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Causes and implications of extreme atmospheric moisture demand during the record-breaking 2011 wildfire season in the southwest United States

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Abstract

In 2011, exceptionally low atmospheric moisture content combined with moderately high temperatures to produce record-high vapor-pressure deficit (VPD) in the southwestern United States (SW). These conditions combined with record-low cold-season precipitation to cause widespread drought and extreme wildfires. Although interannual VPD variability is generally dominated by temperature, high VPD in 2011 was also driven by lack of atmospheric moisture. May–July 2011 dew point in the SW was 5.1 standard deviations below the long-term mean. Lack of atmospheric moisture was promoted by already very dry soils and amplified by a strong ocean-to-continent sea-level pressure gradient and upper-level convergence that drove dry northerly winds and subsidence upwind of and over the SW. Subsidence drove divergence of rapid and dry surface winds over the SW, suppressing southerly moisture imports and removing moisture from already dry soils. By the 2050s, model projections developed for the fifth phase of the Coupled Model Intercomparison Project (CMIP5) suggest that warming trends will cause mean warm-season VPD to be comparable to the record-high VPD observed in 2011. CMIP5 projections also suggest increased interannual variability of VPD, independent of trends in background mean levels, due to increased variability of dew point, temperature, vapor pressure, and saturation vapor pressure. Increased variability in VPD translates to increased probability of 2011-type VPD anomalies, which would be superimposed on ever-greater background VPD levels. While temperature will continue to be the primary driver of interannual VPD variability, 2011 served as an important reminder that atmospheric moisture content can also drive impactful VPD anomalies.
1. Introduction

The southwest United States (SW) experienced extreme drought in 2011, related at least in part to a La Niña event in the tropical Pacific Ocean (Rupp et al. 2012; Hoerling et al. 2013; Seager et al. 2014). The 2011 SW drought event was accompanied by record-breaking total burned area (Williams et al. in press) and record-size “megafires” in the forests of eastern Arizona and northern New Mexico. Extreme drought and wildfire conditions prompted widespread concern as to whether the anomalous 2011 conditions foreshadowed continued intensification of regional drought-driven wildfires in the SW due to greenhouse warming (e.g., Miller 2012; Nijhuis 2012).

Temperature has been shown to influence wildfire behavior in the SW by positively influencing drought (e.g., Westerling et al. 2006; Littell et al. 2009; Abatzoglou and Kolden 2013). The effect of temperature on drought operates via an exponential forcing on atmospheric moisture demand, or vapor-pressure deficit (VPD) (Anderson 1936; Williams et al. 2013; Williams et al. in press). VPD is defined as atmospheric saturation vapor pressure (the water-vapor holding capacity, which is purely a function of temperature) minus actual vapor pressure. Therefore, the influence of temperature on drought conditions can be mitigated or amplified by variations in atmospheric moisture content. Importantly, temperature exponentially influences VPD via its Clausius-Clapeyron effect on saturation vapor pressure.

In 2011, very large burned area co-occurred with high moisture deficit (driven by high VPD and low precipitation), consistent with the well-known positive correlation between drought and wildfire in the region (e.g., Swetnam and Betancourt 1990, 1998; Westerling et al. 2003; Westerling and Swetnam 2003; Westerling et al. 2006; Littell et al. 2009; Abatzoglou and
Kolden 2013; Williams et al. 2013; Williams et al. in press). While the causes of low cold-season precipitation in 2010–2011 (which only reached extreme anomalies in Texas, east New Mexico, and Mexico) have been diagnosed (Hoerling et al. 2013; Seager et al. 2014), causes of extreme warm-season VPD have not. Here we diagnose the large-scale climate processes that resulted in exceptionally high VPD in 2011. We then evaluate modeled projections to better understand how, if at all, the processes causing extreme 2011 VPD anomalies are projected to change in the future. We also evaluate projected changes in the interannual variability of VPD and its sub-components to understand projected changes in the frequencies of extreme temperature, humidity, and VPD excursions that are superimposed upon projected background trends.

