

Climate change in the Fertile Crescent and implications of the recent Syrian drought

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Before the Syrian uprising that began in 2011, the greater Fertile Crescent experienced the most severe drought in the instrumental record. For Syria, a country marked by poor governance and unsustainable agricultural and environmental policies, the drought had a catalytic effect, contributing to political unrest. We show that the recent decrease in Syrian precipitation is a combination of natural variability and a long-term drying trend, and the unusual severity of the observed drought is here shown to be highly unlikely without this trend. Precipitation changes in Syria are linked to rising mean sea-level pressure in the Eastern Mediterranean, which also shows a long-term trend. There has been also a long-term warming trend in the Eastern Mediterranean, adding to the drawdown of soil moisture. No natural cause is apparent for these trends, whereas the observed drying and warming are consistent with model studies of the response to increases in greenhouse gases. Furthermore, model studies show an increasingly drier and hotter future mean climate for the Eastern Mediterranean. Analyses of observations and model simulations indicate that a drought of the severity and duration of the recent Syrian drought, which is implicated in the current conflict, has become more than twice as likely as a consequence of human interference in the climate system.

drought | Syria | climate change | unrest | conflict

Beginning in the winter of 2006/2007, Syria and the greater Fertile Crescent (FC), where agriculture and animal herding began some 12,000 years ago (1), experienced the worst 3-year drought in the instrumental record (2). The drought exacerbated existing water and agricultural insecurity and caused massive agricultural failures and livestock mortality. The most significant consequence was the migration of as many as 1.5 million people from rural farming areas to the peripheries of urban centers (3, 4). Characterizing risk as the product of vulnerability and hazard severity, we first analyze Syria's vulnerability to drought and the social impacts of the recent drought leading to the onset of the Syrian civil war. We then use observations and climate models to assess how unusual the drought was within the observed record and the reasons it was so severe. We also show that climate models simulate a long-term drying trend for the region as a consequence of human-induced climate change. If correct, this has increased the severity and frequency of occurrence of extreme multiyear droughts such as the recent one. We also present evidence that the circulation anomalies associated with the recent drought are consistent with model projections of human-induced climate change and aridification in the region and are less consistent with patterns of natural variability.

Heightened Vulnerability and the Effects of the Drought

Government agricultural policy is prominent among the many factors that shaped Syria's vulnerability to drought. Despite growing water scarcity and frequent droughts, the government of President Hafez al-Assad (1971–2000) initiated policies to further increase agricultural production, including land redistribution and irrigation projects, quota systems, and subsidies for diesel fuel to garner the support of rural constituents (5–9). These policies endangered

Syria's water security by exploiting limited land and water resources without regard for sustainability (10).

One critical consequence of these unsustainable policies is the decline of groundwater. Nearly all rainfall in the FC occurs during the 6-month winter season, November through April, and this rainfall exhibits large year-to-year variability (Figs. 1*A* and 2*A*). In Syria, the rain falls along the country's Mediterranean Sea coast and in the north and northeast, the primary agricultural region. Farmers depend strongly on year-to-year rainfall, as two thirds of the cultivated land in Syria is rain fed, but the remainder relies upon irrigation and groundwater (11). For those farms without access to irrigation canals linked to river tributaries, pumped groundwater supplies over half (60%) of all water used for irrigation purposes, and this groundwater has become increasingly limited as extraction has been greatly overexploited (4). The government attempted to stem the rate of groundwater depletion by enacting a law in 2005 requiring a license to dig wells, but the legislation was not enforced (6). Overuse of groundwater has been blamed for the recent drying of the Khabur River in Syria's northeast (6). The depletion of groundwater during the recent drought is clearly evident from remotely sensed data by the NASA Gravity Recovery and Climate Experiment (GRACE) Tellus project (Fig. 2*C*) (12).

