



# 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-13-00055.1](https://doi.org/10.1175/BAMS-D-13-00055.1)

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



# Causes and Predictability of the 2012 Great Plains Drought

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13 June 2013

Revised Manuscript

Submitted to the

***Bulletin of the American Meteorological Society***

## Abstract

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Central Great Plains precipitation deficits during May-August 2012 were the most severe since at least 1895, eclipsing the Dust Bowl summers of 1934 and 1936. Drought developed suddenly in May, following near-normal precipitation during winter and early spring. Its proximate causes were a reduction in atmospheric moisture transport into the Great Plains from the Gulf of Mexico. Processes that generally provide air mass lift and condensation were mostly absent, including a lack of frontal cyclones in late spring followed by suppressed deep convection in summer owing to large-scale subsidence and atmospheric stabilization.

Seasonal forecasts did not predict the summer 2012 central Great Plains drought development, which therefore arrived without early warning. Climate simulations and empirical analysis suggest that ocean surface temperatures together with changes in greenhouse gases did not induce a substantial reduction in summertime precipitation over the central Great Plains during 2012. Yet, diagnosis of the retrospective climate simulations also reveals a regime shift toward warmer and drier summertime Great Plains conditions during the recent decade, most probably due to natural decadal variability. As a consequence, the probability for severe summer Great Plains drought may have increased in the last decade compared to the 1980s and 1990s, and the so-called tail-risk for severe drought may have been heightened in summer 2012. Such an extreme drought event was nonetheless still found to be a rare occurrence within the spread of 2012 climate model simulations.

71 Implications of this study's findings for U.S. seasonal drought forecasting are  
72 discussed.

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94 **1. The Drought's Morphology and Impacts**

95 Central Great Plains' rains, occurring mostly during May-August, failed in 2012.  
96 Absent was the usual abundance of slow soaking precipitation-bearing systems and  
97 evening thunderstorms that characterize Great Plains climate, and as a result surface  
98 moisture conditions greatly deteriorated. The U.S. Drought Monitor estimated that  
99 over three-quarters of the contiguous U.S. experienced at least abnormally dry  
100 conditions by summer's end with nearly half of the region, especially the Great  
101 Plains, experiencing severe-unprecedented drought. Conditions were comparable to  
102 those of a quarter-century earlier during 1988, and the combination of rainfall  
103 deficits and high temperatures even rivaled those observed during the Dust Bowl  
104 era of the 1930s.

105

106 Daily rainfall time series from observations taken at weather stations across the  
107 Great Plains (Fig. 1) illustrate the timing of drought onset. After a period of near to  
108 above normal winter and early spring precipitation at most stations over the central  
109 Great Plains, rains abruptly halted in May. For instance, there were virtually no rainy  
110 days at Cedar Rapids, IA during May, a signature of the paucity in migratory cyclones  
111 and frontal systems that have been previously identified as drought-causing  
112 mechanisms for spring and some summer droughts (e.g. Dole 2000). Neighboring  
113 stations also experienced prolonged stretches of rain-free days, with no measurable  
114 precipitation at Omaha, NE during July consistent with an absence of rain-producing  
115 thunderstorms that typically account for the bulk of mid-summer rainfall in the U.S.  
116 heartland (e.g., Dai 2001). Likewise, the western Plains stations of Goodland, KS and

117 Cheyenne, WY saw only infrequent rains of light intensity during July and August.  
118 By contrast, Dallas-Fort Worth, which was near the center of the prior year's  
119 southern Plains drought, accumulated above normal rainfall for the prior 6-month  
120 period through summer 2012. This greatly improved their soil moisture balance,  
121 and the U.S. Drought Monitor estimated that northeast Texas was drought-free by  
122 May 2012. Oklahoma City also showed strong signs of recovery from the 2011  
123 drought with above average rains falling through May 2012, but then skies abruptly  
124 cleared and June through July was virtually rain-free attesting to the dearth of  
125 thunderstorm activity that also plagued other Great Plains areas.

126

127 Various measures of drought intensity paint a consistent picture of widespread and  
128 severe surface moisture deficits that spanned the central Great Plains during May-  
129 August 2012. The summer-averaged precipitation was nearly 2 standardized  
130 departures below normal from the Rockies to the Ohio Valley (Fig. 2a) indicative of  
131 meteorological drought. Surface temperatures were likewise about 2 standardized  
132 departures above normal over this region (Fig. 2b), consistent with the strong  
133 inverse relationship between summer rainfall and surface air temperature (e.g.  
134 Madden and Williams 1978; Hoerling et al. 2013). Severe agricultural drought  
135 occurred throughout the region as affirmed by estimated soil moisture anomalies  
136 that were in the lower decile of the historical distribution (Fig. 2d). And, as expected  
137 from the deficient rainfall and depleted soil moisture, estimated surface runoff was  
138 also in the lower decile, especially in the western Missouri and lower Ohio River  
139 drainage basins (Fig. 2c).

140

141 Impacts from the drought emerged swiftly. Loss estimates by the end of July 2012,  
142 were \$12B ([http://www.kansascityfed.org/publicat/mse/MSE\\_0312.pdf](http://www.kansascityfed.org/publicat/mse/MSE_0312.pdf)).

143 The USDA estimated that corn yield (per acre of planted crop) was only 123 bushels.  
144 (<http://www.nass.usda.gov>). This is 26% below the 166-bushel yield expectation  
145 that the USDA had at the commencement of the growing season. Figure 3 shows the  
146 time series of U.S. corn yield since 1866, the most prominent feature of which is the  
147 growth in yield since about WWII as a consequence of improved agricultural  
148 practices and more productive and heartier strains of seed. However, 2012 corn  
149 yield fell strikingly below the recent trend line. The 2012 crop yield deficit and the  
150 implied climatic impact was a *historic event*. In terms of absolute loss in bushels of  
151 corn production, no single year since 1866 experienced so large a curtailment as  
152 occurred during 2012.

153

154 It was mostly via extrapolation of the recent historical yield time series that the  
155 USDA offered its initial expectation in spring 2012 that annual corn yield would be  
156 about 166 bushels per acre. This is a reasonable prediction given that year-to-year  
157 variations are mostly small relative to the trend “signal” of unabated improved  
158 yields. Of course, these variations----relative to trend --- are mostly the result of  
159 climate variability. The question is thus whether this drought could have been  
160 anticipated, and if actionable prediction of climate impacts on agriculture (among  
161 many other sectors vulnerable to drought) might have been rendered.

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165 **2. Historical Context and Relationships to Antecedent Conditions**

166

167 By measures of rainfall deficits, the summer of 2012 was an unprecedented year.

168 Figure 4 shows the 1895-2012 time series of May-August rainfall departures

169 averaged over the multi-state region (WY, CO, NE, KS, MO, IA) that experienced the

170 most severe drought conditions in 2012. The deficit in rainfall in 2012 was -34.2

171 mm, which was about 53% of the region's long-term mean rainfall (73.5 mm). This

172 deficit broke the record of -28.4 mm observed in 1934, and corresponds to a

173 departure of 2.7 standard deviations.

174

175 The 2012 event would not have been anticipated from simple considerations of

176 central U.S. rainfall behavior in the recent past. The 1930s droughts lay in distant

177 memory, and though not forgotten, may have resulted from unique conditions of that

178 era (Schubert et al. 2004; Seager et al. 2005; Cook et al. 2009). These included

179 remote effects of tropical sea surface temperatures, land use practices and the

180 potential feedbacks that abundant soil-related aerosols may have exerted on rainfall.

181 An important role for random atmospheric internal variability has also been

182 proposed (Hoerling et al. 2009). However, since the 1930s, summer rainfall has

183 shown less severe declines in the 1950s and 1970s, while the last 2 decades were

184 noted mostly by abundant summer rainfall (e.g. Wang et al. 2009). Looking at the

185 whole time period, there is no clear long-term trend towards either drying or

186 wetting. The 2012 drought thus appears to be a climate surprise from such

187 empirical considerations alone.

188

189 But did early warning signs exist based on other information, for instance in the  
190 sequence of seasonal events that immediately preceded the 2012 drought? Much of  
191 the southern and central Great Plains experienced near normal precipitation during  
192 the period October 2011 thru April 2012 (not shown), and this situation  
193 significantly improved soil moisture conditions over the southern Plains by spring  
194 2012 (Fig. S1), and was responsible for the amelioration of agricultural drought  
195 severity over this region that had developed in prior years. Precipitation was thus  
196 mainly driving a recovery in soil moisture through spring 2012 over the southern  
197 Plains, and surface moisture conditions over the central Plains were not severely  
198 stressed despite a very warm early spring.

199  
200 Is there empirical evidence that droughts over the southern Plains, such as occurred  
201 during 2010-11, tend to migrate northward as part of a life cycle? Here the  
202 instrumental record dating to 1895 is examined to explore how Great Plains  
203 droughts typically evolve. From the historical time series (Fig. 4), the prior driest  
204 May-August periods are identified. The 10 driest years (including 2012), ranked in  
205 order of their rainfall deficits, were: 2012, 1934, 1936, 1901, 1976, 1913, 1988,  
206 1953, 1911, and 1931.

207  
208 For these 9 historical cases, composite averages of precipitation for the 12 months  
209 preceding peak central Great Plains May-August rainfall deficits were calculated and  
210 are shown in Fig. S2. No evidence for appreciable dryness in the prior summer over  
211 Texas is found in this composite; suggesting that southern Plains drought such as  
212 occurred in 2011 is not a necessary condition for subsequent central Great Plains

213 drought. There is some indication for prevailing dryness in the antecedent  
214 conditions across the central Great Plains as a whole, however. This dry signature is  
215 partly related to the fact that several of the individual driest central Plains summers  
216 in the composite were immersed within dry epochs that spanned much of the 1930s  
217 and also from the late-1940s through the mid-1950s.