2. Data and methods

We define the SW as the areas of Arizona, New Mexico, Texas, Oklahoma, Colorado, and Utah that lie south of 38°N, north of 28.5°N, and west of 100°W (as in Williams et al. in press). We used the ~4 km gridded monthly (January 1895 – June 2014) PRISM dataset developed at Oregon State University (accessed July 2014) to evaluate precipitation, maximum daily temperature (T_{max}), minimum daily temperature (T_{min}), dew point, and VPD anomalies (VPD calculated as in Williams et al. 2013). Precipitation and temperature data come from the latest version of the PRISM dataset (www.prism.oregonstate.edu) but dew point data come from the previous version (http://oldprism.nacse.org) because dew-point data are not yet included in the new dataset. We calculate VPD using temperature from the old dataset through 2013 to be consistent with the dew point data. We calculate 2014 VPD using new-dataset temperature because the old-dataset temperature record ends in 2013. Although PRISM may not be ideal for evaluating long-term trends or temporal anomalies at some specific locations or regions (e.g.,
Hamlet and Lettenmaier 2005), Williams et al. (in press) demonstrate that PRISM climate records for the SW are comparable to those calculated using a wide variety of data products. An exception is for records of atmospheric moisture (dew point) prior to 1961, when station-based humidity measurements were rare. We therefore report dew point and VPD anomalies relative to both the post-1895 and post-1961 periods.

Additionally, we accessed surface wind-speed (hourly) and soil moisture (monthly) data gridded at 0.125° resolution from the North American Land Data Assimilation System project phase 2 (NLDAS-2, Mitchell et al. 2004) for 1979–2014. NLDAS-2 near-surface (10 m) wind data are based upon the National Center for Environmental Protection’s (NCEP’s) 3-hourly, 32-km North America Regional Reanalysis (NARR), produced using an assimilation of surface measurements, radiosonde data, and atmospheric modeling (Mesinger et al. 2006). For soil moisture, we used NLDAS-2 data modeled with the Noah land-surface model (Xia et al. 2012). We also evaluated three-dimensional reanalysis climate data using the Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al. 2011). Geographic resolution of MERRA data ranges from 0.5–1.25° and temporal coverage is 1979–2014. Data are available at a vertical resolution of 25 hPa from the surface to 700 hPa, and a resolution of 50 hPa for 700–100 hPa. Climate indices evaluated were the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), the Southern Oscillation Index (SOI; Trenberth 1984), and the Pacific North American pattern (PNA; based upon Wallace and Gutzler 1981 but with the modified point-wise method described at www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/month_pna_index2.shtml).

We utilized the ensemble of monthly climate model projections made for the fifth phase of the Coupled Model Intercomparison Project (CMIP5) using the Intergovernmental Panel on Climate
Change (IPCC) historical experiment through 2005 and the emissions scenario RCP 8.5 for 2006–2100 (anthropogenic radiative forcing is ~8.5 Wm\(^{-2}\) by 2100; Moss et al. 2010; van Vuuren et al. 2011). A list of the 37 models considered is provided in Supplemental Table S1. For temperature, precipitation, dew point, and wind speed, we created monthly time series for the SW by linearly interpolating monthly climate fields to 0.25° geographic resolution and calculating the mean monthly value of grid cells within the SW. We calculated monthly modeled VPD as in Williams et al. (2013). We also calculated modeled projections of the PDO index, the SOI, and the PNA index. We calculated the PDO index following Lapp et al. (2011), the PNA index using the modified point-wise method, and the SOI as the difference in surface pressure between Tahiti and Darwin (Trenberth 1984). All model realizations of climate have biases in terms of mean and variance. For each variable, we standardized all model realizations of climate to a mean of zero and a standard deviation of one (i.e., z-scores) during 1961–2005. We measured magnitudes of future climate changes as the ensemble-median and inner-quartile anomalies averaged across 2035–2079 versus those for 1961–2005. Ensemble-median and inner-quartile differences between the two time periods were calculated by considering each model only once, regardless of number of model runs available for each model. Multiple model runs for a given model were averaged together. For each variable and each model run, we generated 10,000 pseudo-random time series that contain the modeled historical 1961–2005 lag-1 autocorrelation and variability to determine 95% and 99% confidence intervals for significant anomalies accounting for lag-1 autocorrelation. Interannual variability of modeled SW April–June dew point, temperature, vapor pressure, saturation vapor pressure, and VPD were evaluated by removing the long-term projected trend from all modeled annual time series. The long-term projected trend for each variable was developed in 3 steps. First each model run for the historic
and future scenario was smoothed with a 31-year filter. Then all 31-year smoothed time series
were averaged together to create a single smoothed record for 1900–2099 for each model. Next,
the long-term projected trend is calculated as the ensemble-median smoothed record, where
decadal variability is cancelled out due to the large number of models and multiple runs
considered for many models. Finally, the long-term trend was removed from each model run by
linearly fitting the long-term trend to each model’s annual 1900–2099 annual time series,
averaged across all runs, and then subtracting the adjusted trend from each annual time series.
Variabilities of the resulting detrended time series were analyzed.