The reduced supply of groundwater dramatically increased Syria's vulnerability to drought. When a severe drought began in 2006/2007, the agricultural system in the northeastern "bread-basket" region, which typically produced over two-thirds of the country's crop yields, collapsed (13). In 2003, before the drought's onset, agriculture accounted for 25% of Syrian gross domestic product. In 2008, after the driest winter in Syria's observed record, wheat production failed and the agricultural share fell to 17% (14). Small- and medium-scale farmers and herders

Significance

There is evidence that the 2007–2010 drought contributed to the conflict in Syria. It was the worst drought in the instrumental record, causing widespread crop failure and a mass migration of farming families to urban centers. Century-long observed trends in precipitation, temperature, and sea-level pressure, supported by climate model results, strongly suggest that anthropogenic forcing has increased the probability of severe and persistent droughts in this region, and made the occurrence of a 3-year drought as severe as that of 2007–2010 2 to 3 times more likely than by natural variability alone. We conclude that human influences on the climate system are implicated in the current Syrian conflict.

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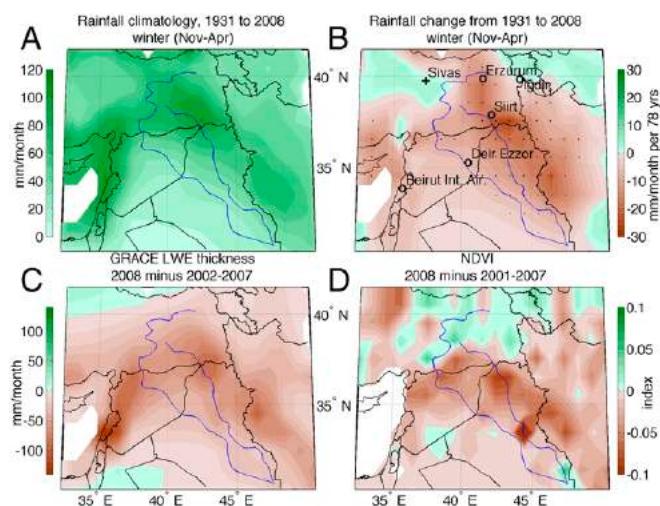


Fig. 2. (A) Observed winter (November–April) precipitation climatology, 1931–2008, UEA CRU version 3.1 data. (B) The spatial pattern of the CRU change in 6-month winter precipitation from 1931 to 2008 based on a linear fit (shading); those GHCN stations that indicate a significant ($P < 0.1$) trend over their respective records are shown as circles and crosses (indicating drying/wetting). (C) The difference in liquid water equivalent (LWE) between 2008 (annual) and the mean of the previous 6 years using the NASA GRACE Tellus project data. (D) The difference in the Normalized Difference Vegetation Index (NDVI) between 2008 (annual) and the mean of the previous 7 years.

The Drought in Context

Having established Syria's vulnerability to droughts, we now examine the 2007–2010 drought itself. The severity and persistence of the drought can be seen in the area mean of FC rainfall according to the University of East Anglia Climatic Research Unit (UEA CRU) data (Fig. 1A) and in the two Global Historical Climatology Network (GHCN) stations located closest to Syria's northeastern agricultural region, Deir ez-Zor on the Euphrates River and Kamishli near the Turkish border (*Materials and Methods*). The 2007/2008 winter was easily the driest in the observed records. Multiyear drought episodes, here defined as three or more consecutive years of rainfall below the century-long normal, occurred periodically over the last 80 years (CRU), in the late 1950s, 1980s, and 1990s (Fig. 1A, brown shading). Although less severe, these droughts raise the question of why the effects of the recent drought were so much more dramatic. We offer three reasons: (i) the recent demand for available resources was disproportionately larger than in the 1950s; in addition to the recent emphasis on agricultural production, the total population of Syria (Fig. 1D) grew from 4 million in the 1950s to 22 million in recent years; (ii) the decline in the supply of groundwater has depleted the buffer against years with low rainfall; and (iii) the recent drought occurred shortly after the 1990s drought, which was also severe; Syria was far more vulnerable to a severe drought in the first decade of the 21st century than in the 1950s, and the FC never fully recovered from the late 1990s drought before collapsing again into severe drought. In fact, the region has been in moderate to severe drought from 1998 through 2009, with 7 of 11 years receiving rainfall below the 1901–2008 normal. It is notable that three of the four most severe multiyear droughts have occurred in the last 25 years, the period during which external anthropogenic forcing has seen its largest increase.