218

#### 219 **4. Proximate Causes for the 2012 Drought**

220 Why did the 2012 drought happen the way it did? This is meant as a simple starting  
221 query towards interpreting the drought, though recognizing that answers to this  
222 question alone may not provide predictive understanding. As is common with  
223 droughts, atmospheric moisture in both absolute and relative measures is typically  
224 deficient, and 2012 was no exception. A second, and often inexorably linked factor is  
225 the absence of processes that produce rainfall over the central Plains. These include  
226 springtime low pressure systems and their attending warm and cold fronts that act  
227 to lift air masses and produce widespread rains. During summertime, the key  
228 process involves thunderstorms that normally occur with considerable frequency  
229 and from which the majority of precipitation falls in July and August. Both of these  
230 mechanisms were largely absent or inoperative to considerable degree in 2012 over  
231 the central Great Plains.

232

233 Diagnosis of 500-hPa height anomalies during summer 2012 reveals considerable  
234 monthly variability (Fig. 5), implying that such a sustained and extreme drought was  
235 not a consequence of some steady sustained forcing. Yet each of these monthly

236 anomaly patterns in their own manner squelched rainfall-inducing processes over  
237 the central Plains. In May and June (Fig. 5, top panels), a zonal ridge of high pressure  
238 anomalies inhibited the typical southward push of cold fronts from Canada that  
239 often serve to organize widespread rains. July (bottom left) saw a somewhat  
240 different pattern, though no less effective in inhibiting rainfall. An intense  
241 anticyclone was centered over the northern Plains region, preventing frontal  
242 incursions while also stabilizing the atmosphere and inhibiting deep convection that  
243 typically contributes appreciably to mid-summer rainfall totals. The August 500 hPa  
244 height pattern (bottom right), though also drought producing, was yet different  
245 again from May, June and July. A deep Ohio Valley trough acted to inhibit Gulf of  
246 Mexico moisture inflow, while subsidence over the western Great Plains was  
247 enhanced on the western edge of this low pressure system.

248

249 Together, these conditions conspired to create a 4-month sequence of record rainfall  
250 reduction over the central Great Plains. The impression is rendered of a sequence of  
251 unfortunate events given the considerable monthly variability in the upper level  
252 circulation over North America. There were nonetheless indications of more  
253 persistent planetary scale features of atmospheric circulation during summer 2012  
254 that consisted of zonally averaged positive height anomalies in middle latitudes and  
255 negative anomalies in subtropical latitudes (not shown). Previous studies have  
256 found such distinct zonally symmetric features of the Northern Hemisphere  
257 summertime circulation to be at least weakly controlled by sea surface temperature  
258 anomalies (e.g. Schubert et al., 2002; Kumar et al., 2002; Ding et al. 2011). Such a

259 global pattern entails widespread poleward shift of the prevailing westerlies, and is  
260 consistent with the fact that the Eurasian grain belt also experienced record heat  
261 and drought beginning in May 2012. These reduced harvests together with the  
262 impacts on U.S. production resulted in substantial wheat price increases world-wide  
263 ([http://www.businessweek.com/news/2012-08-23/russia-may-run-out-of-](http://www.businessweek.com/news/2012-08-23/russia-may-run-out-of-exportable-grain-surplus-in-november)  
264 [exportable-grain-surplus-in-november](http://www.businessweek.com/news/2012-08-23/russia-may-run-out-of-exportable-grain-surplus-in-november)).

265

266 Over the U.S., the aggregate consequence of these various drought inducing  
267 circulation features was that the principal source of water vapor in summer over the  
268 central U.S. from the Gulf of Mexico region was greatly impaired. The spatial  
269 distribution of climatological 700 hPa meridional (north-south component) wind  
270 (Fig. S3) exhibits a peak 2 m/s southerly flow immediately on the coast of southwest  
271 Texas, a feature related to the clockwise air motion around the mean subtropical  
272 high of the Atlantic Ocean. This climatological influx of Gulf air masses is also a  
273 signature of the integrated effects of migratory mid-latitude storm systems,  
274 especially in the late springtime when they exhibit a geographically preferred  
275 cyclogenesis in the lee of the southern Rocky Mountains. The southerly flow was  
276 50% reduced during May-August 2012, with a seasonal anomaly of about -1 m/s  
277 along the Gulf Coast region (Fig. S3). Consistent with this, the summertime 700 hPa  
278 specific humidity was anomalously low throughout the Great Plains.

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285 **5. Underlying Causes for the 2012 Drought**

286 Why did drought occur over the central Great Plains during summer 2012 (and what  
287 caused the proximate conditions discussed above)? We have already surmised, from  
288 empirical analysis, that the central Plains drought was unlikely part of a single multi-  
289 year drought life cycle having its incipient stage over the southern Plains in late  
290 2010 and subsequently spreading northward. Although large portions of the U.S. are  
291 experiencing a third year of drought, it is plausible that various phases may have had  
292 different causes (see Hoerling et al 2013; Seager et al. 2013 for studies of the 2010-  
293 2011 drought). Here we explore whether particular forcings, including sea surface  
294 temperature (SST) and sea ice conditions, and also the trace gas composition of the  
295 atmosphere, may have contributed to the occurrence of a drought over the central  
296 Plains in summer 2012.

297

298 Concerning SST forcing, it is useful to first assess the evidence for recurrent patterns  
299 of ocean conditions attending the prior nine severe summer droughts in the  
300 historical record. For these events, 3 cases (1910/11; 1933/34; 1975/76)  
301 experienced moderate La Niña conditions the prior winter season, two occurred  
302 after wintertime El Niño conditions (1930/31; 1987/88), while the remaining 4  
303 cases were neutral with respect to ENSO's phase. Consistent with this weak  
304 evidence for a coherent *precursor* SST condition, at least in the equatorial east  
305 Pacific, evidence for a strong *simultaneous* SST effect is not found either. An analysis  
306 of the linear correlation between the index of central Great Plains summer  
307 precipitation with summertime global ocean surface temperatures for the entire

308 1895-2011 period (Fig. S4) reveals no statistically significant relationship. The lack  
309 of such relationships between summer US precipitation and sea surface  
310 temperatures has thwarted efforts at successful seasonal forecasting.

311

312

313 Global SSTs have appreciably changed, however, since the occurrence of past major  
314 central Plains droughts. Figure 6 presents two analyses for the SST anomalies of  
315 May-August 2012, one calculated relative to a 1901-1990 climatology (top) that  
316 brackets the era in which the prior nine historical droughts occurred, and the other  
317 relative to a conventional modern 1981-2010 30-year climatology (bottom). A key  
318 point is the indication for an appreciable warming of most ocean basins as revealed  
319 by the much larger warm ocean anomalies during the 2012 summer when  
320 calculated relative to the long historical reference. The implication is that the prior  
321 severe Great Plains droughts occurred when global oceans, and climate overall, was  
322 appreciably cooler. Nonetheless, several regional features of SST conditions in 2012  
323 are robust to choice of reference, including the presence of anomalous warmth in  
324 the North Atlantic and an enhanced east-west contrast in equatorial SSTs between  
325 the climatological warm pool of the Indo-west Pacific and typically cooler waters of  
326 the central to east Pacific.

327

328 Given such non-stationarity in climate, and in particular the change in global SSTs, it  
329 becomes important to examine the particular attributes of climate forcings that  
330 operated during 2012 and assess how they may have conditioned the probability for  
331 severe drought over the central Great Plains in 2012. The warm SSTs in the Atlantic

332 basin during 2012 are noteworthy, and recent studies point to a summertime U.S.  
333 climate sensitivity to Atlantic forcing (e.g. Schubert et al. 2009; Findell and Delworth.  
334 2010; Kushnir et al. 2010). Also, the tropical-wide SST anomalies of the past year  
335 have attributes of the so-called "perfect ocean for drought" pattern, with an  
336 enhanced west-east contrast in ocean temperatures between the Indo-Pacific and  
337 central Pacific. Land precipitation was found to be sensitive to this structure,  
338 especially for the cold-season over the southern U.S. (Hoerling and Kumar 2003).

339  
340 Retrospective climate simulations in which the variations of ocean surface  
341 conditions and atmospheric trace gas composition during 1979-2012 have been  
342 specified are next diagnosed (see Appendix 1 for model details and an assessment of  
343 model climatology). Two particular aspects of the simulated sensitivity are of  
344 interest. First is the average response to the specified forcings, and here we  
345 diagnose the ensemble mean response of 30 simulations based on 2 different  
346 climate models. Second is the so-called "tail response", an assessment exploring  
347 how the probability of a particular threshold exceedance (e.g., the odds of eclipsing a  
348 prior record value) changes as a consequence of the specified forcing.