3. Results and Discussion

3.1. Drought anomalies in 2011
We expect that temperature, precipitation, VPD, and dew point are all related and that anomalies
in all these variables influenced the anomalous drought conditions in 2011. For each variable, we
identified the window of three or more consecutive months during August 2010 through July
2011 when average SW conditions were most anomalous relative to 1895–2013 (2014 not
included here because July 2014 data were not yet available). Figure 1 indicates that these four
climate variables had strong anomalies in the months before and during the peak drought
conditions and wildfire season of spring and early summer, 2011. These windows were January–
July for precipitation total (Fig. 1a), March–July for T_{\text{max}} (Fig. 1b), May–July for dew point (Fig.
1c), and March–July for VPD (Fig. 1d). Maps in Figure 1 indicate that sub-regional anomalies
for precipitation, dew point, and VPD exceeded 6 standard deviation units (\(\sigma\)) in parts of east
New Mexico, west and north Texas, and southwest Oklahoma. Anomalies for dew point were, by
far, the strongest among the variables evaluated. Averaged across the SW, the May–July dew
point anomaly was -4.6 $\sigma$ (-3.7 $\sigma$ relative to 1961–2013). This dew-point anomaly was expressed
as a vapor-pressure anomaly of -3.9 $\sigma$, or -21% (-3.2 $\sigma$, -20% relative to 1961–2013) and 10%
lower than the second most anomalous May–July vapor-pressure value in 1971. $T_{\text{max}}$ anomalies
were not as severe when averaged across the SW (5th highest on record for March–July), but
anomalies reached +4 $\sigma$ in east New Mexico and parts of Texas and were highest on record when
averaged across the portion of the SW east of 105°W. March–July $T_{\text{min}}$ was also high in this
portion of the SW (3rd highest on record).

Although March–July $T_{\text{max}}$ and $T_{\text{min}}$ anomalies were only +1.9 $\sigma$ and +1.7 $\sigma$, respectively, when
averaged across the SW (+1.7 $\sigma$ and +1.2 $\sigma$ relative to 1961–2013), the March–July VPD
anomaly was +3.2 $\sigma$ (+2.6 $\sigma$ relative to 1961–2013). Part of the discrepancy between
temperature and VPD anomalies was due to a disproportionately large influence of strong $T_{\text{max}}$
anomalies in the eastern SW (caused by the exponential influence of temperature on VPD).
However, the 2011 VPD anomaly was also strongly influenced by extremely low specific
humidity, shown in Fig. 1c. In Figure 2, red and blue lines indicate contributions of temperature
and dew point variability, respectively, toward VPD anomalies (black line) during March–July,
the period when VPD was most anomalous. Dew-point contributions were calculated by holding
monthly temperatures within each PRISM grid cell at their climatological means and only
allowing dew point to vary. Temperature contributions were calculated oppositely. Although
temperature normally dominates VPD variability in the SW (Seager et al. in review),
exceptionally low dew point in 2011 was responsible for 45% of the VPD anomaly in March–
July 2011 (57% when only May-July is considered). The powerful impact of low dew point on
VPD in 2011 is in contrast to the more negligible impact of dew-point anomalies during other
recent temperature-driven anomalous VPD years such as 2000–2002, 2006, and 2012 (Fig. 2),
highlighting the uniqueness of the 2011 drought event.

3.2. Causes of low humidity and high VPD in 2011

Although VPD was anomalously high during all spring and summer months, we focus for the
rest of this paper on April–June (AMJ), the three months centered within the most anomalous
period. In 2011, sustained upper-level convergence occurred above and to the west (upwind) of
the SW (Fig. 3b) as a result of the wave train of circulation anomalies likely associated with the
La Niña sea-surface temperature (SST) pattern and reduced atmospheric heating over the tropical
Pacific Ocean (Fig. 3h). Consistent with La Niña-like atmospheric circulation, upper-level
westerly anomalies above the central and eastern Pacific Ocean were contained within cyclones
straddling the equator. Poleward and east of these cyclones were enhanced upper-level
anticyclonic circulation patterns which, over the North Pacific, translated into a weaker than
normal Aleutian Low (Fig. 3b,d,f). On the eastern flanks of the upper-level subtropical cyclone
and mid-latitude anticyclone (near the west coast of Mexico), southerly wind anomalies
converged with northerly anomalies above western North America (Fig. 3b,d), forcing
subsidence.

