Causes and Predictability of the 2012 Great Plains Drought

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Abstract

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50   Central Great Plains precipitation deficits during May-August 2012 were the most

51   severe since at least 1895, eclipsing the Dust Bowl summers of 1934 and 1936.

52   Drought developed suddenly in May, following near-normal precipitation during

53   winter and early spring. Its proximate causes were a reduction in atmospheric

54   moisture transport into the Great Plains from the Gulf of Mexico. Processes that

55   generally provide air mass lift and condensation were mostly absent, including a

56   lack of frontal cyclones in late spring followed by suppressed deep convection in

57   summer owing to large-scale subsidence and atmospheric stabilization.

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59   Seasonal forecasts did not predict the summer 2012 central Great Plains drought

60   development, which therefore arrived without early warning.   Climate simulations

61   and empirical analysis suggest that neither ocean surface temperatures nor changes

62   in greenhouse gases induced a substantial reduction in summertime precipitation

63   over the central Great Plains during 2012. Yet, diagnosis of the retrospective

64   climate simulations also reveals a regime shift toward warmer and drier

65   summertime Great Plains conditions during the recent decade, most probably due to

66   natural decadal variability.   As a consequence, the probability for severe summer

67   Great Plains drought may have increased in the last decade compared to the 1980s

68   and 1990s, and the so-called tail-risk for severe drought may have been heightened

69   in summer 2012.   Such an extreme drought event was nonetheless still found to be

70   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

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1. The Drought's Morphology and Impacts

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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

98   surface moisture conditions greatly deteriorated. The U.S. Drought Monitor

99   estimated that over three-quarters of the contiguous U.S. experienced at least

100   abnormally dry conditions by summer's end with nearly half of the region,

101   especially the Great Plains, experiencing severe-unprecedented drought. Conditions

102   were comparable to those of a quarter-century earlier during 1988, and the

103   combination of rainfall deficits and high temperatures even rivaled those observed

104   during the Dust Bowl era of the 1930s.

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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

110   rainy days at Cedar Rapids, IA during May, a signature of the paucity in migratory

111   cyclones and frontal systems that have been previously identified as drought-

112   causing mechanisms for spring and some summer droughts (e.g. Dole 2000).

113   Neighboring stations also experienced prolonged stretches of rain-free days, with no

114   measurable precipitation at Omaha, NE during July consistent with an absence of

115   rain-producing thunderstorms that typically account for the bulk of mid-summer

116   rainfall in the U.S. heartland (e.g., Dai 2001). Likewise, the western Plains stations of

117   Goodland, KS and Cheyenne, WY saw only infrequent rains of light intensity during

118   July and August.   By contrast, Dallas-Fort Worth, which was near the center of the

119   prior year's southern Plains drought, accumulated above normal rainfall for the

120   prior 6-month period through summer 2012. This greatly improved their soil

121   moisture balance, and the U.S. Drought Monitor estimated that northeast Texas was

122   drought-free by May 2012. Oklahoma City also showed strong signs of recovery

123   from the 2011 drought with above average rains falling through May 2012, but then

124   skies abruptly cleared and June through July was virtually rain-free attesting to the

125   dearth of 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

137   expected from the deficient rainfall and depleted soil moisture, estimated surface

138   runoff was also in the lower decile, especially in the western Missouri and lower

139   Ohio River drainage basins (Fig. 2c).

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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).

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**

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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

178 that 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

181 rainfall. An important role for random atmospheric internal variability has also

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

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

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

185 the 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.

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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

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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.

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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

225   is the absence of processes that produce rainfall over the central Plains. These

226   include springtime low pressure systems and their attending warm and cold fronts

227   that act to lift air masses and produce widespread rains. During summertime, the

228   key process involves thunderstorms that normally occur with considerable

229   frequency and from which the majority of precipitation falls in July and August.

230   Both of these mechanisms were largely absent or inoperative to considerable

231   degree in 2012 over 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

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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

238   pressure anomalies inhibited the typical southward push of cold fronts from Canada

239   that 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

250   rainfall reduction over the central Great Plains. The impression is rendered of a

251   sequence of unfortunate events given the considerable monthly variability in the

252   upper level circulation over North America.   There were nonetheless indications of

253   more persistent planetary scale features of atmospheric circulation during summer

254   2012 that consisted of zonally averaged positive height anomalies in middle

255   latitudes and negative anomalies in subtropical latitudes (not shown).   Previous

256   studies have found such distinct zonally symmetric features of the Northern

257   Hemisphere summertime circulation to be at least weakly controlled by sea surface

258   temperature anomalies (e.g. Schubert et al., 2002; Kumar et al., 2002; Ding et al.

259   2011).   Such a global pattern entails widespread poleward shift of the prevailing

260   westerlies, and is consistent with the fact that the Eurasian grain belt also

261   experienced record heat and drought beginning in May 2012. These reduced

262   harvests together with the impacts on U.S. production resulted in substantial wheat

263   price increases world-wide (http://www.businessweek.com/news/2012-08-

264   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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5. Underlying Causes for the 2012 Drought

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

286   Why did drought occur over the central Great Plains during summer 2012 (and

287   what caused the proximate conditions discussed above)? We have already

288   surmised, from empirical analysis, that the central Plains drought was unlikely part

289   of a single multi-year drought life cycle having its incipient stage over the southern

290   Plains in late 2010 and subsequently spreading northward. Although large portions

291   of the U.S. are experiencing a third year of drought, it is plausible that various

292   phases may have had different causes (see Hoerling et al 2013; Seager et al. 2013 for

293   studies of the 2010-2011 drought).   Here we explore whether particular forcings,

294   including sea surface temperature (SST) and sea ice conditions, and also the trace

295   gas composition of the atmosphere, may have contributed to the occurrence of a

296   drought over the central 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

306   analysis 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.

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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

334   Delworth. 2010; Kushnir et al. 2010). Also, the tropical-wide SST anomalies of the

335   past year have attributes of the so-called "perfect ocean for drought" pattern, with

336   an 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). Two particular

343   aspects of the simulated sensitivity are of interest. First is the average response to

344   the specified forcings, and here we diagnose the ensemble mean response of 30

345   simulations based on 2 different climate models. Second is the so-called "tail

346   response", an assessment exploring how the probability of a particular threshold

347   exceedance (e.g., the odds of eclipsing a prior record value) changes as a

348   consequence of the specified forcing.