349  
350  
351 Figure 7 compares the observed May-August 2012 anomalies for rainfall (left), soil  
352 moisture (middle), and surface air temperature (right) with the ensemble mean  
353 signal of the fully forced climate model simulations. A forced signal of reduced  
354 rainfall is apparent in the models, though geographically focused over the Southwest  
355 and intermountain West rather than over the central Great Plains region (outlined in  
356 the black box), and having magnitudes much weaker than those observed. For the

357 central Great Plains region, the area-averaged simulated rainfall is -0.5 standardized  
358 departures, a dry signal appreciably smaller than the -2.0 standardized departures  
359 observed, and there is virtually no dry signal simulated east of the Missouri River  
360 where observed drought was quite severe. A similar assessment holds for soil  
361 moisture, though the standardized departure of the model's soil moisture deficit is  
362 somewhat greater than that of its simulated rainfall deficit. This reflects two factors.  
363 One is the long memory of soil moisture, and the effect of a simulated signal of  
364 reduced rainfall over the Southwest during prior seasons and into 2011 (not  
365 shown). The other is the strong contemporaneous warming of surface air  
366 temperature during summer 2012 (right side panels) that may have also  
367 contributed to land surface drying via increased evapotranspiration. For the central  
368 Great Plains region, the area-averaged simulated warmth is 0.8 standardized  
369 departures compared to the 2.3 standardized warm anomaly observed,  
370  
371 Perhaps more compelling is the indication for an increase in the probability for an  
372 extreme drought event having the intensity observed in 2012. The box-whisker  
373 display in Fig. 8 shows the model distribution of its 30 simulations for summer 2012  
374 (far right), and also for each summer during 1979-2012 for both rainfall (top) and  
375 surface air temperature (bottom). The overall distribution for various rainfall  
376 anomaly thresholds within the 30 realizations shifts toward drier states in 2012,  
377 consistent with the simulated mean signal of reduced rainfall. Interestingly, for  
378 summer 2012, the extreme driest model member (red asterisk) is also the single  
379 driest simulation occurring in any year during 1979-2012.  
380

381 It is difficult to reliably determine the change in extreme drought event probability  
382 for 2012 from such a small 30-member simulation suite. However, inspection of the  
383 full 33-yr time series of such distributions suggests that the recent drought may  
384 have occurred during a climate regime supporting increased likelihood for severe  
385 Great Plains drought events. There is, for instance, a roughly 4-fold increase in the  
386 frequency of occurrence for a 2 standardized rainfall deficit in the 17-yr period after  
387 1996 compared to 17-yr period before. Once again, this is consistent with an  
388 ensemble mean dry signal in the model in virtually all years in the recent period, and  
389 not due to increased variability per se. The increased probability, nonetheless,  
390 represents the risk of an event that remains rare within the model spread.

391

392 It is reasonable to propose, based on analysis of these model experiments that the  
393 fact that a drought of such severity did occur in 2012 was largely coincidental, and  
394 that such an occurrence was almost as likely during any prior year since the late  
395 1990s, but more likely than in the years prior to the mid-to-late 1990s. To be sure,  
396 event likelihood is seen as a low probability in any given year. Yet, it is an intriguing  
397 conjecture that, while perhaps unbeknownst and undetectable from the  
398 observations, the recent 10-15 year period may have been one of heightened risk for  
399 the occurrence of a record setting summer drought over the central Great Plains.

400

401 The indication from the model simulations is of an abrupt shift to a warmer (Fig. 8,  
402 bottom) and drier (Fig. 8, top) climate in the late 1990s over the Great Plains, at  
403 least relative to the climate of the preceding decade. (This is hard to discern based  
404 on the observational record alone as seen in Figure 4.) There are at least two

405 candidate mechanisms that may explain the model behavior, both associated with  
406 known patterns of natural variability. One is a tropical Pacific shift with no large El  
407 Niños but an abundance of strong La Niñas in the period since the 1997/98 El Niño.  
408 A second is a sudden shift in North Atlantic SST conditions from a persistent cool  
409 state during the 1980s to late 1990s, followed by a persistent warm state of the  
410 North Atlantic thereafter, consistent with North Atlantic multi-decadal variability  
411 (e.g. Delworth and Mann 2000). Analysis of model sensitivity experiments by  
412 Schubert et al. (2009) found that a combination of warm Atlantic and cool tropical  
413 Pacific SST patterns produced substantial precipitation deficits and surface warming  
414 for annual mean responses over the continental U.S. The model sensitivity is  
415 supported by empirical evidence for a relationship between natural multi-decadal  
416 states of the Pacific and Atlantic Oceans and multi-decadal drought frequency over  
417 the U.S. (McCabe et al. 2004).

418  
419 An additional question these results pose is whether the simulated change in  
420 extreme drought risk is a symptom of climate change forcing related to global  
421 warming. There are several indications that this behavior is largely unrelated to the  
422 model's sensitivity to gradually increasing anthropogenic forcing. One indication is  
423 the rather sudden character of change in model simulations toward dry conditions  
424 in the late 1990s. Though one cannot dismiss the possibility that a steady forcing  
425 (for instance increasing CO<sub>2</sub>) may provoke an abrupt change in responses, there are  
426 other plausible physical explanations for the shift in model behavior in the 1990s  
427 including natural swings in ocean states as mentioned above. A second issue  
428 concerns the lack of any appreciable long-term change in seasonal mean climate

429 during summer over the central Great Plains since 1895 (see Fig. 4). Nor has there  
430 been an indication for an increasing trend in the occurrences of severe summer  
431 droughts over the region, with the last severe drought happening a quarter century  
432 earlier. Additional analysis will be required to assess the role of global warming on  
433 recent precipitation variability over the Great Plains using the full suite of Climate  
434 Model Intercomparison Project (CMIP5) models.

435  
436 **6. Predictions of the 2012 Drought**

437  
438 The summer 2012 central Great Plains drought developed without an early warning.  
439 NOAA's operational seasonal drought outlook, issued 17 May 2012 for the  
440 subsequent June-August period (Fig. 9, top), did not predict a tendency toward  
441 increasing drought over the central Great Plains. Instead, surface moisture  
442 conditions were expected to improve over Iowa and western Nebraska. Otherwise,  
443 the majority of the central Great Plains was forecast to experience near normal  
444 moisture conditions. Only over the interior West was drought expected to persist or  
445 intensify.

446  
447 The drought outlook reflected three primary considerations. One was the initial  
448 monitored state of drought, for which the U.S. Drought Monitor revealed surface  
449 moisture over the Great Plains had appreciably recovered during winter/early  
450 Spring. The second was the seasonal rainfall forecast, which did not yield strong  
451 guidance on the summer rainfall pattern. For instance, the May 2012 initialized  
452 predictions for June-August based on the composite of 12-centers' seasonal forecast

453 systems showed no appreciable rainfall signal (Fig. 9, bottom left), although it did  
454 indicate a widespread large amplitude warm signal (Fig. 9, bottom right).

455

456 A third consideration for the drought outlook was the expectation for rainy season  
457 onset. The climatological normal rainy season over the Great Plains is May-  
458 August. Since empirical and dynamical tools gave no strong reason to suspect it  
459 wouldn't arrive as usual, those rains were expected to alleviate existing surface  
460 moisture deficits. In many ways, the drought outlook and the results from  
461 initialized coupled model predictions are thus consistent with the retrospective  
462 climate simulations presented in Section 5, though there may be additional useful  
463 information in the ensemble spread of the retrospective climate simulations that  
464 were not readily available to the forecasters.

465

466

## 467 **7. Summary Comments on the 2012 Drought and Implications for Forecasting**

468

### 469 *a. Overall Assessment of Origin and Cause*

470

471 The 2012 drought developed rapidly over the central Great Plains during May and  
472 reached peak intensity by August. In many ways, the event was a "flash drought",  
473 owing to the unusual speed and intensity with which it developed and became  
474 entrenched over the Great Plains in summer. The 4-month cumulative rainfall  
475 deficit, averaged over a 6-state area of the central Great Plains, was the greatest  
476 since record keeping began in 1895, ranking this event as the most severe  
477 summertime seasonal drought over the central Great Plains in 117 years, eclipsing  
478 1988, 1934 and 1936. The immediate cause for the drought was predominately

479 meteorological in nature. This involved reduced Gulf of Mexico moisture transport  
480 and reduced cyclone and frontal activity in late spring. It also involved an inhibition  
481 of summer convection resulting from increased subsidence and atmospheric  
482 stabilization that accompanied an anomalous upper tropospheric high pressure over  
483 the region. The drought can thus be seen as the symptom of classical  
484 meteorological conditions that control the region's warm season rains.

485  
486 The 2012 summertime central Great Plains drought resulted mostly from natural  
487 variations in weather. The assessment did not find substantial evidence for  
488 underlying causes associated with the effects of long-lived boundary forcings.  
489 Retrospective climate simulations identify a mean dry signal during 2012 summer  
490 having a magnitude 4 times weaker than that observed for an area-average of the  
491 Great Plains region. Indicated hereby is that neither the variations in ocean states  
492 nor in greenhouse gases played significant roles in determining the intensity of the  
493 rainfall deficits in summer 2012. Furthermore, analysis of the retrospective climate  
494 simulations found virtually no dry signal over major corn producing regions of the  
495 eastern Great Plains including most of Missouri, Iowa, southern Wisconsin, Illinois,  
496 and Indiana where severe drought occurred and resulted in major curtailment of  
497 corn crop yields, indicating that neither the variations in ocean states nor in  
498 greenhouse gases played significant roles in determining the precise location of  
499 rainfall deficits during summer 2012. The simulations did reveal, however, a more  
500 substantial drying over the Southwest U.S and the far western Great Plains especially  
501 New Mexico, Colorado, western Nebraska, western Kansas, and Wyoming. These  
502 areas also suffered severe drought in 2012.