Figure 4b indicates a large region over the eastern North Pacific where upper-level (300 hPa)
convergence anomalies exceeded 2 σ (relative to 1979–2014) during AMJ 2011 across the
northwest and southwest flanks of the North Pacific high-pressure zone. In addition to the impact
of upper-level convergence, the northerly flow anomaly in the weaker Aleutian Low was, on its
own, associated with descending motion via balances between advection of planetary vorticity
and vortex stretching, and between anomalous cold (northerly) advection and compressional warming. Reanalysis data indicate that AMJ 2011 vertical velocities averaged across the SW between the surface and 300 hPa were anomalously downward (Fig. 4d), with AMJ 2011 downward velocities ranking second strongest on record according to MERRA and strongest on record according to the North America Regional Reanalysis (NARR; Mesinger et al. 2006; see Supplemental section S1). Figure 4d indicates that 2011 vertical-velocity anomalies (MERRA) were spatially heterogeneous, with subsidence anomalies exceeding 2–3 \( \sigma \) throughout much of Arizona and New Mexico, and ascending anomalies in west Texas. Figure 4e,f shows the vertical structure of specific humidity and the northwesterly wind pattern traveling along the average low-level wind path from the coastal northeast Pacific toward and across the SW (path indicated by the orange line in Fig. 4c). This profile view indicates that the subsidence anomalies described above were generally present throughout the atmospheric profile upwind of and over the SW (Fig. 4f).

Subsidence brings dry, high altitude air to the surface and contributes to enhanced low-level divergence. According to NLDAS-2 hourly surface wind data, AMJ 2011 wind speed averaged across the SW was 2.6 \( \sigma \) (18\%) above the 1979–2014 mean and surface wind divergence anomalies were \( >2 \sigma \) across much of the SW (not shown). Divergence of dry, rapidly moving air over the SW worked to suppress low-level moisture fluxes from the usual sources in the subtropical Pacific and Gulf of Mexico regions (Fig. 4g,h, southerly surface moisture flux anomalies into the SW were \(-0.5 \text{ to } -2 \sigma\)). This is corroborated by a moisture-tagging experiment (see Supplemental section S2), indicating that SW atmospheric moisture transported from the subtropical Pacific and Gulf of Mexico regions was substantially reduced in 2011.
Low-level humidity in the SW was further suppressed by low evaporation rates from land due to very dry soils, which resulted from low precipitation in preceding months. Near-surface (0–10 cm) modeled soil moisture averaged across the SW was the lowest on record (-2.1 $\sigma$), causing evapotranspiration to be the lowest on record (-2.0 $\sigma$) despite record-breaking potential evapotranspiration (2.2 $\sigma$) (anomalies based on 1979–2014 NLDAS-2). Based on our vapor-tagging analysis, water vapor derived from land-surface evaporation in and around the SW was virtually missing from the eastern portion of the SW atmosphere in AMJ 2011 (Supplemental section S2). Continuous exposure to dry westerly winds and high sensible heat flux due to very dry soils combined to cause record-breaking spring and early summer temperature anomalies throughout much of west Texas, further amplifying VPD in this region.

### 3.3. Interrelation among variables underlying unique 2011 conditions

Figure 5 shows how atmospheric circulation (wind speed and geopotential height) and surface temperatures correlated with SW dew point (panels on left) and temperature (panels on right) during AMJ 1979–2013. Importantly, there are strong similarities between the conditions typically associated with low dew points (Fig. 5, left panels) and the climate anomalies in 2011 (Figure 3). There is less correspondence between anomalies in 2011 and the conditions typically associated with high temperature (Fig. 5, right panels).