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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

355   Southwest and intermountain West rather than over the central Great Plains region

356   (outlined in the black box), and having magnitudes much weaker than those

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357   observed. For the central Great Plains region, the area-averaged simulated rainfall

358   deficit is about a factor of 4 less than observed, and there is virtually no dry signal

359   simulated east of the Missouri River where observed drought was quite severe.   A

360   similar assessment holds for soil moisture, though the standardized departure of the

361   model's soil moisture deficit is somewhat greater than that of its simulated rainfall

362   deficit. This reflects two factors. One is the long memory of soil moisture, and the

363   effect of a simulated signal of reduced rainfall over the Southwest during prior

364   seasons and into 2011 (not shown). The other is the strong contemporaneous

365   warming of surface air temperature during summer 2012 (right side panels) that

366   may have also contributed to land surface drying via increased evapotranspiration.

367
368   Perhaps more compelling is the indication for an increase in the probability for an

369   extreme drought event having the intensity observed in 2012.   The box-whisker

370   display in Fig. 8 shows the model distribution of its 30 simulations for summer 2012

371   (far right), and also for each summer during 1979-2012 for both rainfall (top) and

372   surface air temperature (bottom).   The overall distribution for various rainfall

373   anomaly thresholds within the 30 realizations shifts toward drier states in 2012,

374   consistent with the simulated mean signal of reduced rainfall. Interestingly, for

375   summer 2012, the extreme driest model member (red asterisk) is also the single

376   driest simulation occurring in any year during 1979-2012.

377

378   It is difficult to reliably determine the change in extreme drought event probability

379   for 2012 from such a small 30-member simulation suite. However, inspection of the

380   full 33-yr time series of such distributions suggests that the recent drought may

381   have occurred during a climate regime supporting increased likelihood for severe

382   Great Plains drought events. There is, for instance, a roughly 4-fold increase in the

383   frequency of occurrence for a 2 standardized rainfall deficit in the 17-yr period after

384   1996 compared to 17-yr period before. Once again, this is consistent with an

385   ensemble mean dry signal in the model in virtually all years in the recent period,

386   and not due to increased variability per se. The increased probability, nonetheless,

387   represents the risk of an event that remains rare within the model spread.

388

389   It is reasonable to propose, based on analysis of these model experiments that the

390   fact that a drought of such severity did occur in 2012 was largely coincidental, and

391   that such an occurrence was almost as likely during any prior year since the late

392   1990s, but more likely than in the years prior to the mid-to-late 1990s. To be sure,

393   event likelihood is seen as a low probability in any given year. Yet, it is an intriguing

394   conjecture that, while perhaps unbeknownst and undetectable from the

395   observations, the recent 10-15 year period may have been one of heightened risk for

396   the occurrence of a record setting summer drought over the central Great Plains.

397
398   The indication from the model simulations is of an abrupt shift to a warmer (Fig. 8,

399   bottom) and drier (Fig. 8, top) climate in the late 1990s over the Great Plains, at

400   least relative to the climate of the preceding decade. (This is hard to discern based

401   on the observational record alone as seen in Figure 4.) There are at least two

402   candidate mechanisms that may explain the model behavior, both associated with

403   known patterns of natural variability. One is a tropical Pacific shift with no large El

404   Niños but an abundance of strong La Niñas in the period since the 1997/98 El Niño.

405   A second is a sudden shift in North Atlantic SST conditions from a persistent cool

406   state during the 1980s to late 1990s, followed by a persistent warm state of the

407   North Atlantic thereafter, consistent with North Atlantic multi-decadal variability

408   (e.g. Delworth and Mann 2000).   Analysis of model sensitivity experiments by

409   Schubert et al. (2009) found that a combination of warm Atlantic and cool tropical

410   Pacific SST patterns produced substantial precipitation deficits and surface warming

411   for annual mean responses over the continental U.S.   The model sensitivity is

412   supported by empirical evidence for a relationship between natural multi-decadal

413   states of the Pacific and Atlantic Oceans and multi-decadal drought frequency over

414   the U.S. (McCabe et al. 2004).

415
416   An additional question these results pose is whether the simulated change in

417   extreme drought risk is a symptom of climate change forcing related to global

418   warming. There are several indications that this behavior is largely unrelated to the

419   model's sensitivity to gradually increasing anthropogenic forcing. One indication is

420   the rather sudden character of change in model simulations toward dry conditions

421   in the late 1990s. Though one cannot dismiss the possibility that a steady forcing

422   (for instance increasing CO_2) may provoke an abrupt change in responses, there are

423   other plausible physical explanations for the shift in model behavior in the 1990s

424   including natural swings in ocean states as mentioned above.   A second issue

425   concerns the lack of any appreciable long-term change in seasonal mean climate

426   during summer over the central Great Plains since 1895 (see Fig. 4). Nor has there

427   been an indication for an increasing trend in the occurrences of severe summer

428   droughts over the region, with the last severe drought happening a quarter century

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429   earlier.   Additional analysis will be required to assess the role of global warming on

430   recent precipitation variability over the Great Plains using the full suite of Climate

431   Model Intercomparison Project (CMIP5) models.

432
433   **6. Predictions of the 2012 Drought**
434
435   The summer 2012 central Great Plains drought developed without an early warning.

436   NOAA's operational seasonal drought outlook, issued 17 May 2012 for the

437   subsequent June-August period (Fig. 9, top), did not predict a tendency toward

438   increasing drought over the central Great Plains. Instead, surface moisture

439   conditions were expected to improve over Iowa and western Nebraska. Otherwise,

440   the majority of the central Great Plains was forecast to experience near normal

441   moisture conditions. Only over the interior West was drought expected to persist or

442   intensify.

443

444   The drought outlook reflected three primary considerations. One was the initial

445   monitored state of drought, for which the U.S. Drought Monitor revealed surface

446   moisture over the Great Plains had appreciably recovered during winter/early

447   Spring.   The second was the seasonal rainfall forecast, which did not yield strong

448   guidance on the summer rainfall pattern. For instance, the May 2012 initialized

449   predictions for June-August based on the composite of 12-centers' seasonal forecast

450   systems showed no appreciable rainfall signal (Fig. 9, bottom left), although it did

451   indicate a widespread large amplitude warm signal (Fig. 9, bottom right).

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453   A third consideration for the drought outlook was the expectation for rainy season

454   onset. The climatological normal rainy season over the Great Plains is May-

455   August. Since empirical and dynamical tools gave no strong reason to suspect it

456   wouldn't arrive as usual, those rains were expected to alleviate existing surface

457   moisture deficits.   In many ways, the drought outlook and the results from

458   initialized coupled model predictions are thus consistent with the retrospective

459   climate simulations presented in Section 5, though there may be additional useful

460   information in the ensemble spread of the retrospective climate simulations that

461   were not readily available to the forecasters.