503

504 A few words are in order concerning the model suggestion of a regime shift to  
505 warmer and drier summers over the last 10-15 years, especially over the Southwest  
506 U.S. and western Plains. The underlying tendency since the late 1990s for drought  
507 conditions over the U.S. has a plausible physical basis, being likely linked to natural  
508 states of the Pacific and Atlantic Oceans. In this sense, while the 2012 drought was  
509 not well predicted, it perhaps should not be a surprise that a drought of some  
510 severity occurred (see also McCabe et al. 2004). Large portions of the U.S. are  
511 experiencing a third year of drought, although the Central Plains drought of 2012  
512 was not a simple progression or northward creeping of the prior year's Southern  
513 Plains drought event. Further, the southwestern U.S. has been overwhelmingly in a  
514 state of abnormally dry or drought conditions since 1998. This widespread state of  
515 dryness appears at least qualitatively consistent with a longer time scale climate  
516 control associated with natural oceanic variability. In the Southwest it is also  
517 consistent with the expected climate response to rising greenhouse gases (e.g.,  
518 Seager and Vecchi 2010), though that influence on precipitation is likely smaller at  
519 the current time than the influence of natural long term variability. However,  
520 despite the role of these ocean and radiative boundary conditions in tilting the odds  
521 towards a dry state, the peculiar severity of summer 2012 can only be explained by  
522 an additional heavy role for random weather variability.

523

524 *b. Implications for Drought Prediction*

525 What are some of the lessons learned in this assessment concerning U.S. drought  
526 forecasting? On the one hand, the appraisal offered herein paints a picture of an  
527 extreme event that apparently had limited potential for skillful prediction. This  
528 conclusion would thus appear to be consistent, and furthermore offer an  
529 explanation for, the poor performance of both official forecasts of drought and  
530 numerical predictions of rainfall that were rendered in late May 2012 for the  
531 subsequent June-August 2012 season. On the other hand, our diagnosis of the  
532 spread among an ensemble of retrospective climate simulations indicates an  
533 increased probability for an extreme Great Plains drought event in 2012. For  
534 instance, the single driest simulation for Great Plains summer conditions, among the  
535 sample of 990 summer simulations during the entire 1979-2012 period analyzed  
536 herein (30-members for each year of the 33-year period), occurred in the suite of  
537 2012 runs. The models thus reveal that so-called tail-risk was heightened in  
538 summer 2012. Furthermore, these same simulations indicate that the statistical  
539 likelihood for a severe summer drought occurring over the Great Plains during the  
540 last decade may have been several-fold greater than the odds of occurrence during  
541 the prior period spanning the 1980s and 1990s. The retrospective analysis thus  
542 argues for elevated risk of an extreme drought event, even though the precise timing  
543 of any single event was uncertain, and the overall strength of the signal on *seasonal*  
544 *mean rainfall* was quite small.

545

546 Given the existing practices of operational drought prediction, what might have been  
547 the impact on the forecast process if various information contained in this

548 assessment had been available in early 2012? It is useful to frame that question in  
549 the context of expected skill. The history of operational seasonal forecast  
550 performance reveals little or no skill for U.S. summer rainfall since routine forecasts  
551 were issued beginning in the mid-1990s . Furthermore, an assessment of U.S.  
552 drought hindcast skill over a longer period since 1982 recently concluded that  
553 dynamical seasonal predictions did not materially increase summer skill over the  
554 Great Plains beyond a persistence forecast benchmark (Quan et al. 2012). The  
555 reason given for the limited overall skill was small SST sensitivity of that region's  
556 summer rainfall and a small impact of antecedent soil moisture conditions, on  
557 average, upon the region's summer rainfall.

558

559 A pathway forward for summer drought prediction might thus be to consider  
560 conditional skill, and to identify so-called "events of opportunity". There are ample  
561 examples of those for rainfall and drought during the cold season in the southern  
562 U.S. associated with the strong conditioning by the El Niño/Southern Oscillation  
563 phenomenon. For instance, there was considerable skill in the seasonal forecasts of  
564 the 2010-11 southern Plains drought, especially during the winter and spring  
565 season (e.g. Hoerling et al. 2013). The current study builds upon a body of climate  
566 sensitivity studies and physical reasoning that a conditioning of U.S. summer rainfall  
567 by particular large-scale oceanic conditions may also exist (e.g. Schubert et al. 2009;  
568 Findell and Delworth 2010). Yet, contrary to ENSO effects, the magnitude of that  
569 conditioning is still highly uncertain and requires further investigation before it can  
570 be quantitatively incorporated into seasonal forecasts.

571

572 One of the opportunities for improving seasonal drought predictions is to move  
573 toward expressing the outlooks in a probabilistic manner, as is done currently for  
574 seasonal forecasts of precipitation and surface temperature. The current drought  
575 outlook product is deterministic, notwithstanding some subjective language that  
576 attempts to express the most probable tendency of drought conditions over the  
577 upcoming season. The full information of ensemble prediction systems, in  
578 particular the spread information contained in such tools, can thus not be readily  
579 incorporated into current practices for U.S. drought forecasting. Further research is  
580 also required on evaluating the spread information on drought statistics from such  
581 ensemble modeling systems. Much has yet to be learned about the robustness of  
582 spreads across multi-models, and how those spreads differ when examined in  
583 simulation mode (using uninitialized models) versus prediction mode (using  
584 initialized models). In the case of the 2012 drought, for instance, it remains to be  
585 determined if the particular event's probability was materially conditioned by  
586 antecedent soil moisture.

587

588 A related issue is the need to reconcile the identification of a modest Great Plains  
589 dry signal in the retrospective climate simulations studied herein with the lack of  
590 any dry signal in the summertime 2012 predictions of the WMO GPC multi-model  
591 ensemble. It is unclear if this was a consequence of errors in the SST predictions.  
592 Did the process of averaging 12 different models and merging them in producing the  
593 GPC forecast cause large cancellation among appreciably different signals occurring

594 in individual models? Or was the ensemble mean prediction for drier than normal  
595 conditions in these models simply too small in amplitude, and thus perhaps deemed  
596 unreliable to include in the forecasts?

597

598 One might reasonably wonder, given the suggestion from the rainfall time series  
599 produced in the retrospective climate simulations, whether the risk of a severe Great  
600 Plains drought is once again elevated in 2013 or beyond. Clarification will require  
601 better knowledge of the factors controlling the low frequency variability of Great  
602 Plains moisture conditions. The analysis presented here has mainly proposed the  
603 roles of long time scale natural variability in sea surface temperatures. And, while  
604 this study is not intended to be a comprehensive assessment of the possible effects  
605 of global warming on the 2012 central Plains drought, the results here are  
606 inconclusive on that specific question. Here we merely note the conclusion of the  
607 U.S. Climate Change Science Program Synthesis and Assessment Products (SAP 1.3,  
608 2008) that SST anomalies have been important in forcing some multi-year severe  
609 droughts over the U.S. during the last half-century, whereas short-term droughts  
610 (“flash droughts” having monthly-seasonal time scales) were judged to be mostly  
611 due to atmospheric variability, in some cases amplified by local soil moisture  
612 conditions. The report assessed that it is unlikely that a systematic change has  
613 occurred in either the frequency or area-coverage of drought over the contiguous US  
614 from the mid-20<sup>th</sup> century to the present. Subsequently, in 2012, the Special Report  
615 of the Intergovernmental Panel on Climate Change (IPCC) regarding extreme events  
616 expressed only medium confidence in a *projected* increase in drought in some

617 regions by end of the 21<sup>st</sup> Century, including the southern Great Plains and Mexico,  
618 but not the northern Plains and Midwest regions. How Great Plains drought will  
619 respond under global warming therefore continues to be a key unresolved question  
620 and a matter of future research.

621  
622 **Acknowledgments**

623  
624 The authors acknowledge resources and organizational support for the Drought  
625 Task Force from the Modeling, Analysis, Predictions and Projections Program  
626 (MAPP) of NOAA's Climate Program Office; activities are supported by MAPP in  
627 partnership with the National Integrated Drought Information System (NIDIS)  
628 Program. The authors also gratefully acknowledge support from their home  
629 institutions and various funding agencies, which help sustain their work.

630  
631 This research article is a follow-up study to an initial assessment of the 2012 Central  
632 Great Plains drought by the Drought Task Force Narrative Team. Authors gratefully  
633 acknowledge members of the Narrative Team and other Drought Task Force  
634 participant for their input and discussions.

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### **Appendix 1: Climate Model Simulations**

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787 Two global atmospheric models are run over the period 1979-2012. The only  
788 constraining information representing observed conditions in these simulations is  
789 the sea surface temperature, sea ice, and external radiative forcing which are  
790 specified in the model as monthly time evolving boundary conditions from January  
791 1979- December 2012. Climate simulations of this type are referred to as 'AMIP  
792 (Atmospheric Model Intercomparison Project)' experiments, and are designed to  
793 determine the sensitivity of the atmosphere, and the extent to which its temporal  
794 evolution is constrained by known boundary forcings.

795

796 Key to this modeling technique for assessing the impact of boundary conditions is an  
797 ensemble approach, whereby the period of simulation is repeated a multitude of  
798 times. Here simulations that have been repeated 30 times (a 30-member ensemble),  
799 and which differ from one another only in the initial atmospheric conditions in  
800 January 1979 but in which identical time evolving forcings are specified, are

801 analyzed. The strategy is to average the monthly variability across the 30 members  
802 in order to determine the mean response to specified forcings. The process of  
803 averaging eliminates the random internal variability of the atmosphere, and  
804 facilitates identifying the coherent signal from the forcing.

805

806 One model used is the National Center for Atmospheric Research (NCAR) CAM4  
807 global climate model (Gent et al. 2011), with the simulations performed at a 1°  
808 (~100 km) resolution and 26 atmospheric, and for which a 20-member ensemble is  
809 available. The second global climate model is the European Center Hamburg model  
810 version 5 (ECHAM5; Roeckner et al 2003), with simulations performed at T159  
811 (~80km) resolution and 31 atmospheric levels, and for which a 10-member  
812 ensemble is available. In both models, monthly varying SSTs and sea ice and the  
813 external radiative forcings consisting of greenhouse gases (e.g. CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>2</sub>, O<sub>3</sub>,  
814 CFCs) are specified. CAM4 runs also specify varying anthropogenic aerosols, solar,  
815 and volcanic aerosols. The model output has been interpolated to U.S. climate  
816 divisions to facilitate comparison with observations. Ensemble means are  
817 computed by doing simple equal weighted averages of the CAM4 and ECHAM5 20-  
818 member and 10-member averages, respectively.