Correspondence between the 2011 anomaly maps in Figure 3 and the dew-point correlation maps in Figure 5 indicates that AMJ 2011 climate was in many ways an amplification of the same atmospheric and oceanic conditions responsible for low dew points in the SW during other years.
in recent decades. In particular, the 2011 anomaly patterns and dew-point correlation fields share a sea-level pressure (SLP) gradient between the North Pacific High and low pressure over central North America (Figs. 3f, 5e). Considering 1961–2014, the AMJ SLP gradient (SLP_g) between the North Pacific (20–45°N, 90–110°W) and North America (30–50°N, 130–170°W) was strongest on record in 2011 (2.8 σ) and correlates negatively with AMJ dew point in the SW (r = -0.59, Table 1; see Supplemental section S3 for methods to calculate SLP_g). A strong SLP_g drives northerly winds down the North American coast, exposing the SW to anomalously dry air from the north and from above via subsidence. Strong SLP_g and low SW dew point are associated with SST patterns resembling the cold phase of the PDO and La Niña (Figs. 3h, 5g), where intensified SLP_g promotes, and is reinforced by, northerly low-level wind that drives upwelling of cold water in the eastern North Pacific. SW dew point may be also partially suppressed during cold-phase years because relatively cool SSTs suppress atmospheric moisture across large spatial scales. During 1961–2014, AMJ the PDO correlated positively, and the Southern Oscillation Index (SOI) correlated negatively, with SW dew point (r = 0.47 and -0.46, respectively; Table 1). Crimmins (2010) shows that La Niña and the PDO cold phase correspond positively with the frequency of days during which meteorology is conducive to wildfire in the SW.

Another key similarity between the 2011 anomalies and the conditions generally associated with low SW dew point is a strengthened mid- and upper-level geopotential height gradient between anomalously low heights over the Pacific Northwest United States and anomalously positive heights over the eastern North Pacific and western Mexico. These strong gradients promote mid- and upper-level convergence and subsidence anomalies upwind of and above the SW (Fig. 3b,
5a). To represent the strength of these upper-atmospheric pressure gradients and associated convergence/subsidence processes, we developed a simple geopotential height gradient index (G\textsubscript{300}) based upon the 300 hPa height patterns in Figs. 3b and 5a. Here, G\textsubscript{300} is the mean of two height gradients (gradient #1: North Pacific minus Pacific Northwest; gradient #2: west Mexico minus Pacific Northwest; North Pacific: 35–50°N, 160–142°W; Pacific Northwest: 40–50°N, 125–107.5°W; west Mexico: 17.5–30°N, 122.5–97.5°W). G\textsubscript{300} is strongly related to SLP\textsubscript{g} (r = 0.87; Table 1) and correlates negatively with SW dew point (r = -0.65; Table 1). Positive G\textsubscript{300} tends to correspond with the negative phase of the Pacific/North American (PNA) index, which tends to be favored by cold (La-Niña) phases of the SOI or PDO (Table 1) (Zhang et al. 1997; Ault et al. 2011), yet may also result from internal variability.

Land-surface moisture in 2011 also had a similar spatial anomaly pattern (Fig. 6a) to that associated with low SW dew point historically (Fig. 6b). Historically, low dew point has corresponded with dry soil across much of the SW and northern Mexico, and wet soil in the Pacific Northwest, similar to spatial structures for precipitation and temperature in Figure 1. This is due partly to the influences that the SOI and PDO oscillations have on the geographic distribution of winter and spring precipitation in western North America (e.g., Dettinger et al. 1998), which subsequently impact warm-season humidity and temperature (Table 1). Positive SOI and negative PDO also tend to enhance SLP\textsubscript{g} and G\textsubscript{300}, promoting northerly wind and cool temperatures throughout much of the west (as in Fig. 1d). However, enhanced subsidence, decreased cloud shading, and increased surface wind speed combine to increase temperature and potential evapotranspiration toward the eastern SW, drawing soil moisture down and increasing surface sensible heat fluxes when soil moisture is limiting, as in 2011. The resultant spatial
structure of surface temperature and moisture in 2011 may have further promoted high VPD in
the SW via land-surface feedbacks on large-scale atmospheric circulation (e.g., enhancement of a
surface heat low and tropospheric ridging) that reinforced low humidity and high surface
temperature throughout much of the SW, as in the European heat wave of 2003 (e.g., Zaitchik et
al. 2006; Fischer et al. 2007). Therefore, although extreme 2011-like years appear possible only
when a suite of factors are in place, many of these factors are interrelated and may be largely
distilled down to factors that promote dry soils (primarily low precipitation) and strong, dry wind
sourced from the north (primarily $G_{300}$ and SLP$_g$).