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464   **7. Summary Comments on the 2012 Drought and Implications for Forecasting**
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466   *a. Overall Assessment of Origin and Cause*
467
468   The 2012 drought developed rapidly over the central Great Plains during May and

469   reached peak intensity by August.   In many ways, the event was a "flash drought",

470   owing to the unusual speed and intensity with which it developed and became

471   entrenched over the Great Plains in summer. The 4-month cumulative rainfall

472   deficit, averaged over a 6-state area of the central Great Plains, was the greatest

473   since record keeping began in 1895, ranking this event as the most severe

474   summertime seasonal drought over the central Great Plains in 117 years, eclipsing

475   1988, 1934 and 1936.   The immediate cause for the drought was predominately

476   meteorological in nature. This involved reduced Gulf of Mexico moisture transport

477   and reduced cyclone and frontal activity in late spring. It also involved an inhibition

478   of summer convection resulting from increased subsidence and atmospheric

479 stabilization that accompanied an anomalous upper tropospheric high pressure

480 over the region.   The drought can thus be seen as the symptom of classical

481 meteorological conditions that control the region's warm season rains.

482
483 The 2012 summertime central Great Plains drought resulted mostly from natural

484 variations in weather. The assessment did not find substantial evidence for

485 underlying causes associated with the effects of long-lived boundary forcings.

486 Retrospective climate simulations identify a mean dry signal during 2012 summer

487 having a magnitude 4 times weaker than that observed for an area-average of the

488 Great Plains region. Indicated hereby is that neither the variations in ocean states

489 nor in greenhouse gases played significant roles in determining the intensity of the

490 rainfall deficits in summer 2012.   Furthermore, analysis of the retrospective

491 climate simulations found virtually no dry signal over major corn producing regions

492 of the eastern Great Plains including most of Missouri, Iowa, southern Wisconsin,

493 Illinois, and Indiana where severe drought occurred and resulted in major

494 curtailment of corn crop yields, indicating that neither the variations in ocean states

495 nor in greenhouse gases played significant roles in determining the precise location

496 of rainfall deficits during summer 2012.   The simulations did reveal, however, a

497 more substantial drying over the Southwest U.S and the far western Great Plains

498 especially New Mexico, Colorado, western Nebraska, western Kansas, and Wyoming.

499 These areas also suffered severe drought in 2012.

500

501 A few words are in order concerning the model suggestion of a regime shift to

502 warmer and drier summers over the last 10-15 years, especially over the Southwest

503 U.S. and western Plains. The underlying tendency since the late 1990s for drought

504 conditions over the U.S. has a plausible physical basis, being likely linked to natural

505 states of the Pacific and Atlantic Oceans. In this sense, while the 2012 drought was

506 not well predicted, it perhaps should not be a surprise that a drought of some

507 severity occurred (see also McCabe et al. 2004).   Large portions of the U.S. are

508 experiencing a third year of drought, although the Central Plains drought of 2012

509 was not a simple progression or northward creeping of the prior year's Southern

510 Plains drought event.   Further, the southwestern U.S. has been overwhelmingly in a

511 state of abnormally dry or drought conditions since 1998. This widespread state of

512 dryness appears at least qualitatively consistent with a longer time scale climate

513 control associated with natural oceanic variability.   In the Southwest it is also

514 consistent with the expected climate response to rising greenhouse gases (e.g.,

515 Seager and Vecchi 2010), though that influence on precipitation is likely smaller at

516 the current time than the influence of natural long term variability. However,

517 despite the role of these ocean and radiative boundary conditions in tilting the odds

518 towards a dry state, the peculiar severity of summer 2012 can only be explained by

519 an additional heavy role for random weather variability.

520

521 *b. Implications for Drought Prediction*

522 What are some of the lessons learned in this assessment concerning U.S. drought

523 forecasting?   On the one hand, the appraisal offered herein paints a picture of an

524 extreme event that apparently had limited potential for skillful prediction. This

525 conclusion would thus appear to be consistent, and furthermore offer an

526   explanation for, the poor performance of both official forecasts of drought and

527   numerical predictions of rainfall that were rendered in late May 2012 for the

528   subsequent June-August 2012 season. On the other hand, our diagnosis of the

529   spread among an ensemble of retrospective climate simulations indicates an

530   increased probability for an extreme Great Plains drought event in 2012. For

531   instance, the single driest simulation for Great Plains summer conditions, among the

532   sample of 990 summer simulations during the entire 1979-2012 period analyzed

533   herein (30-members for each year of the 33-year period), occurred in the suite of

534   2012 runs. The models thus reveal that so-called tail-risk was heightened in

535   summer 2012. Furthermore, these same simulations indicate that the statistical

536   likelihood for a severe summer drought occurring over the Great Plains during the

537   last decade may have been several-fold greater than the odds of occurrence during

538   the prior period spanning the 1980s and 1990s. The retrospective analysis thus

539   argues for elevated risk of an extreme drought event, even though the precise timing

540   of any single event was uncertain, and the overall strength of the signal on *seasonal*

541   *mean rainfall* was quite small.

542

543   Given the existing practices of operational drought prediction, what might have

544   been the impact on the forecast process if various information contained in this

545   assessment had been available in early 2012? It is useful to frame that question in

546   the context of expected skill. The history of operational seasonal forecast

547   performance reveals little or no skill for U.S. summer rainfall since routine forecasts

548   were issued beginning in the mid-1990s . Furthermore, an assessment of U.S.

22

549   drought hindcast skill over a longer period since 1982 recently concluded that

550   dynamical seasonal predictions did not materially increase summer skill over the

551   Great Plains beyond a persistence forecast benchmark (Quan et al. 2012).   The

552   reason given for the limited overall skill was small SST sensitivity of that region's

553   summer rainfall and a small impact of antecedent soil moisture conditions, on

554   average, upon the region's summer rainfall.

555

556   A pathway forward for summer drought prediction might thus be to consider

557   conditional skill, and to identify so-called "events of opportunity". There are ample

558   examples of those for rainfall and drought during the cold season in the southern

559   U.S. associated with the strong conditioning by the El Niño/Southern Oscillation

560   phenomenon.   For instance, there was considerable skill in the seasonal forecasts of

561   the 2010-11 southern Plains drought, especially during the winter and spring

562   season (e.g. Hoerling et al. 2013). The current study builds upon a body of climate

563   sensitivity studies and physical reasoning that a conditioning of U.S. summer rainfall

564   by particular large-scale oceanic conditions may also exist (e.g. Schubert et al. 2009;

565   Findell and Delworth 2010). Yet, contrary to ENSO effects, the magnitude of that

566   conditioning is still highly uncertain and requires further investigation before it can

567   be quantitatively incorporated into seasonal forecasts.