819

820 For the May-August period and for a spatial average of 6-state Central Great Plains  
821 region, the combined GCMs' climatological mean precipitation (temperature) is 302  
822 mm (22°C) versus 298 mm (20°C) observed. The standard deviation of May-August  
823 precipitation (temperature) in the combined GCM is 12 mm (0.9°C) versus 13 mm

824 (0.7°C) observed.

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### Figure Captions

846

847 Figure 1. Daily precipitation (mm) time series during 2012 for indicated stations.  
848 For each station, top portions show the climatological precipitation (smooth curve),  
849 the actual 2012 precipitation, and their difference (color shading; brown denotes a  
850 deficit, green a surplus). Lower portions show the occurrences of daily precipitation  
851 events. Data source is NOAA Climate Prediction Center.

852

853 Figure 2. Standardized anomalies averaged over May-August 2012 for a)  
854 precipitation, b) surface air temperature, c) 3-month accumulated runoff, and d) soil  
855 moisture. Precipitation data were taken from the CPC unified precipitation analysis.  
856 Temperature data were taken from the surface temperature analysis from the  
857 University of Washington. The May-August mean and standard deviation were

858 computed using the base period 1979-2011. The contour intervals are given by the  
859 color bar. (b) same as (a). The runoff index and soil moisture are shown as  
860 percentiles, with those data taken from the ensemble mean NCEP North American  
861 Land Data Assimilation (four land surface models: Noah, Mosaic, VIC and SAC).

862

863 Figure 3. Historical U.S. corn yields from 1866 to 2012 (bushels/acre). Linear fit to  
864 different segments of the time series shown in solid lines, including regression  
865 formula. The 2012 yield is plotted in the blue circle, based on August estimates.  
866 Subsequent data revised the 2012 yield downward to about 123 bushels. Data  
867 source is USDA.

868

869 Figure 4. 1895-2012 time series of May-August central Great Plains rainfall  
870 departures (mm, top) and surface air temperature departures (°C, bottom).  
871 Reference period is 1895-2011. Black curve is a 9-point Gaussian filter. The area is  
872 comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

873 Data source is the NOAA U.S. Climate Divisions.

874

875 Figure 5. Observed monthly 500 hPa geopotential height anomalies (m) for May,  
876 June, July, and August 2012. Data from the NCEP/NCAR reanalysis, and anomalies  
877 are relative to a 1981-2010 climatology.

878

879 Figure 6. The May-August 2012 sea surface temperature anomalies (°C) calculated  
880 relative to a 1901-1990 historical reference period during which the prior nine

881 severe Great Plains droughts occurred (top) and relative to a modern 1981-2010  
882 reference period (bottom).

883

884 Figure 7. The May-August 2012 standardized anomalies of precipitation (left), soil  
885 moisture (middle), and surface air temperature (right) for observations (top) and  
886 general circulation model (GCM) simulations (bottom). Observed soil moisture  
887 estimated from the CPC a one-layer bucket water balance model driven with  
888 observations of monthly temperature and precipitation. The GCM is based on a 30-  
889 member multi-model ensemble simulation forced with the observed SSTs, sea ice,  
890 and greenhouse gas conditions for 2012. For the model data, the standardization is  
891 calculated for each separate run, and the standardized anomalies are then averaged  
892 across all 30 realizations. Period of reference is 1981-2010.

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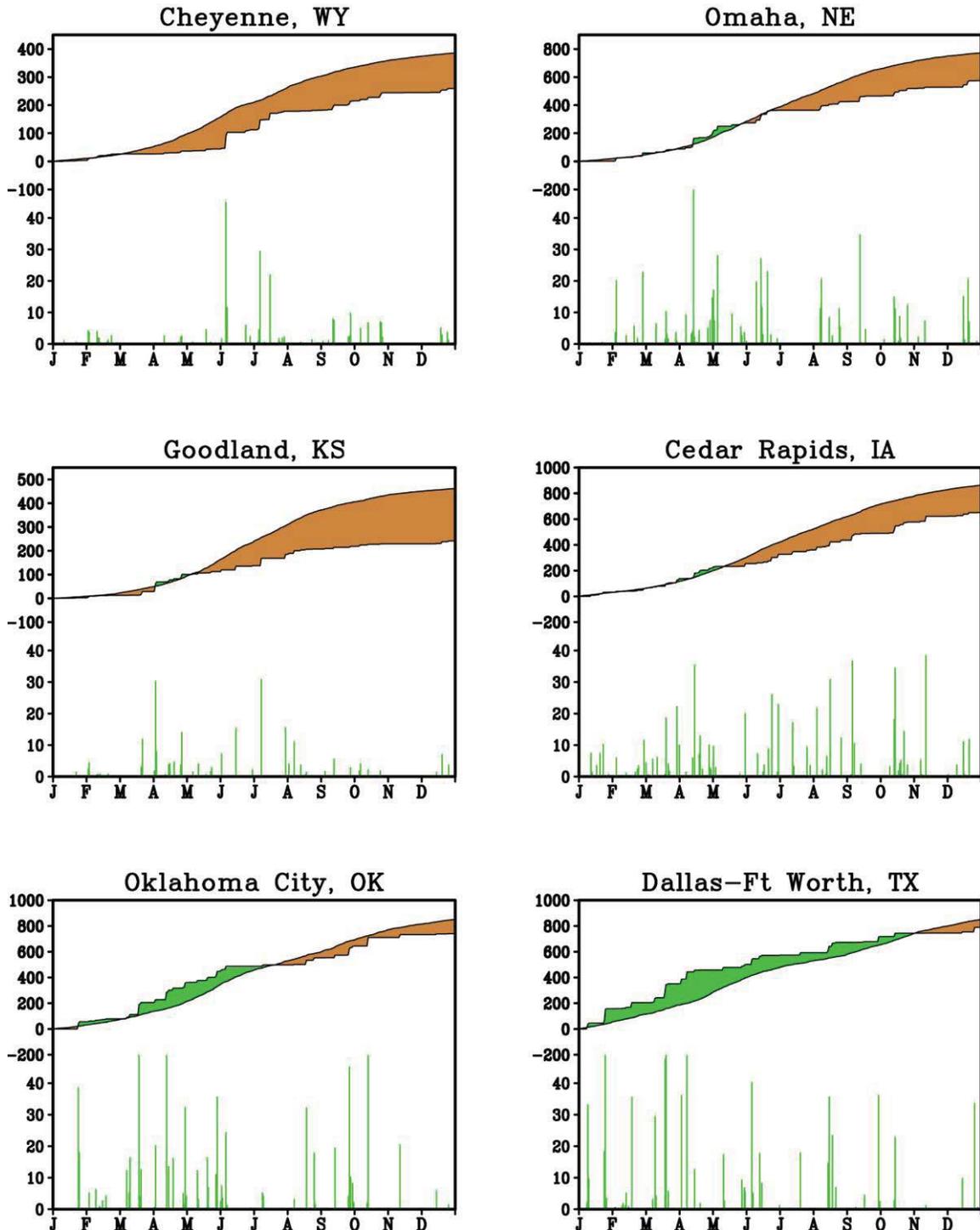
894 Figure 8. Box-whisker plots of the May-August simulated central Great Plains  
895 rainfall anomalies (top, mm) and surface temperature anomalies (bottom, °C) for  
896 1979-2012. The distribution summarizes the statistics of 30 simulations for each  
897 summer. Red (blue) asterisk denote the extreme dry (wet) ensemble member for  
898 each summer, and the dashed red lines are the model's 1-standardized departures of  
899 May-August precipitation and temperature. Green circles plot the observed values.  
900 The region consists of the 6-state average of WY, CO, NE, KS, MO, and IA. Anomalies  
901 are relative to a 1981-2010 reference.

902

903 Figure 9. (top) The NOAA official seasonal drought outlook for the contiguous U.S.  
904 issued on May 17 2012 and valid for the period May17 – August 31 2012. (bottom)  
905 The equal-weighted composites of 12 operational centers' seasonal predictions for  
906 June-August 2012 for North American sector precipitation departures (mm, left)  
907 and for North American sector surface temperature anomalies (°C, right). Forecasts  
908 are based on May 2012 initializations. Data source is the WMO GPC project.  
909 (<https://www.wmolc.org/>).