Regional Climate Variability and Trend

Agriculture in Syria depends not only on the precipitation that falls within Syria and on local groundwater but also on water from the Euphrates and Tigris rivers and their numerous tributaries.

These rivers have long provided water to the region via precipitation in their headwaters in the mountains of eastern Turkey. Despite Turkey's control over the water flows of the Euphrates and Tigris through its upstream placements of dams, Syria and Turkey have cooperated in recent years, and Turkey increased water flow to Syria during the recent drought (28). It has been previously shown that natural winter-to-winter rainfall variability in western Turkey is due largely to the influence of the North Atlantic Oscillation (NAO) (29). For eastern Turkey and in Syria and the other FC countries, however, the NAO influence is weak or insignificant. This has allowed observational analyses to identify an externally forced winter drying trend over the latter half of the 20th century that is distinguishable from natural variability (30–32). Furthermore, global coupled climate models overwhelmingly agree that this region will become drier in the future as greenhouse gas concentrations rise (33), and a study using a high-resolution model able to resolve the complex orography of the region concluded that the FC, as such, is likely to disappear by the end of the 21st century as a result of anthropogenic climate change (34).

That the neighboring regions of southeast Turkey and northern Iraq also experienced recent drought, to a lesser extent, perhaps begs the question as to why the effects in Syria were so grave. Syria was far more vulnerable to drought, given its stronger dependence on year-to-year rainfall and declining groundwater for agriculture. Water scarcity in Syria has been far more severe than in Turkey or Iraq, with Syria's total annual water withdrawal as a percentage of internal renewable water resources reaching 160%, with Iraq at 80% and Turkey at around 20% in 2011 (35). Furthermore, Turkey's geographic diversity and investment in the southeast region's irrigation allowed it to better buffer the drought, whereas the populace in northwest Iraq is far less dependent on agriculture than their counterparts in northeast Syria (36, 37).

To address the question of whether the recent drought was made more severe by a contribution from long-term trends, we first determined the long-term change in winter rainfall. The FC as a whole has experienced a statistically significant ($P < 0.05$) winter rainfall reduction (13%) since 1931 (Fig. 1A). Observational uncertainty was large before 1930 due to sparseness of station data. Further examination of the linear trends present in the individual GHCN stations for the FC corroborate the drying trend, as 5 of 25 stations exhibited a statistically significant ($P < 0.1$) negative rainfall trend (Fig. 2B). The pattern of this trend (Fig. 2B) is similar to the climatological rainfall pattern (Fig. 2A), concentrated along the coast and in northeastern Syria. The long-term drying trend is closely mirrored by recent changes in satellite measurements of groundwater (measured in terms of liquid water equivalent) (Fig. 2C) and, to a lesser extent, by estimates of vegetation changes (Fig. 2D).

The annual surface temperature in the FC also increased significantly ($P < 0.01$) during the 20th century (Fig. 1B). The warming in this region since 1901 has outpaced the increase in global mean surface temperature, with much of this increase occurring over the last 20 years (all years from 1994 through 2009 were above the century-long mean) (Fig. 1B, red shading). The trend during the summer half year (1.2 degrees, Fig. S2) is also important, as this is the season of highest evaporation, and winter crops such as wheat are strongly dependent on reserves of soil moisture. Reductions in winter precipitation and increases in summer evaporation both reduce the excess of precipitation over evaporation that sustains soil moisture, groundwater and streamflow. The recent strong warming is concomitant with the three most recent severe multiyear droughts, together serving to strongly dry the region during winter and summer.