568

569   One of the opportunities for improving seasonal drought predictions is to move

570   toward expressing the outlooks in a probabilistic manner, as is done currently for

571   seasonal forecasts of precipitation and surface temperature. The current drought

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572   outlook product is deterministic, notwithstanding some subjective language that

573   attempts to express the most probable tendency of drought conditions over the

574   upcoming season.   The full information of ensemble prediction systems, in

575   particular the spread information contained in such tools, can thus not be readily

576   incorporated into current practices for U.S. drought forecasting.   Further research

577   is also required on evaluating the spread information on drought statistics from

578   such ensemble modeling systems. Much has yet to be learned about the robustness

579   of spreads across multi-models, and how those spreads differ when examined in

580   simulation mode (using uninitialized models) versus prediction mode (using

581   initialized models). In the case of the 2012 drought, for instance, it remains to be

582   determined if the particular event's probability was materially conditioned by

583   antecedent soil moisture.

584

585   A related issue is the need to reconcile the identification of a modest Great Plains

586   dry signal in the retrospective climate simulations studied herein with the lack of

587   any dry signal in the summertime 2012 predictions of the WMO GPC multi-model

588   ensemble. It is unclear if this was a consequence of errors in the SST predictions.

589   Did the process of averaging 12 different models and merging them in producing the

590   GPC forecast cause large cancellation among appreciably different signals occurring

591   in individual models? Or was the ensemble mean prediction for drier than normal

592   conditions in these models simply too small in amplitude, and thus perhaps deemed

593   unreliable to include in the forecasts?

594

595   One might reasonably wonder, given the suggestion from the rainfall time series

596   produced in the retrospective climate simulations, whether the risk of a severe

597   Great Plains drought is once again elevated in 2013 or beyond. Clarification will

598   require better knowledge of the factors controlling the low frequency variability of

599   Great Plains moisture conditions.   The analysis presented here has mainly proposed

600   the roles of long time scale natural variability in sea surface temperatures. And,

601   while this study is not intended to be a comprehensive assessment of the possible

602   effects of global warming on the 2012 central Plains drought, the results here are

603   inconclusive on that specific question.   Here we merely note the conclusion of the

604   U.S. Climate Change Science Program Synthesis and Assessment Products (SAP 1.3,

605   2008) that SST anomalies have been important in forcing some multi-year severe

606   droughts over the U.S. during the last half-century, whereas short-term droughts

607   ("flash droughts" having monthly-seasonal time scales) were judged to be mostly

608   due to atmospheric variability, in some cases amplified by local soil moisture

609   conditions. The report assessed that it is unlikely that a systematic change has

610   occurred in either the frequency or area-coverage of drought over the contiguous US

611   from the mid-20th century to the present. Subsequently, in 2012, the Special Report

612   of the Intergovernmental Panel on Climate Change (IPCC) regarding extreme events

613   expressed only medium confidence in a *projected* increase in drought in some

614   regions by end of the 21st Century, including the southern Great Plains and Mexico,

615   but not the northern Plains and Midwest regions. How Great Plains drought will

616   respond under global warming therefore continues to be a key unresolved question

617   and a matter of future research.

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619 **Acknowledgments**
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Appendix 1: Climate Model Simulations

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784   Two global atmospheric models are run over the period 1979-2012. The only

785   constraining information representing observed conditions in these simulations is

786   the sea surface temperature, sea ice, and external radiative forcing which are

787   specified in the model as monthly time evolving boundary conditions from January

788   1979- December 2012. Climate simulations of this type are referred to as 'AMIP

789   (Atmospheric Model Intercomparison Project)' experiments, and are designed to

790   determine the sensitivity of the atmosphere, and the extent to which its temporal

791   evolution is constrained by known boundary forcings.

792

793   Key to this modeling technique for assessing the impact of boundary conditions is

794   an ensemble approach, whereby the period of simulation is repeated a multitude of

795   times. Here simulations that have been repeated 30 times (a 30-member ensemble),

796   and which differ from one another only in the initial atmospheric conditions in

797   January 1979 but in which identical time evolving forcings are specified, are

798   analyzed. The strategy is to average the monthly variability across the 30 members

799   in order to determine the mean response to specified forcings. The process of

800   averaging eliminates the random internal variability of the atmosphere, and

801   facilitates identifying the coherent signal from the forcing.

802

803   One model used is the National Center for Atmospheric Research (NCAR) CAM4

804   global climate model (Gent et al. 2011), with the simulations performed at a 1°

805   (~100 km) resolution and 26 atmospheric, and for which a 20-member ensemble is

806   available. The second global climate model is the European Center Hamburg model

807   version 5 (ECHAM5; Roeckner et al 2003), with simulations performed at T159

808   (~80km) resolution and 31 atmospheric levels, and for which a 10-member

809   ensemble is available. In both models, monthly varying SSTs and sea ice and the

810   external radiative forcings consisting of greenhouse gases (e.g. CO_2, CH_4, NO_2, O_3,

811   CFCs) are specified. CAM4 runs also specify varying anthropogenic aerosols, solar,

812   and volcanic aerosols. The model output has been interpolated to U.S. climate

813   divisions to facilitate comparison with observations.   Ensemble means are

814   computed by doing simple equal weighted averages of the CAM4 and ECHAM5 20-

815   member and 10-member averages, respectively.

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Figure Captions

838 Figure 1. Daily precipitation (mm) time series during 2012 for indicated stations.

839 For each station, top portions show the climatological precipitation (smooth curve),

840 the actual 2012 precipitation, and their difference (color shading; brown denotes a

841 deficit, green a surplus). Lower portions show the occurrences of daily precipitation

842 events. Data source is NOAA Climate Prediction Center.

843

844 Figure 2. Standardized anomalies averaged over May-August 2012 for a)

845 precipitation, b) surface air temperature, c) 3-month accumulated runoff, and d) soil

846 moisture. Precipitation data were taken from the CPC unified precipitation

847 analysis. Temperature data were taken from the surface temperature analysis from

848 the University of Washington. The May-August mean and standard deviation were

849 computed using the base period 1979-2011. The contour intervals are given by the

850 color bar. (b) same as (a). The runoff index and soil moisture are shown as

851 percentiles, with those data taken from the ensemble mean NCEP North American

852 Land Data Assimilation (four land surface models: Noah, Mosaic, VIC and SAC).

853

854 Figure 3. Historical U.S. corn yields from 1866 to 2012 (bushels/acre). Linear fit to

855 different segments of the time series shown in solid lines, including regression

856 formula. The 2012 yield is plotted in the blue circle, based on August estimates.

857 Subsequent data revised the 2012 yield downward to about 123 bushels. Data

858 source is USDA.

859

860   Figure 4. 1895-2012 time series of May-August central Great Plains rainfall

861   departures (mm, top) and surface air temperature departures (°C, bottom).

862   Reference period is 1895-2011. Black curve is a 9-point Gaussian filter. The area is

863   comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.

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

865

866   Figure 5. Observed monthly 500 hPa geopotential height anomalies (m) for May,

867   June, July, and August 2012. Data from the NCEP/NCAR reanalysis, and anomalies

868   are relative to a 1981-2010 climatology.