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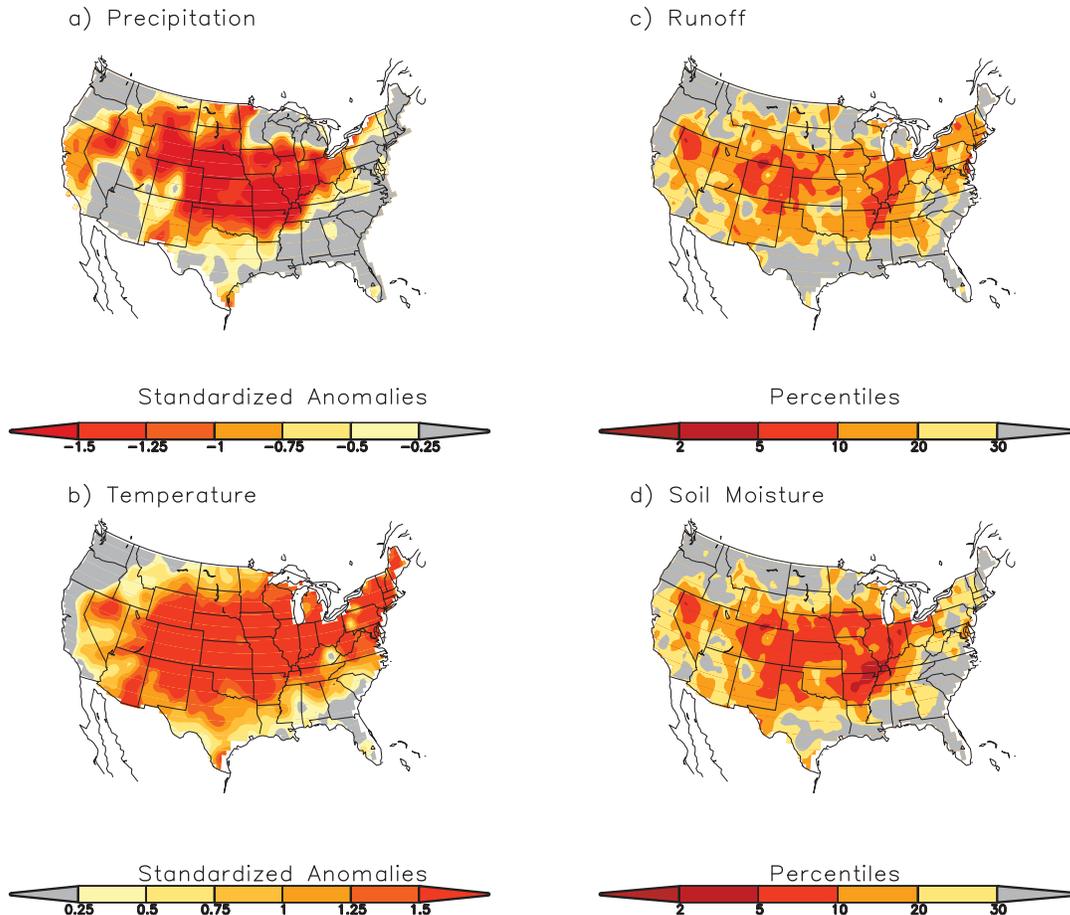
## Daily Precipitation 1 Jan 2012–31 Dec 2012



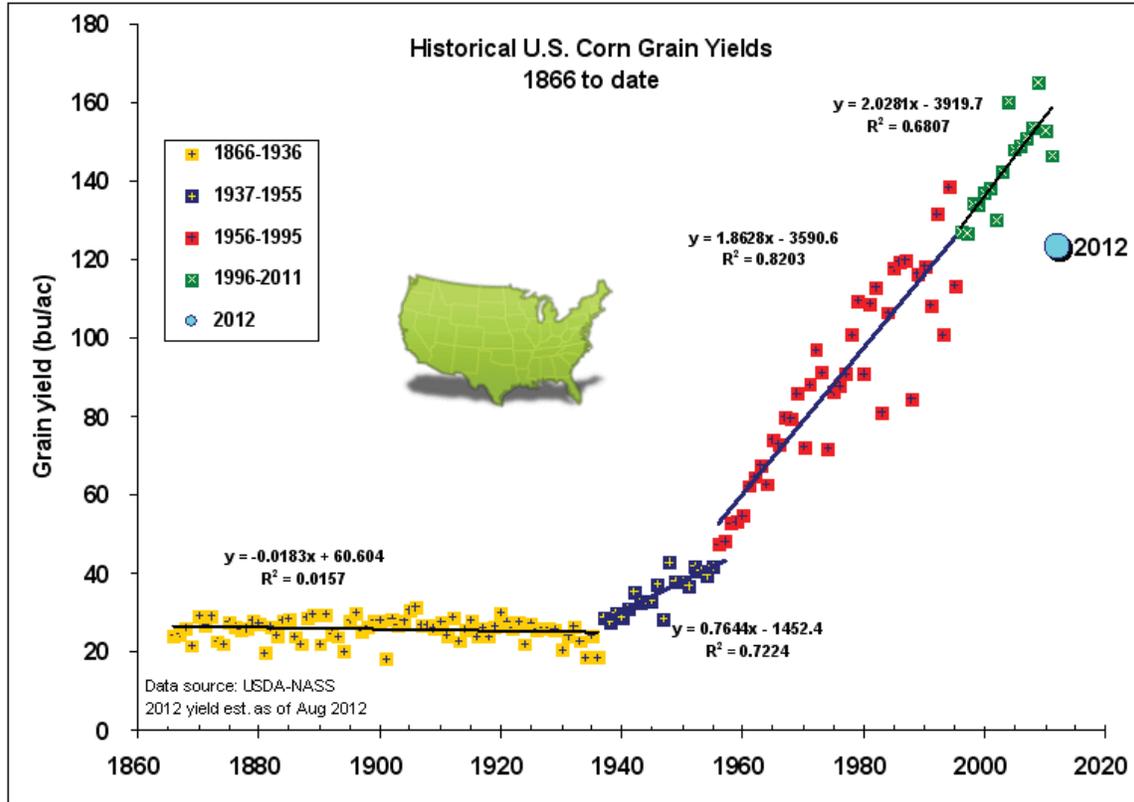
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 914 **Figure 1.** Daily precipitation (mm) time series during 2012 for indicated stations.  
 915 For each station, top portions show the climatological precipitation (smooth curve),  
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 917 green a surplus). Lower portions show the occurrences of daily precipitation  
 918 events. Data source is NOAA Climate Prediction Center.

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### Surface Conditions(May–Aug 2012)



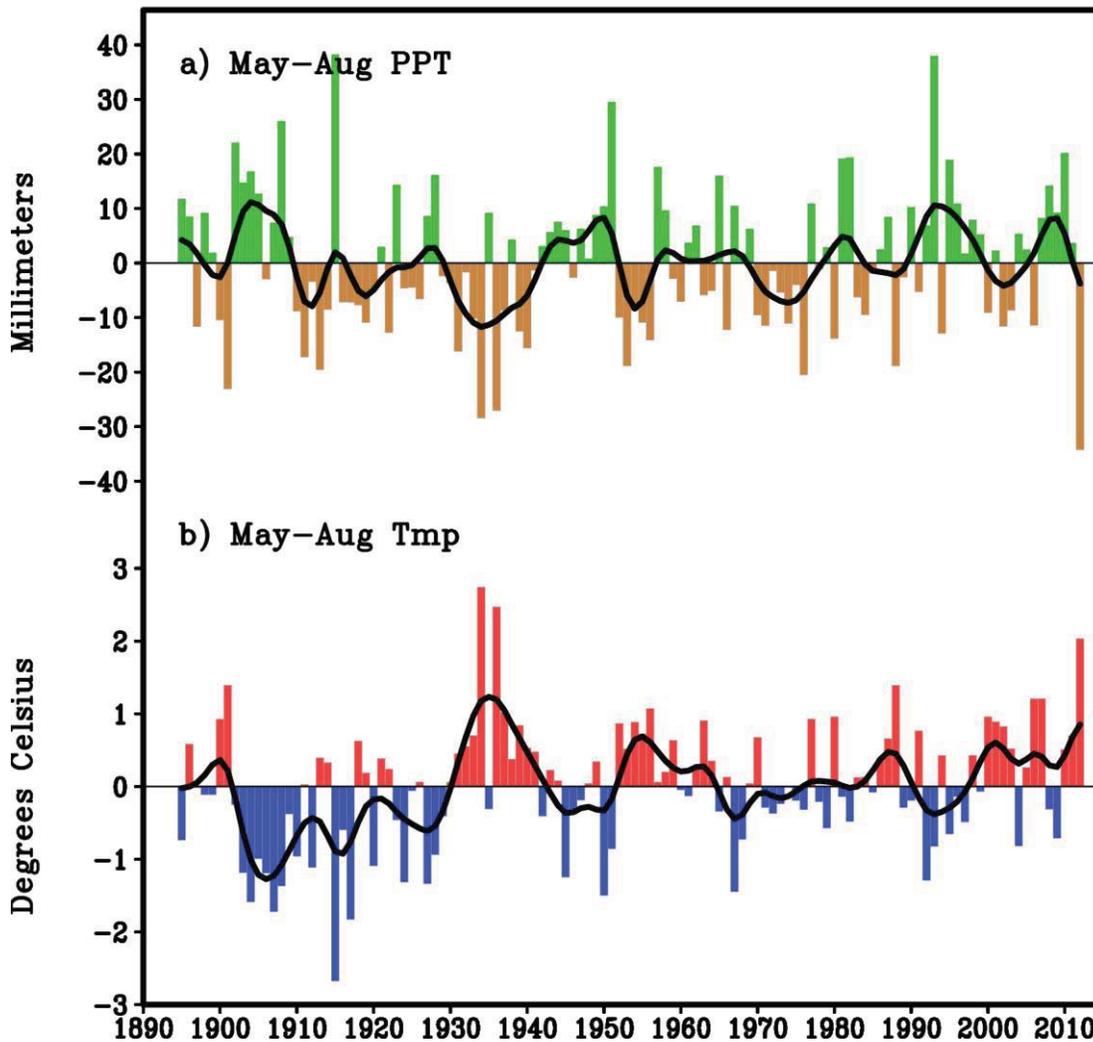
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922 **Figure 2.** Standardized anomalies averaged over May-August 2012 for a)  
923 precipitation, b) surface air temperature, c) 3-month accumulated runoff, and d) soil  
924 moisture. Precipitation data were taken from the CPC unified precipitation analysis.  
925 Temperature data were taken from the surface temperature analysis from the  
926 University of Washington. The May-August mean and standard deviation were  
927 computed using the base period 1979-2011. The contour intervals are given by the  
928 color bar. (b) same as (a). The runoff index and soil moisture are shown as  
929 percentiles, with those data taken from the ensemble mean NCEP North American  
930 Land Data Assimilation (four land surface models: Noah, Mosaic, VIC and SAC).  
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**Figure 3.** Historical U.S. corn yields from 1866 to 2012 (bushels/acre). Linear fit to different segments of the time series shown in solid lines, including regression formula. The 2012 yield is plotted in the blue circle, based on August estimates. Subsequent data revised the 2012 yield downward to about 123 bushels. Data source is USDA.