3.4. Implications for the future

Figure 7 shows CMIP5 ensemble-median (red bars) and inner-quartile climate-model projections
of climate anomalies during 2035–2079 (relative to 1961–2005) for the variables that appear to
have contributed to the extreme 2011 VPD event in the SW. Black bars show 2011 anomalies for
comparison. During AMJ, the mean SW temperature anomaly is projected to be +2.87 °C in
2035–2079 (Fig. 7a). The projected warming trend drives an ensemble-median VPD anomaly of
+3.01 hPa during 2035–2079 (19.5% higher than 1961–2005) (Fig. 7b).

The other component of VPD, atmospheric moisture content, is also projected to rise (Fig. 7c) in
accordance with general increases in atmospheric and ocean temperatures globally. Increasing
atmospheric moisture content mitigates the effect of warming on VPD, but the exponential
Clausius-Clapeyron relationship between temperature and saturation vapor pressure dictates that
VPD would increase due to warming even if atmospheric moisture content increased enough to
maintain constant relative humidity (RH) (Anderson 1936). In reality, models do not project
atmospheric moisture increases to maintain stable RH levels in the SW (Fig. 7d). This is partly because of limited surface moisture in the SW, but also due to moisture divergence trends in the mean state of the SW atmospheric circulation (Seager et al. in press). Suppressed increases in atmospheric moisture content work to amplify the effects of warming on SW VPD.

It appears that the processes involved in suppressing projected increases in atmospheric moisture content were at work in suppressing 2011 atmospheric moisture content in multiple respects. Considering the climate variables identified in Sections 3.2 and 3.3 as generally associated with SW dew-point variability and also anomalous in 2011 (SLP$_g$, G$_{300}$, October–June precipitation, PDO, SOI, PNA, and wind speed), Figure 7e–k indicates that ensemble-median projected trends share the same sign as 2011 anomalies for all variables evaluated (though projected trends are very weak for some variables). While the ensemble-median trend in SLP$_g$ is relatively weak, the spatial pattern of ensemble-median projected SLP trends is similar to that associated with low SW dew point (Figs 3,5) and 35 of the 36 models evaluated converge upon increased SLP over the northeast Pacific Ocean in the region of the Aleutian Low (Supplemental Fig. S4). The projections evaluated here suggest that some of the large-scale processes projected to suppress future increases in SW atmospheric moisture content in the SW were at work in 2011.

Model projections of increasing atmospheric moisture imply that the extremely low atmospheric moisture levels observed in 2011 and the multi-decade decline that began in the early 1990s should be becoming increasingly improbable (Fig. 8a). The observed decadal trends shown in Figure 8a are undoubtedly dominated by internal climate variability, but models within the CMIP5 archive do not tend to simulate the observed level of multi-decadal internal variability.
During 1990–2014, observed AMJ dew point declined by 3.82°C (according to linear trend), corresponding to a vapor-pressure decline of 20.9%. Histograms in Figure 8b,c show the CMIP5 ensemble distribution of linear changes in (b) dew point and (c) vapor pressure during all possible 25-year periods of the historical scenario (1850–2005). Only one of the 30 models with adequate data (CSIRO-Mk3-6-0) simulates a 25-year dew-point decline of more than 3.82°C, and this occurs at the beginning of the 20th century in just one of 10 historical runs. This is also the only model that simulates a 25-year period when vapor pressure declines by 20.9% or more. The mismatch between observed and modeled decadal variability in atmospheric moisture content indicates that either the ongoing decline in SW atmospheric moisture is a truly exceptional event or that the CMIP5 ensemble largely misrepresents decadal atmospheric moisture variability in the SW. If models do indeed underrepresent decadal variability in SW atmospheric moisture, this would imply that repeated occurrences of 2011-like atmospheric moisture anomalies are more likely than projected by the CMIP5 ensemble.

Enhanced probability of occurrences of 2011-type atmospheric moisture anomalies are also suggested by an analysis of projected interannual variability in dew point and vapor pressure (Fig. 9a,b). Even after removal of long-term projected trends (such as that shown in Fig. 8), the CMIP5 ensemble projects interannual variability of AMJ dew point to be significantly higher ($p < 0.01$ based on t-test) during 2035–2079 than in 1961–2005 (Fig. 9a; standard deviation anomalies in Fig. 9 are based on 1961–2005). Importantly, projected increases in dew-point variability translate to even larger increases in vapor-pressure variability because of the increase in mean dew point and the exponential relationship between dew point and vapor pressure. Comparing the two simulated time periods, the ensemble-median frequency of years when
vapor-pressure anomaly (departure from projected trend) is negative enough to positively force VPD by at least 10% of the 1961–2005 mean (requiring a vapor-pressure anomaly of \(\leq -2.4 \sigma\)) is three times higher in 2035–2079 than in 1961–2005 (Fig. 9b).