869

870   Figure 6. The May-August 2012 sea surface temperature anomalies (°C) calculated

871   relative to a 1901-1990 historical reference period during which the prior nine

872   severe Great Plains droughts occurred (top) and relative to a modern 1981-2010

873   reference period (bottom).

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875   Figure 7. The May-August 2012 standardized anomalies of precipitation (left), soil

876   moisture (middle), and surface air temperature (right) for observations (top) and

877   general circulation model (GCM) simulations (bottom). Observed soil moisture

878   estimated from the CPC a one-layer bucket water balance model driven with

879   observations of monthly temperature and precipitation. The GCM is based on a 30-

880   member multi-model ensemble simulation forced with the observed SSTs, sea ice,

881   and greenhouse gas conditions for 2012. For the model data, the standardization is

882   calculated for each separate run, and the standardized anomalies are then averaged

883   across all 30 realizations. Period of reference is 1981-2010.

884

885   Figure 8. Box-whisker plots of the May-August simulated central Great Plains

886   rainfall anomalies (top, mm) and surface temperature anomalies (bottom, °C) for

887   1979-2012. The distribution summarizes the statistics of 30 simulations for each

888   summer. Red (blue) asterisk denote the extreme dry (wet) ensemble member for

889   each summer, and the dashed red lines are the model's 1-standardized departures

890   of May-August precipitation and temperature. Green circles plot the observed

891   values. The region consists of the 6-state average of WY, CO, NE, KS, MO, and IA.

892   Anomalies are relative to a 1981-2010 reference.

893

894   Figure 9. (top) The NOAA official seasonal drought outlook for the contiguous U.S.

895   issued on May 17 2012 and valid for the period May17 – August 31 2012. (bottom)

896   The equal-weighted composites of 12 operational centers' seasonal predictions for

897   June-August 2012 for North American sector precipitation departures (mm, left)

898   and for North American sector surface temperature anomalies (°C, right).   Forecasts

899   are based on May 2012 initializations. Data source is the WMO GPC project.

900   (https://www.wmolc.org/).

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Daily Precipitation 1 Jan 2012−31 Dec 2012

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

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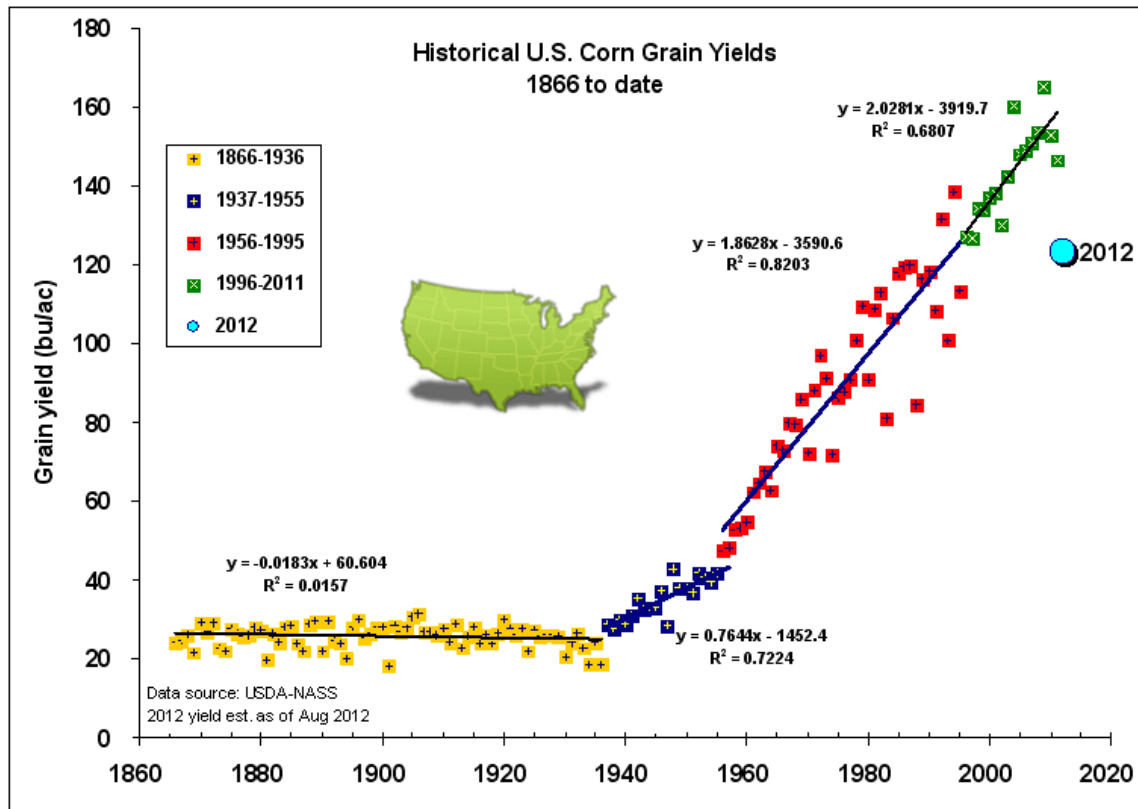
Figure 3. Historical U.S. corn yields from 1866 to 2012 (bushels/acre). Linear fit to different segments of the time series shown in solid lines, including regression formula. The 2012 yield is plotted in the blue circle, based on August estimates. Subsequent data revised the 2012 yield downward to about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

