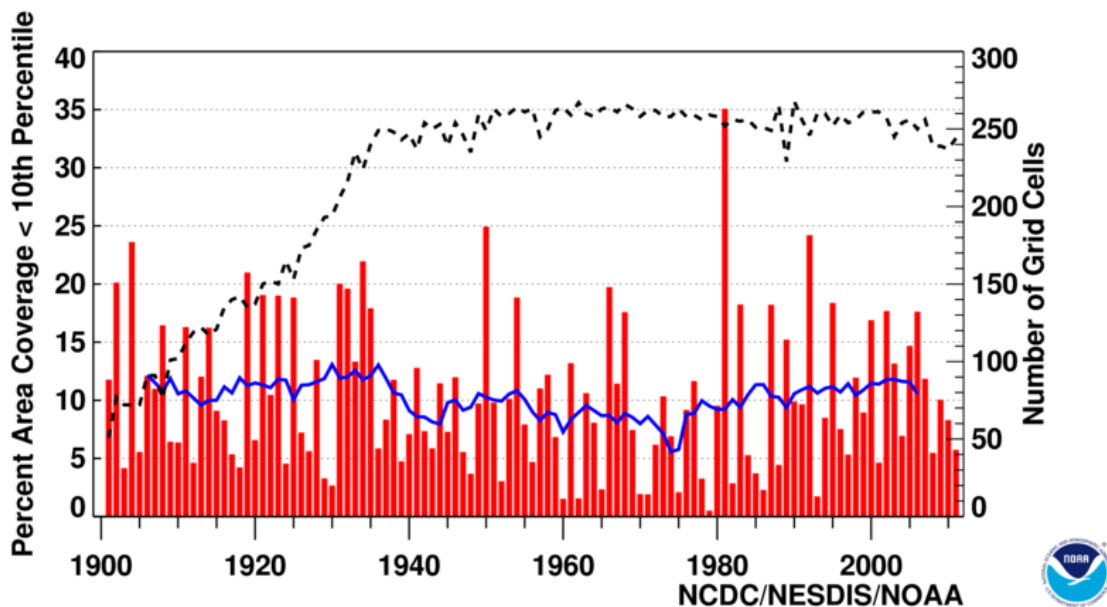
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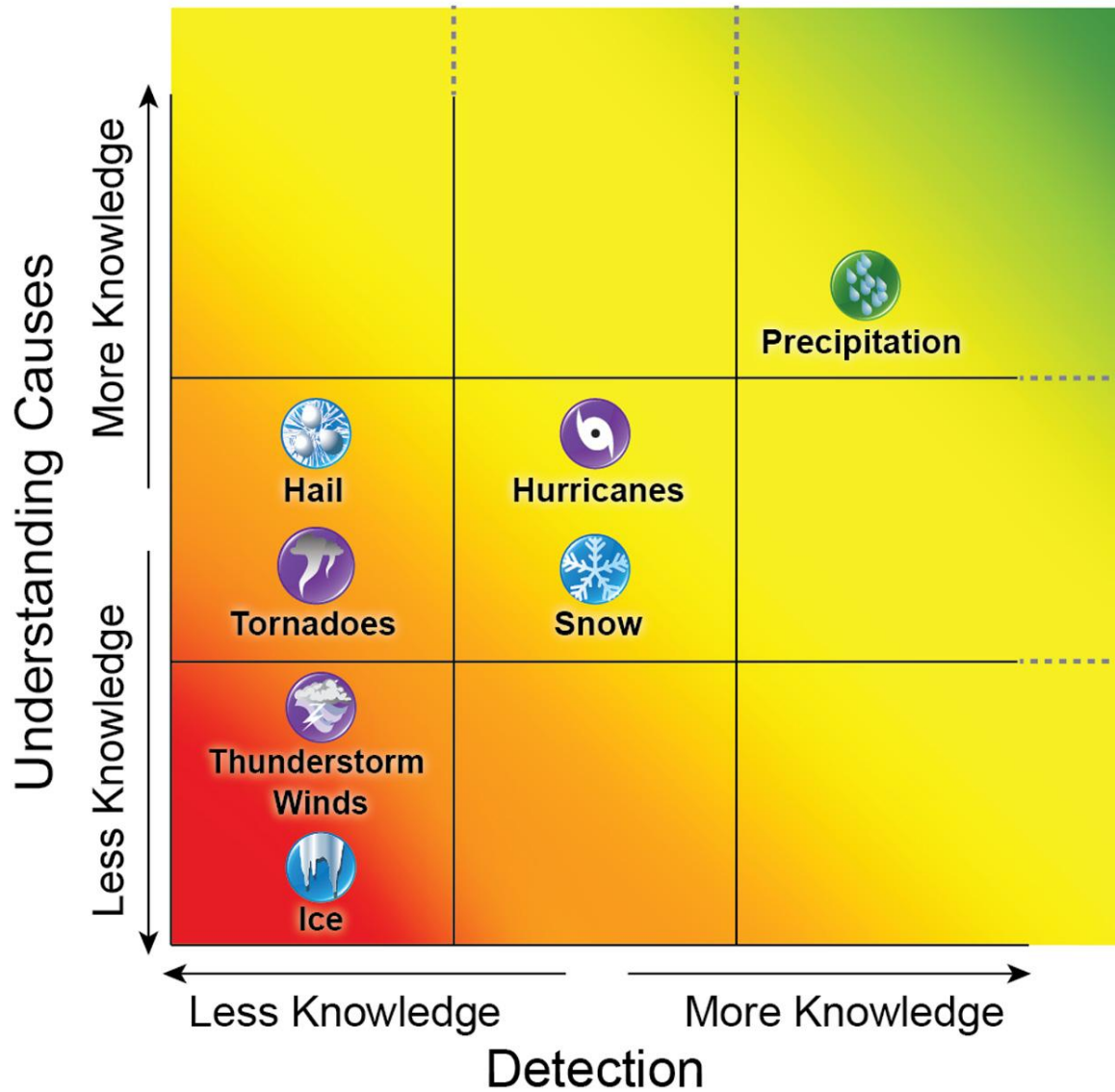
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Adequacy for Detection and Attribution of Changes for Classes of Extreme Storms



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 915 dashed lines on the top and right sides denote that knowledge about phenomena in the top category is
 916 not complete.