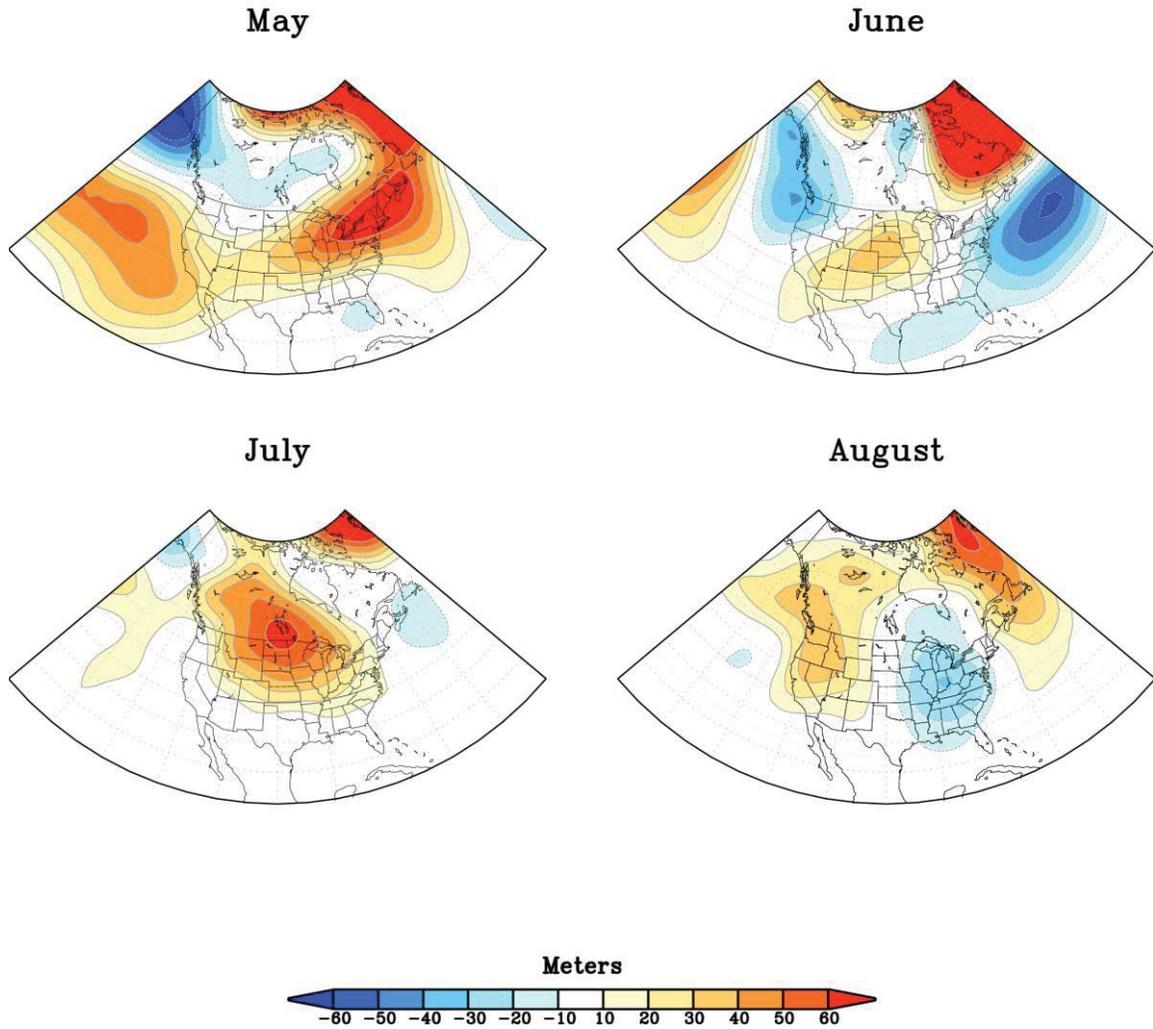
## Great Plains



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**Figure 4.** 1895-2012 time series of May-August central Great Plains rainfall departures (mm, top) and surface air temperature departures (°C, bottom). Reference period is 1895-2011. Black curve is a 9-point Gaussian filter. The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA. Data source is the NOAA U.S. Climate Divisions.

## 2012 500 hPa Geopotential Height Departures

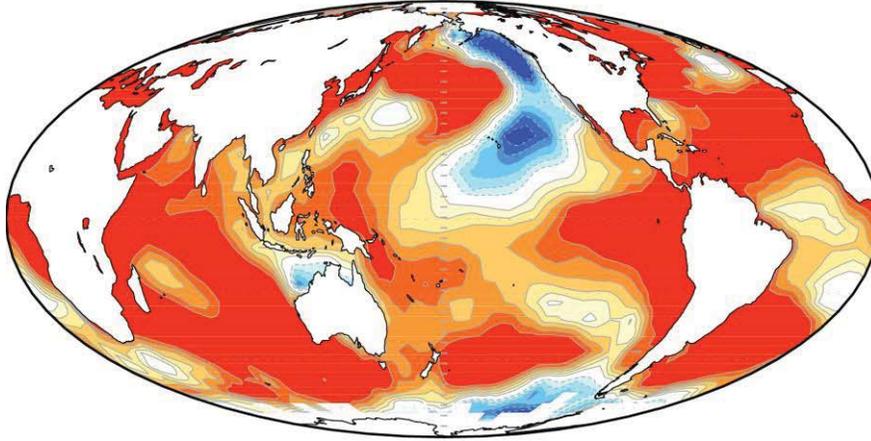


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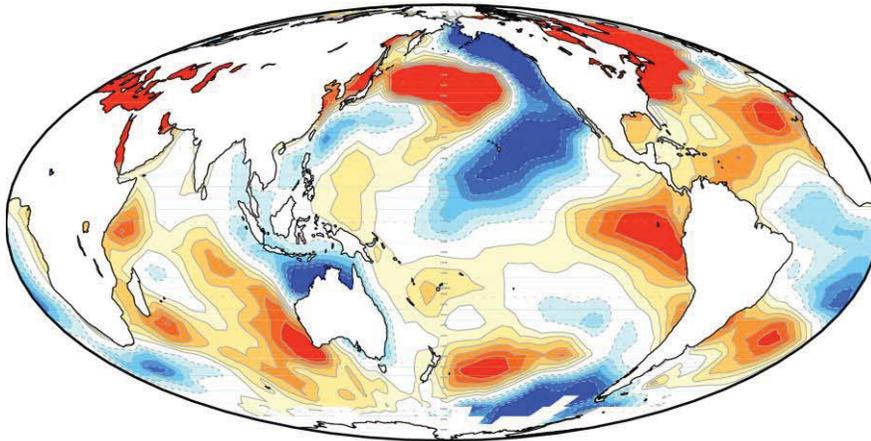
**Figure 5.** Observed monthly 500 hPa geopotential height anomalies (m) for May, June, July, and August 2012. Data from the NCEP/NCAR reanalysis, and anomalies are relative to a 1981-2010 climatology.

## May–Aug 2012 SST Departures

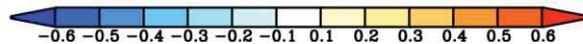
1901–1990 Reference Period



1981–2010 Reference Period



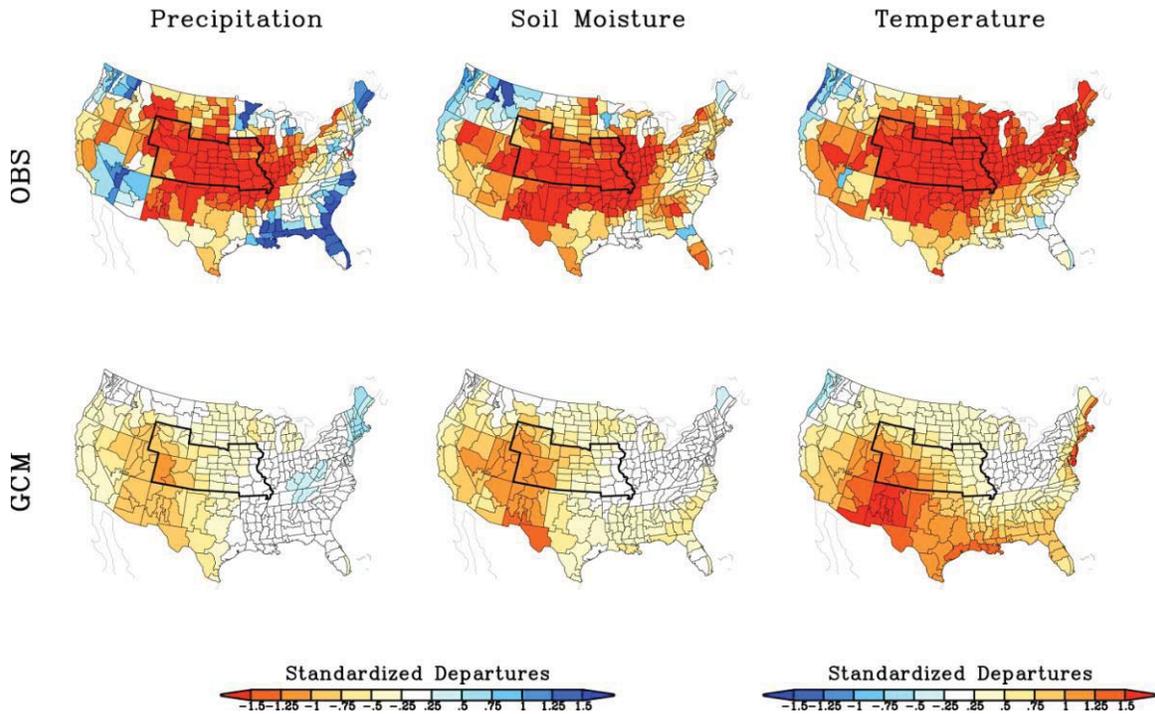
Degrees Celsius



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980 **Figure 6.** The May–August 2012 sea surface temperature anomalies (°C) calculated  
981 relative to a 1901–1990 historical reference period during which the prior nine  
982 severe Great Plains droughts occurred (top) and relative to a modern 1981–2010  
983 reference period (bottom).