Great Plains

a) May–Aug PPT

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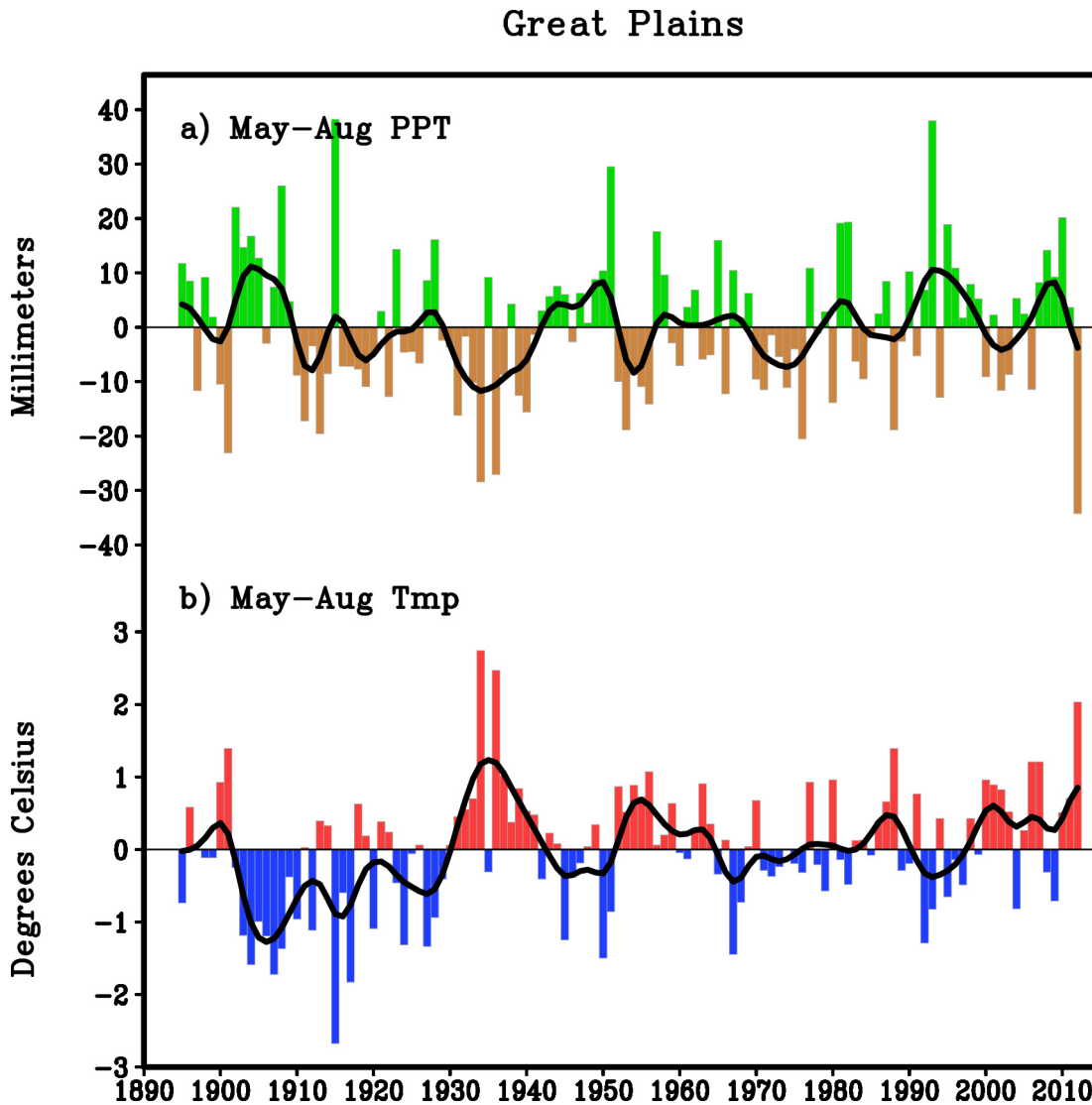
Figure 4. 1895-2012 time series of May-August central Great Plains rainfall departures (mm, top) and surface air temperature departures (°C, bottom). Reference period is 1895-2011.   Black curve is a 9-point Gaussian filter.   The area is comprised of the 6-State region of WY, CO, NE, KS, MO, and IA.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

2012 500 hPa Geopotential Height Departures
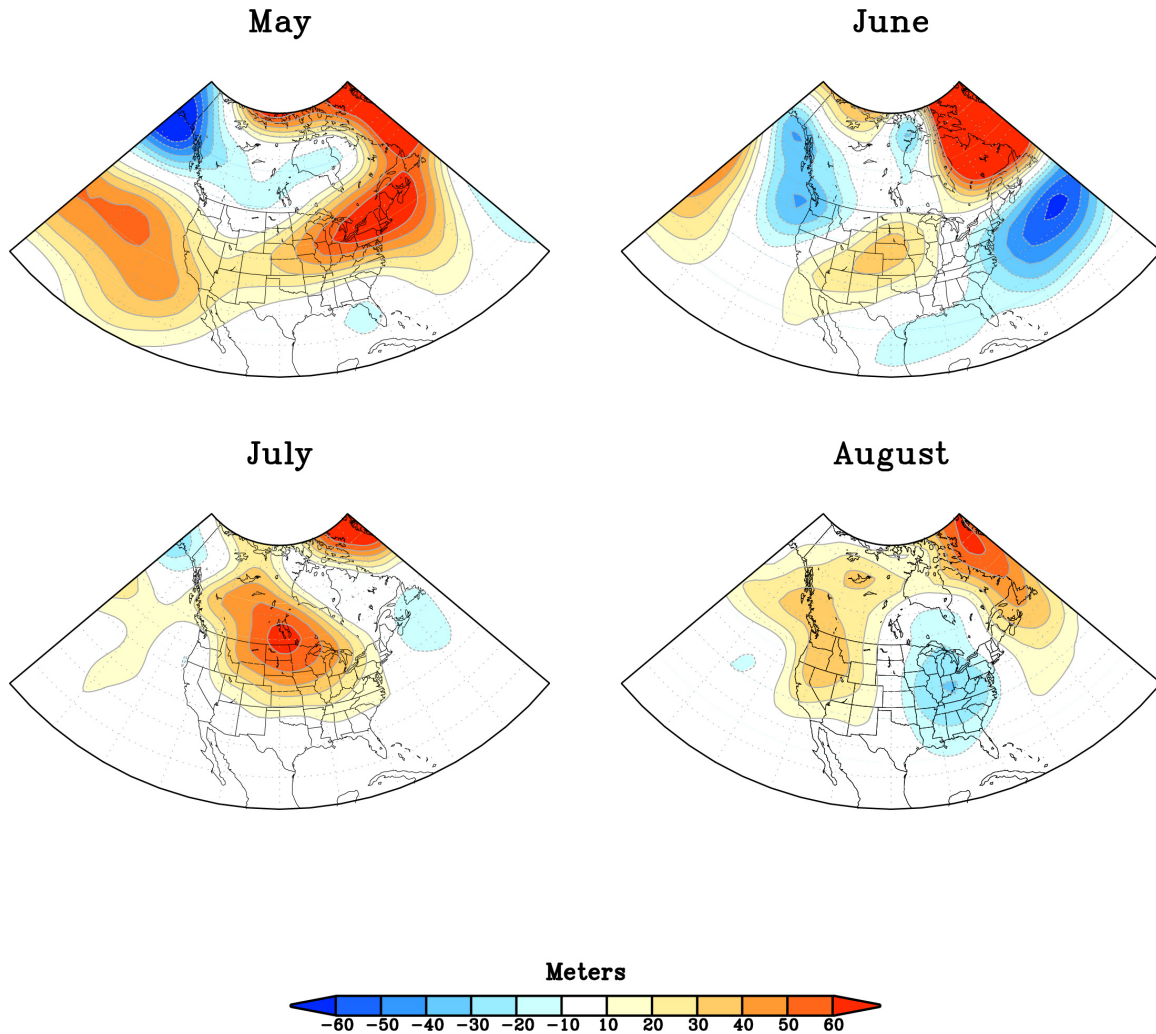
May