The century-long, statistically significant trends in both precipitation and temperature seen in Fig. 1 suggest anthropogenic influence and contributed to the severity of the recent drought. The FC area mean of the self-calibrating Palmer Drought Severity

Index (38), which combines precipitation and temperature as a proxy for cumulative soil moisture change, also exhibits a significant long-term trend (Fig. 1C). Although natural variability on timescales of centuries or longer cannot be entirely ruled out for this region, the long-term observed trends and the recent increase in the occurrence of multiyear droughts and in surface temperature is consistent with the time history of anthropogenic climate forcing. The case for this influence is supported by additional modeling and theoretical and observational evidence (see *Frequency of Multiyear Droughts, Mechanisms, and Supporting Information*).

Frequency of Multiyear Droughts

For Syria and for the greater FC, natural multiyear droughts—here defined as three or more consecutive years of rainfall below the long-term normal—occurred periodically during the 20th century (Fig. 1A). It is a generic property of a time series consisting of a natural oscillatory part and a downward trend that the minimum is most likely to occur toward the end of the time period when the negative influence of the trend is greatest and when the oscillation is also at a minimum. The century-long trends in precipitation and temperature, here implicated as evidence of anthropogenic influence, point toward them being key contributors to the recent severe drought. We therefore estimated the increased likelihood of an extreme 3-year drought such as the recent one due to anthropogenic trend.

We did this in two ways. First we separated the observed anthropogenic precipitation trend from the residual, presumably natural, variability by regressing the running 3-year mean of observed (CRU) 6-month winter precipitation onto the running 3-year mean of observed annual global atmospheric carbon dioxide (CO₂) mixing ratios from 1901–2008 (39, 40). The latter time series was used as an estimate of the monotonic but nonlinear change in total greenhouse gas forcing (*Materials and Methods*). After removing the CO₂ fit from the total observed winter precipitation timeseries (Fig. 3A), we constructed frequency distributions of the total and residual timeseries (Fig. 3B) and applied gamma fits to the distributions. The difference in the total and residual distributions is significant ($P < 0.06$), based on a Kolmogorov–Smirnov test, and is due almost entirely to the difference in the means. Thresholds are shown at 10%, 5%, and 2% (in percent of the total sample size of 76 3-year means) in the dry tail of the timeseries (Fig. 3A) and for the distribution of the total (Fig. 3B). The result is that, when combined, natural variability and CO₂ forcing are 2 to 3 times more likely to produce the most severe 3-year droughts than natural variability alone. Residual, or natural, events exceeding the 10% threshold of the total occur less than half as often (3 versus 8, out of 76). For the residual alone, no values exceed the 5% threshold of the total.

The trend contribution would be quite similar if we simply calculated a linear time trend. There is no apparent natural explanation for the trend, supporting the attribution to anthropogenic greenhouse gases. Further support comes from model simulations. We used 16 Coupled Model Intercomparison Project phase five (CMIP5) models (*Materials and Methods* and Table S1) to construct similar distributions, providing a larger sample size than for the observed 3-year droughts. In this case, rather than removing the CO₂ forcing as in the observed case, we compare the historical and historicalNat runs. The former include all external forcings during the 20th century, including the change in greenhouse gas concentrations, whereas the latter include only the natural forcings (*Materials and Methods*). In this analysis, the models were normalized to the observed CRU mean and standard deviation (SD) (see Fig. S3 for model comparison before normalizing). The resulting distributions support the observed finding, as the driest 3-year events occur less than half as often under natural forcing (historicalNat runs) alone (Fig. 3C). The agreement between the model and observational analysis