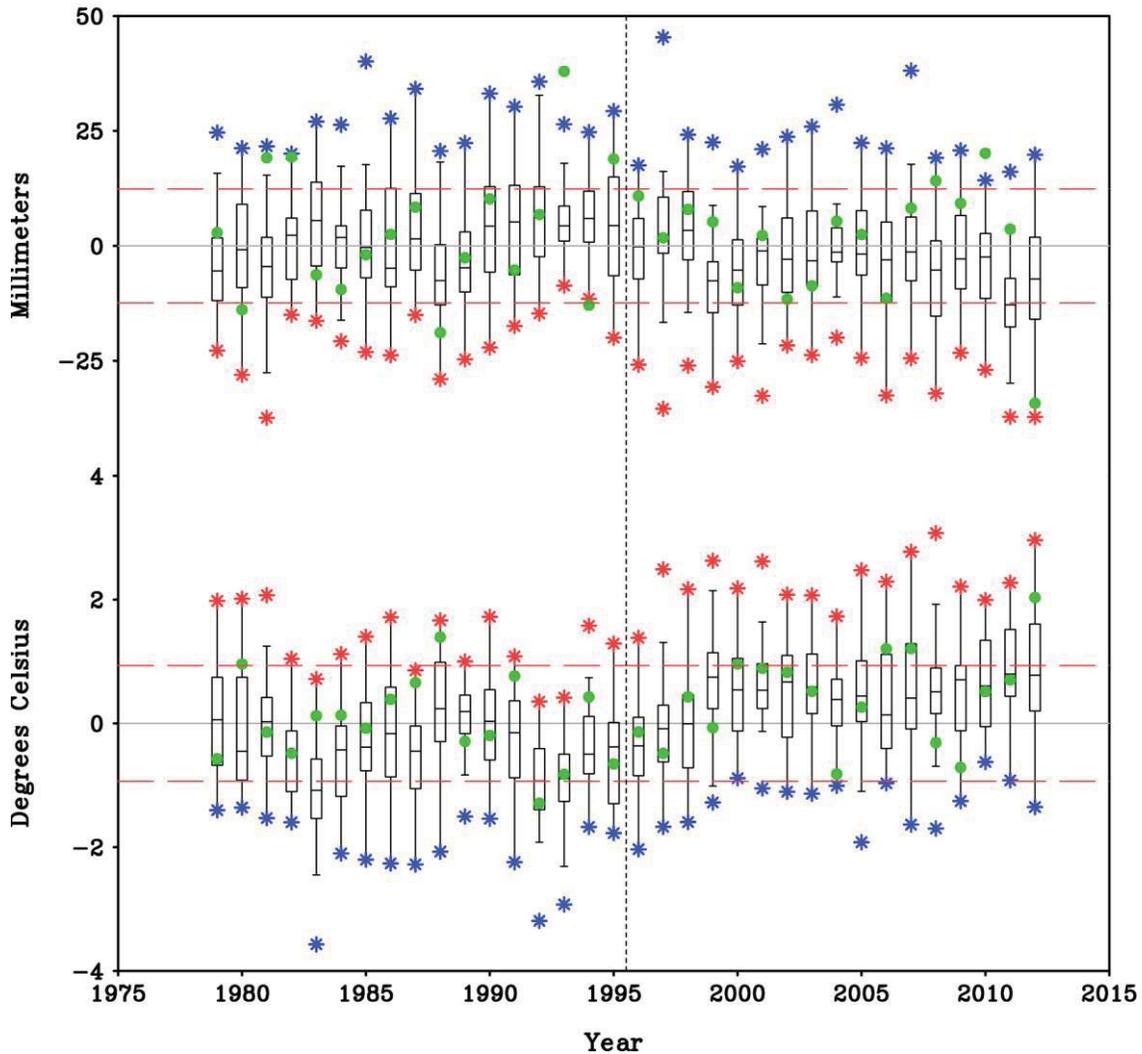
May–Aug 2012



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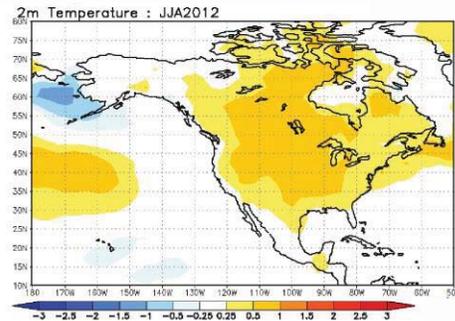
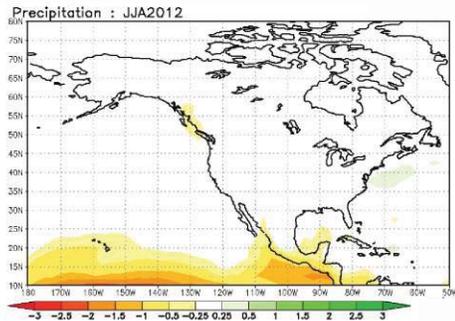
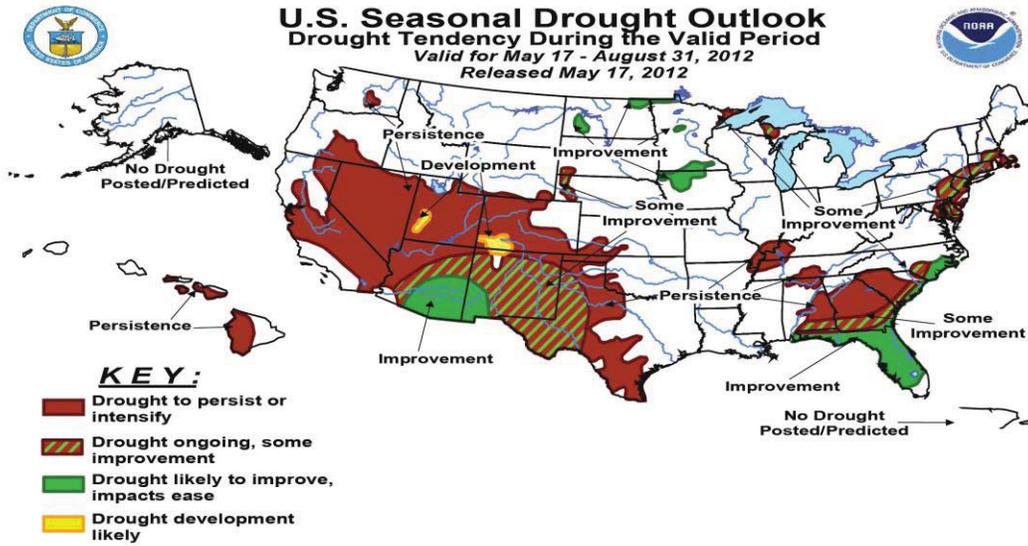
**Figure 7.** The May-August 2012 standardized anomalies of precipitation (left), soil moisture (middle), and surface air temperature (right) for observations (top) and general circulation model (GCM) simulations (bottom). Observed soil moisture estimated from the CPC a one-layer bucket water balance model driven with observations of monthly temperature and precipitation. The GCM is based on a 30-member multi-model ensemble simulation forced with the observed SSTs, sea ice, and greenhouse gas conditions for 2012. For the model data, the standardization is calculated for each separate run, and the standardized anomalies are then averaged across all 30 realizations. Period of reference is 1981-2010.

Great Plains May–Aug Precipitation(top)/Temperature(bottom)  
1979–2012



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**Figure 8.** Box-whisker plots of the May-August simulated central Great Plains rainfall anomalies (top, mm) and surface temperature anomalies (bottom, °C) for 1979-2012. The distribution summarizes the statistics of 30 simulations for each summer. Red (blue) asterisk denote the extreme dry (wet) ensemble member for each summer, and the dashed red lines are the model's 1-standardized departures of May-August precipitation and temperature. Green circles plot the observed values. The region consists of the 6-state average of WY, CO, NE, KS, MO, and IA. Anomalies are relative to a 1981-2010 reference.



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**Figure 9.** (top) The NOAA official seasonal drought outlook for the contiguous U.S. issued on May 17 2012 and valid for the period May17 – August 31 2012. (bottom) The equal-weighted composites of 12 operational centers’ seasonal predictions for June-August 2012 for North American sector precipitation departures (mm, left) and for North American sector surface temperature anomalies (°C, right). Forecasts are based on May 2012 initializations. Data source is the WMO GPC project. (<https://www.wmolc.org/>).