June

July

August

Meters

−60 −50 −40 −30 −20 −10 10 20 30 40 50 60

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

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May−Aug 2012 SST Departures

1901−1990 Reference Period
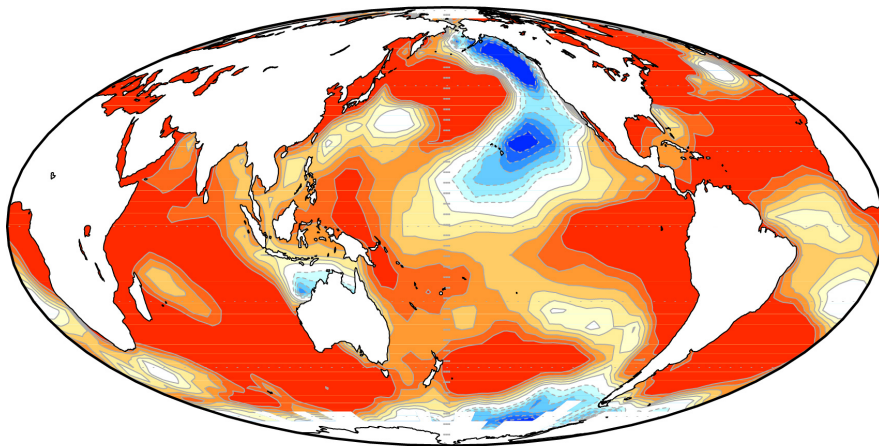
1981−2010 Reference Period
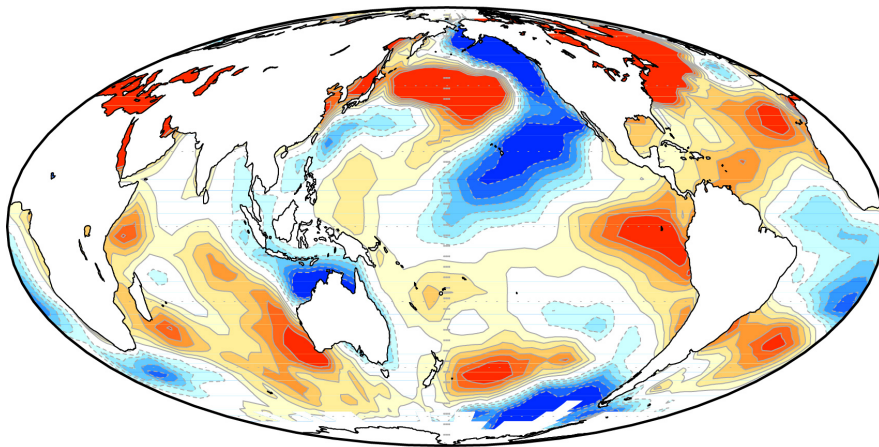
Degrees Celsius
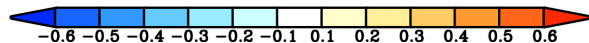
Figure 6. The May-August 2012 sea surface temperature anomalies (°C) calculated relative to a 1901-1990 historical reference period during which the prior nine severe Great Plains droughts occurred (top) and relative to a modern 1981-2010 reference period (bottom).

May−Aug 2012

Precipitation   Soil Moisture   Temperature
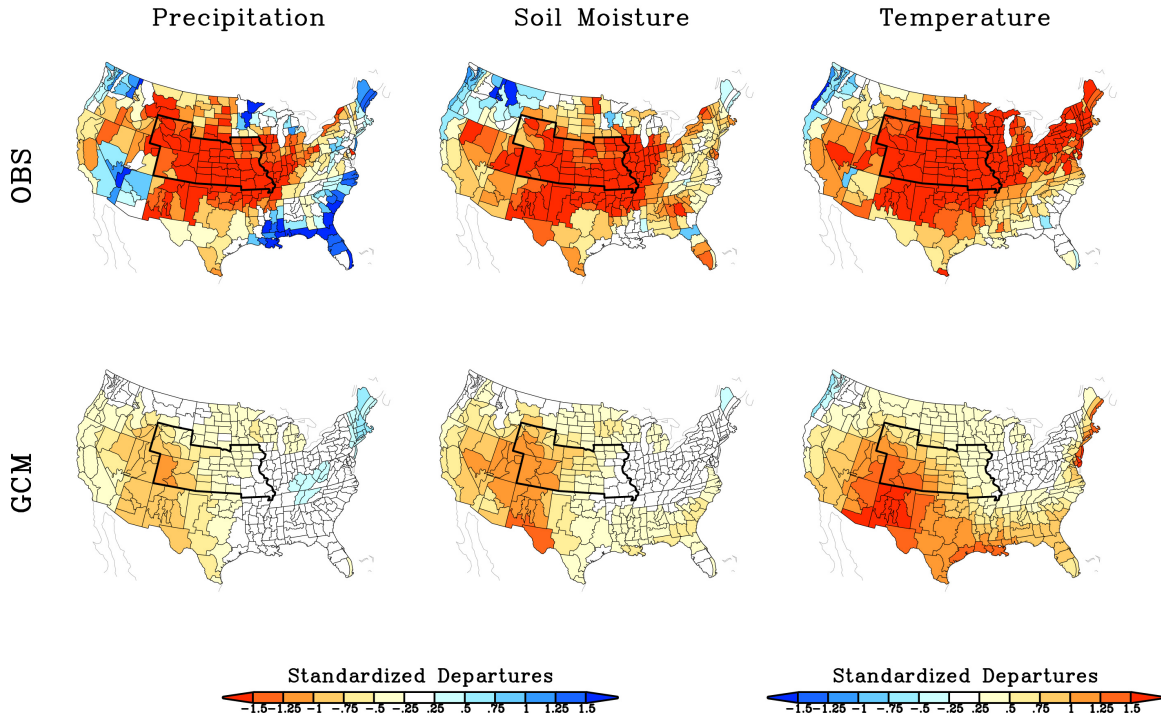
Figure 7. The May-August 2012 standardized anomalies of precipitation (left), soil
moisture (middle), and surface air temperature (right) for observations (top) and
general circulation model (GCM) simulations (bottom). Observed soil moisture
estimated from the CPC a one-layer bucket water balance model 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)
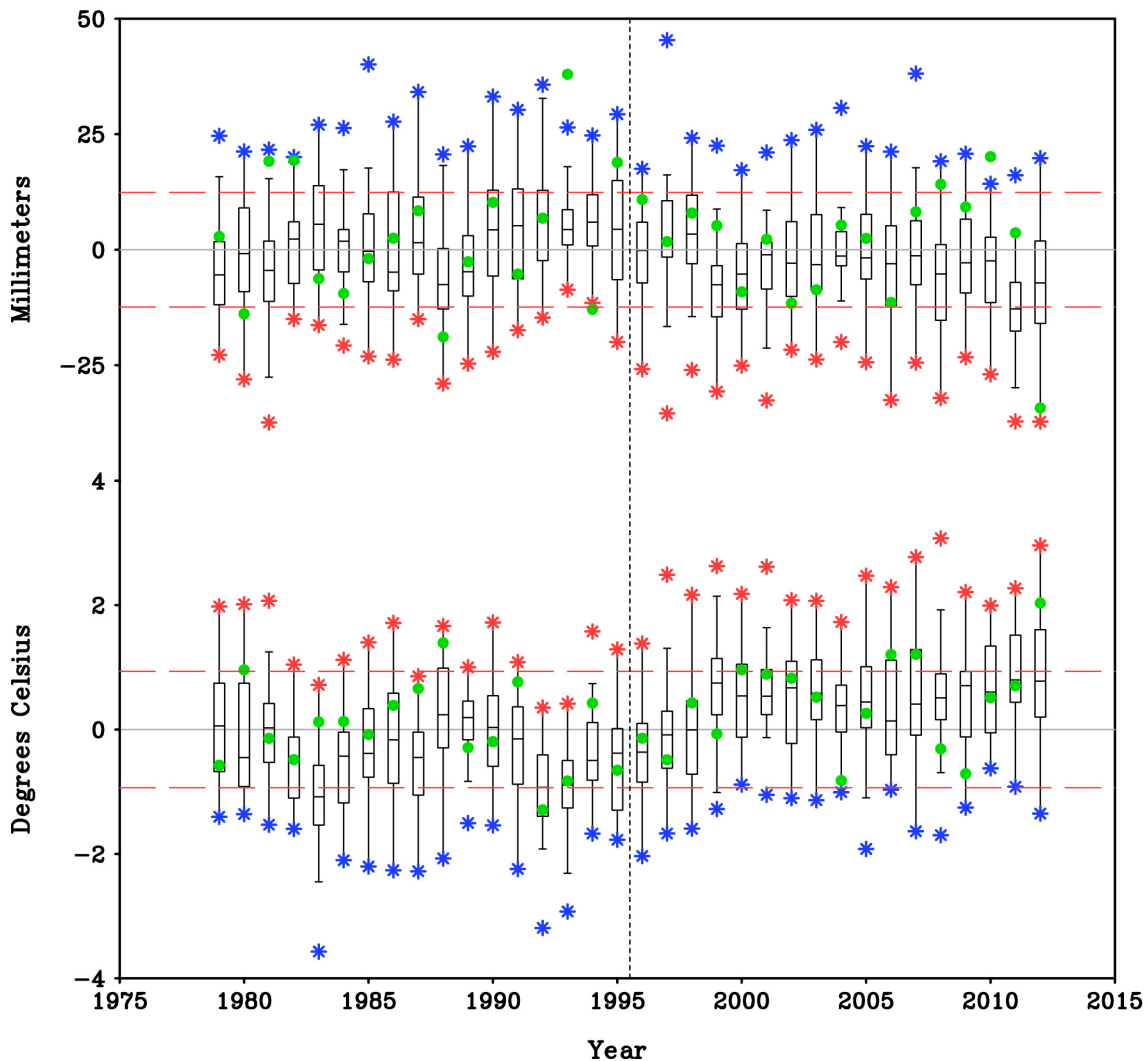1979−2012**