Models also tend to project slight increases in AMJ temperature variability (Fig. 9c). Although these increases are smaller than those for dew point, the non-linear Clausius-Clapeyron relation leads to significantly increased variability in saturation vapor pressure due to warming. Ensemble-median variability in saturation vapor pressure increases by 30%, compared to 20% for vapor pressure. Comparing the two time periods, the ensemble-median frequency of years when AMJ saturation vapor pressure anomaly is positive enough to positively force VPD anomalies by at least 10% (requiring a saturation vapor pressure anomaly of \(\geq 1.3 \sigma\)) of the 1961–2005 mean by approximately 84% (Fig. 9d). While this relative change is much less than the three-fold increase projected for vapor pressure (Fig. 9a), the interannual variability of saturation vapor pressure is approximately 65% larger than variability of actual vapor pressure, dictating that temperature variability will continue to be the dominant driver of VPD departures from the background trend (Fig. 9f). Nonetheless, 2011 serves as an example of the potential for extreme vapor-pressure anomalies to have impactful effects on VPD. Although models generally do not simulate dew-point and vapor-pressure anomalies as strong as those observed in 2011, projections of increased interannual variability for these variables suggests increasing likelihood of repeated 2011-like events where humidity is substantially reduced relative to the projected trend, contributing to positive VPD anomalies.

Combining the lessons learned from analyses of projected trends and variability, it is clear from
Figure 7 that warming and suppressed increases in atmospheric moisture content alone are projected to contribute to an increased frequency of years when VPD matches or exceeds 2011 levels. Superimposed upon the projected increase in mean VPD, interannual variations of temperature and dew point (e.g., departures of dew point from the projected trend line in Fig. 8) will have increasingly amplified effects on VPD due to the exponential relationship between temperature and saturation vapor pressure. Figure 10 demonstrates how VPD would be influenced by a 2011-type event in the 2050s, where observed 2011 temperature and dew-point anomalies are superimposed upon mean 2050s levels. Considering March–August, the period when VPD correlates strongest with SW burned forest area (Williams et al. in press), a 2011-type event in the 2050s would cause VPD to be 47% higher than the 1961–2005 average and 16% higher than in 2011.

4. Summary and Conclusions

2011 was an interesting year in terms of drought-related climate impacts in the SW because it was not exceptionally warm throughout the parts of Arizona and New Mexico where record-breaking forest fires occurred. VPD, on the other hand, was record-breaking in these areas because of exceptionally low atmospheric moisture content. Abatzoglou and Kolden (2013) and Williams et al. (in press) showed that SW annual burned area is closely tied to spring–summer potential evapotranspiration, VPD, and moisture deficit. These studies make it clear that record-breaking wildfire activity in 2011 was very likely promoted by record-low precipitation and record-high VPD.

Interestingly, VPD, which is normally dominated by temperature, was amplified in 2011 by
extremely low atmospheric moisture content. The meteorological conditions responsible for extremely low atmospheric moisture in 2011 were driven by an interaction of atmospheric, oceanic, and land-surface conditions. Among the most important contributing factors appear to have been record-setting low precipitation totals and a record-setting strong sea-level pressure gradient between the North Pacific Ocean and North America that drove dry northwesterly wind and subsidence anomalies toward the SW throughout the troposphere. Subsidence over the SW was enhanced by upper-level convergence associated with the La Niña-forced atmospheric wave train. Subsidence aloft led to divergence of dry, lower atmospheric winds across Arizona and much of New Mexico, blocking advection of moist air from both the subtropical Pacific and the Gulf of Mexico. Convergence of warm, dry winds in eastern New Mexico and west Texas interacted with exceptionally dry soils to cause record-breaking heat, further amplifying VPD in these areas.

Model projections suggest that 2011 conditions were representative of projected future climate in limited ways. CMIP5 climate projections tend to agree upon trends toward an enhanced sea-level pressure gradient between the North Pacific and North America, an enhanced upper-level pressure gradient between Mexico and the Pacific Northwest that drives convergence and subsidence upwind of and above the SW, a more negative PDO, and lower October–June precipitation totals. As atmospheric moisture content increases with warming globally, projected trends in the variables listed here combine to slow the projected atmospheric moisture increases in the SW, as indicated by a significant projected decline in SW relative humidity. These projections do not necessarily indicate increased frequency of 2011-type circulation extremes, but they nonetheless positively influence the frequency with which 2011 levels of VPD are
achieved in the CMIP5 projections. Further, CMIP5 models generally project the interannual
variability of SW dew point to increase, suggesting that large negative deviations of atmospheric
moisture from the background trend, such as that which occurred in 2011, will become
increasingly probable. Increased interannual variability in dew point amplifies the increase in
interannual VPD variability that is already expected due to the exponential Clausius-Clapeyron
response to warming alone.