917 **Supplementary Online Material**

918 1. Time dependent peaks over threshold methodology

919 To produce figure 4, we used data for 1948-2010 from the Global Historical Climate
920 Network-daily dataset for stations in the contiguous United States including only stations
921 providing data for at least 2/3 of the days in that period. At each station, we found the station-
922 specific 97th percentile of daily precipitation based on the entire time period, using only days
923 with at least 1 mm of precipitation. We then fit a station-specific time-varying statistical
924 extreme value model (Coles 2001) to daily exceedances of the 97th percentile. We used only
925 the maximum daily value when consecutive days exceeded the threshold to avoid temporal
926 dependence from multi-day storms (i.e., runs declustering with parameter $r = 1$, Coles 2001).
927 We used a point process model for exceedances over a high threshold (or peaks over
928 threshold), as in Tomassini and Jacob (2009) and Cooley and Sain (2010). The model is
929 equivalent to a generalized Pareto distribution for excesses over a threshold combined with a
930 Poisson process for the occurrence of threshold exceedances and is consistent with a
931 generalized extreme value (GEV) distribution for block maxima. The basic parameters of the
932 point process model can be expressed in terms of those of a GEV, namely location, scale, and
933 shape. The shape parameter determines the heaviness of the tail of the distribution,
934 encompassing the Weibull (bounded tail), Fréchet (heavy tail), and Gumbel (light tail)
935 distributions. We allowed the location parameter to vary linearly in time, while assuming the
936 shape and scale parameters were constant over time. To minimize complexity, any seasonality
937 in these parameters was ignored. As a result of this parameterization, the change over time in
938 the return level (for any return period) is linear with the same slope as that for the location
939 parameter (Coles 2001). An additional consequence is that the change is not a function of the
940 return period considered - that is the 1948-2010 change in the 20-year return level is the same
941 as the 1948-2010 change in the X-year return level for any X. Note that by fitting a separate
942 shape parameter value at each location, we allowed for the possibility that the heaviness of the
943 tail differs by location. Uncertainty estimates were based on the Hessian of the point process
944 likelihood according to standard maximum likelihood theory, with the standard error for the
945 return level depending on not only the standard error for the linear trend parameter, but on
946 the standard errors of the other parameters of the GEV as well. Standard diagnostics for
947 extreme value distributions (Coles 2001) indicated no obvious lack of fit, and analysis with
948 thresholds based on percentiles other than the 97th (90, 95, 98, 99, 99.5) indicated the results
949 did not change substantially apart from the expected bias-variance tradeoff as the percentile
950 increased. The station-specific results are noisy because of the uncertainty in estimating the
951 behavior of extremes from short time series. Statistical approaches that smooth over the noise

952 are feasible, but standard techniques have not been developed, so we show the station-specific
953 results without smoothing. The results are not sensitive to the available data criterion. We
954 repeated the analysis for stations with 90% and 95% available data. We found that the stations
955 excluded by these criterion levels exhibited the same spatial patterns as the stations with more
956 complete data.

957 To account for multiple testing, we carried out a field significance analysis. Each of 1000
958 simulations consisted of 63 years of synthetic data resampled with replacement from the 63
959 years of observations comprising 1948-2010. Each resampled year included all the data from all
960 locations for that year, thereby preserving the spatial dependence and within-year temporal
961 structure, but breaking the between-year dependence. This produced simulated datasets under
962 the null hypothesis of no temporal trend across years. For each of the 1000 simulated datasets,
963 we carried out the point process model analysis, calculating the field significance P-value based
964 on the number of locations with z-score (change in return level divided by its standard error)
965 exceeding 1, 1.64, and 1.96. In all three cases, none of the simulations had as high a proportion
966 of stations with z-scores exceeding the value as the proportion of stations in the original
967 analysis, giving $P < 0.001$.

968

969 2. Extreme Precipitation Water Vapor Analysis

970 A set of extreme precipitation events (daily, 1-in-5yr recurrence) used in Kunkel et al. (2011) was
971 the basis for this analysis. For each station event, radiosonde data from the Integrated Global
972 Radiosonde Archive were used to find the highest precipitable water value occurring within 3 degrees
973 latitude and longitude and on the day before or the day of the event. This was assumed to be the best
974 representation of the water vapor environment available to the precipitation-producing system.

975 For each of the NCA regions, we averaged these precipitable water values for two
976 periods: 1971-1989 and 1990-2009. We also averaged the values of the extreme precipitation
977 index. The statistical significance of the differences was tested using the two-sample t-test.
978 These two periods were compared because they span a period of sizeable changes in extreme
979 precipitation occurrences and the data from the Integrated Global Radiosonde Archive (Durre
980 et al. 2006) are most complete after 1970.

981

982

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