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.
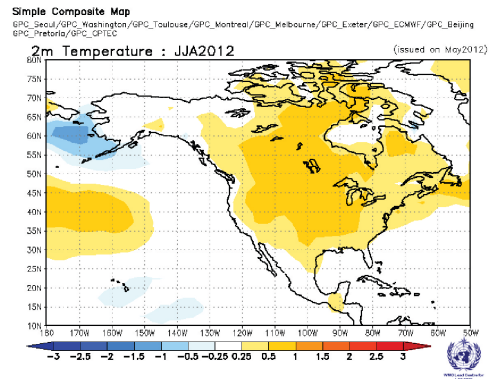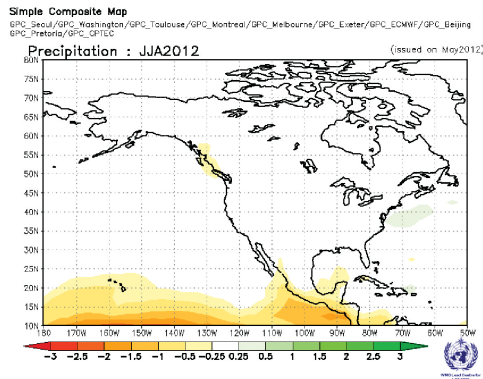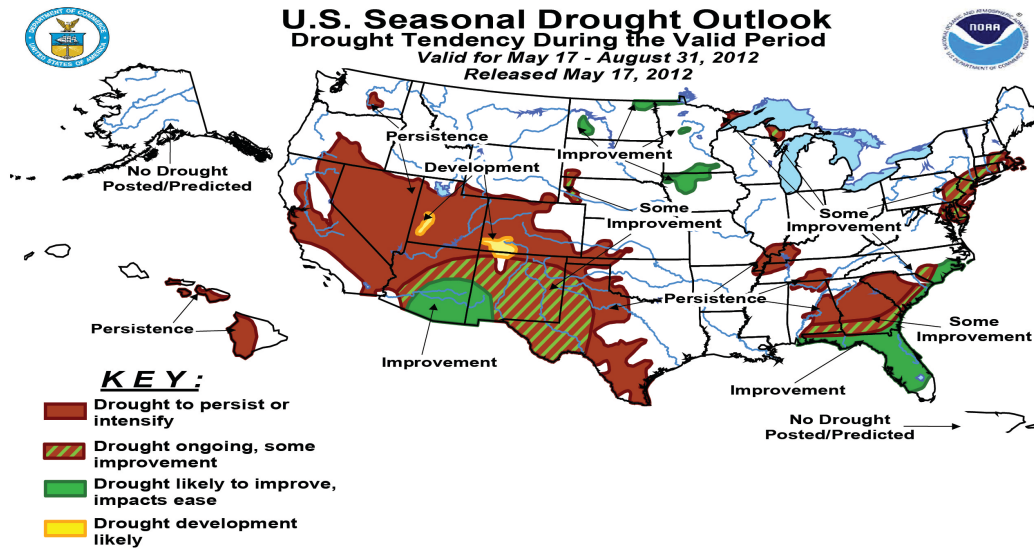
Figure 9. (top) The NOAA official seasonal drought outlook for the contiguous U.S.
issued on May 17 2012 and valid for the period May17 – August 31 2012. (bottom)
The equal-weighted composites of 12 operational centers' seasonal predictions for
June-August 2012 for North American sector precipitation 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/).