Although the exceptional negative atmospheric moisture anomaly in spring–summer 2011 was
unprecedented in the observed record, CMIP5 projections suggest that 2011-like deviations in
atmospheric moisture content from background levels will become increasingly probable as the
globe warms. Importantly, recurrences of 2011-type events when temperature and atmospheric
moisture deviations combine to substantially amplify VPD will be superimposed upon
increasingly warm background temperatures that, on their own, will drive substantial increases in
SW VPD. By the 2050s, average spring–summer VPD is projected to surpass that of 2011.

Strong and non-linear relationships between temperature, VPD, and SW burned area (Williams
et al. in press) suggest that 2011-type precipitation and circulation anomalies, superimposed
upon substantially warmer background conditions, could have far more catastrophic wildfire
consequences than in the record-breaking wildfire year of 2011 if fuel characteristics are not
limiting.

Acknowledgments

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References


**Table 1.** Correlation matrix for 11 interrelated climate variables that influenced extreme SW drought in 2011. All climate records represent April–June except precipitation (October–June). Correlations represent 1961–2014 except for those involving G\textsubscript{300} or soil moisture (soil\textsubscript{m}) (1979–2014). Bold values: correlations significant above 95% confidence, accounting for lag-1 autocorrelation. NLDAS-2 wind-speed data were extended to 1961 using Sheffield et al. (2006) dataset.

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Figure Captions

Figure 1. Surface climate anomalies in 2011 for log(precipitation) (a), daily maximum temperature (b), dew point (c), and VPD (d). For each variable, this figure shows the period of 3–6 months during August 2010 through July 2011 with the strongest anomaly in the SW. Maps show spatial distributions of anomalies as standard deviations from the 1895–2013 mean. Time series show annual values averaged across the SW region, with red dots indicating 2011 values. In maps, red polygons bound the SW, black contours represent drought anomalies of 2 standard deviations, and yellow areas indicate locations of 2011 fires (Williams et al. in press).

Figure 2. March–July VPD anomalies (departure from the 1961–2013 mean of 15.17 hPa). Red and blue lines indicate partial contributions of temperature and dew point anomalies, respectively, toward the total anomaly (thick black). Partial contributions of temperature and dew point anomalies were calculated by only allowing one variable at a time to vary from its 1961–2013 mean.

Figure 3. April–June atmospheric circulation and surface temperature. Left panels: 1979–2014 means. Right panels: 2011 standardized anomalies. Arrow vectors: vertically integrated wind velocity. Panels (a and b): upper troposphere (300–200 hPa), background is 300 hPa geopotential height. Panels (c and d): middle troposphere (600–400 hPa), background is 500 hPa geopotential height. Panels (e and f): lower troposphere (surface to 700 hPa), background is sea-level pressure. Panels (g and h): surface temperature.
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Figure 7. CMIP5 climate projections. Red bars: ensemble-median of the average annual anomaly during 2035–2079 relative to 1961–2005. Whiskers: ensemble inner-quartile anomalies. Black bars: 2011 anomalies. Projected mean anomalies in 2035–2079 that fall within the dark and light grey areas are not significant at the 95% and 99% confidence levels, respectively, accounting for lag-1 autocorrelation in model data. Units of anomalies are standard deviations from the 1961–2005 mean, based on variability during that period. Red values on the left indicate absolute values of the ensemble-median anomalies based upon 1961–2005 observed variability. All variables represent April–June except for precipitation, which represents October–June. N indicates the number of models with required data.

Figure 8. Observed AMJ dew point in the SW during 1961–2014 overlaid on the CMIP5 ensemble-median (thick black curve) and inner-quartile trends (grey shading) trends. Dotted curves indicate standard deviation departures from the ensemble-median trend, based on 1961–2005 observed variability. Model time series were adjusted to exhibit observed variability during 1961–2005 (the period when the observed record overlaps with the historical model simulations) and the observed mean during 1961–2014.
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