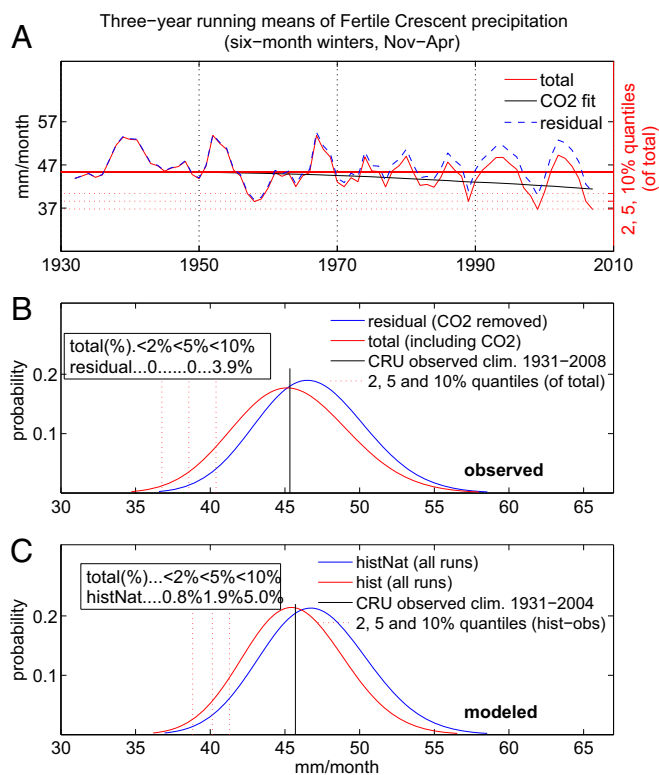


Fig. 3. (A) Timeseries of observed (CRU) 3-year running mean 6-month winter FC (area mean) precipitation: total (red), CO₂ fit from regression (black), and the residual or difference between these (dashed blue). Frequency distributions based on gamma fits of 3-year running mean 6-month winter FC (area mean) precipitation, for the (B) observed data (corresponding with above) and (C) CMIP5 model simulations, comparing historical and histNat runs. Quantile thresholds based on the total (in B) and historical (in C) are shown at 2%, 5%, and 10% (dotted lines). The tables indicate the percentage of actual (B) observed (sample size 76) and (C) model simulated (sample size 46 × 72 for histNat and 69 × 72 for historical) occurrences exceeding the respective thresholds.

results supports the attribution of the century-long negative trend in precipitation to the rise in anthropogenic greenhouse forcing and to the role of the latter in the devastating early 21st century Syrian drought.

Mechanisms

We examine the low-level (850 hPa) regional atmospheric circulation by comparing a composite of driest minus wettest winters (Fig. 4B) to the difference between the periods 1989–2008 and 1931–1950, representing the long-term change, or trend (Fig. 4C). Climatologically, the flow is from the west, bringing moist air (shading represents specific humidity) in from the Mediterranean Sea and allowing moisture convergence that sustains precipitation (Fig. 4A). In both the composite dry anomalies and the trend, the climatological westerly flow is weakened. In both cases, there is a positive geopotential height anomaly over the Mediterranean Sea (consistent with higher surface pressure) and an anomalous anticyclonic (clockwise) circulation (arrows). In the composite case, this anomaly extends over Turkey and beyond the eastern Black Sea, resulting in anomalous northeasterly flow over the FC, advecting dry air and generating anomalous moisture divergence. In the trend case, by contrast, the positive geopotential height anomaly does not extend over most of Turkey, and the flow anomaly is more northerly over most of the FC. This difference between the composite and trend anomalies can be seen in the specific humidity anomalies (Fig. 4B and C,

we first linearly interpolated the models to the same 0.5° by 0.5° horizontal grid as the CRU observations. To determine the change due to trend, we applied linear least-squares fits, except in the case of the estimation of multi-year droughts, when regression onto global CO₂ mixing ratios was used. For the latter, this nonlinear detrending provided a more conservative estimate of the residual than linear detrending. We also examined the sensitivity of using global mean surface temperature rather than CO₂ and found almost no difference in the resulting residual. For analysis of the regional circulation, we used the Twentieth Century Reanalysis Project, with a horizontal resolution of 2° by 2° (50). For composites, dry and wet years are here defined as those outside of ±1 SD (based on the CRU 1931–2008 period).

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