

# El Niño Southern Oscillation (1896 to 2016): Quantifying Effects on Winter Precipitation and Temperature in Southwest Ohio, USA

ROBERT W. RITZI JR<sup>1</sup> and LAUREN M. ROBERSON, Department of Earth and Environmental Sciences, Wright State University, Dayton, OH, USA; MICHAEL BOTTOMLEY, Statistical Consulting Center, Wright State University, Dayton, OH, USA.

**ABSTRACT.** Continental-scale studies of North America suggest that the El Niño Southern Oscillation (ENSO) can cause winters to be warmer, with less precipitation, during El Niño conditions and colder, with more precipitation, during La Niña conditions in the Midwest United States. Two sources of historical records of precipitation and temperature in southwest Ohio from 1896 to 2016 were analyzed. Three statistical methodologies were used to test the hypothesis that anomalies in winter temperature and precipitation occurred in relation to ENSO phases. Eighty percent of El Niño winters had below-average winter precipitation; the average anomaly was  $-5$  cm. Precipitation decreased with increase in El Niño strength as measured by the Multivariate ENSO Index (MEI). These results were statistically significant beyond the 95% level. However, variation in MEI only accounted for 3% of the overall variability in winter precipitation. Many of the drier winters on record, including the extrema, occurred during neutral winters. During La Niña winters precipitation was not statistically significantly different from that in neutral winters. Winter temperature was not statistically significantly different during El Niño and La Niña winters within the century of record. The results were consistent between separate analyses of data from the 2 different sources.

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## INTRODUCTION

The El Niño Southern Oscillation (ENSO) is an atmospheric cycle originating in the central and eastern tropical Pacific Ocean (Diaz and Markgraf 1992; Capotondi et al. 2015; Lindsey 2016). The ENSO oscillates between El Niño and La Niña conditions, which involve changes in sea surface temperature, air temperature, wind circulation, and other sea surface and atmospheric properties. These alter both the Polar and Pacific jet streams, which in turn alter weather patterns around the world, including in North America (Ropelewski and Halpert 1987; Aceituno 1992; Zhang et al. 2011; Yu et al. 2012; Johnson et al. 2013; Yu and Zou 2013; Zhou et al. 2014; Lindsey 2017). In general, the impacts within the United States are during the cold half of the year (Halpert 2014). In affected regions, the resulting anomalies in precipitation and temperature can have societal effects on agriculture, flood control, water supply, and aquatic ecology, etc. (Hansen et al. 2001; Mitra et al. 2014). ENSO phases have variable strengths

(Wolter and Timlin 1998), and phases with similar strengths can have different effects on continental-scale weather (Arndt 2015).

Continental-scale studies have suggested that ENSO may affect winter temperature and precipitation in the Ohio and Upper Mississippi River Valley, and that the effect is most pronounced during the winter months—generally taken to include November through March (Barnston 2015; Lindsey 2017; Gabric et al. [date unknown]). El Niño conditions can extend the Pacific jet stream across the North American continent, causing warmer weather with less precipitation during the winter. La Niña conditions can cause the Polar jet stream to dip further south in North America, causing colder weather with increased precipitation during the winter (Zhang et al. 2011; Lindsey 2017; NOAA CPC 2019; NOAA PSL [date unknown]). Based on data from 1950 to present (Fig. 1), NOAA CPC (2019) indicates that during El Niño winters there is a greater than 80% probability that the Midwest region (Ohio, Indiana, Michigan,

<sup>1</sup>Address correspondence to Robert W. Ritzi Jr., Department of Earth and Environmental Sciences, 3640 Colonel Glenn Hwy., Wright State University, Dayton, OH 45430, USA. Email: robert.ritzi@wright.edu



and Illinois) will have on the order of 3 cm less precipitation. NOAA CPC (2019) also indicate a precipitation increase of the order of 3 cm with 60 to 80% probability during La Niña winters. The NOAA CPC (2019) results are based on data corrected and interpolated onto a  $0.25^\circ$  latitude  $\times$   $0.25^\circ$  longitude grid from an irregular nationwide network of stations as described by Xie et al. (2010). Using the CPC data from 1981 to 2014, Barnston (2015) found a similar precipitation anomaly during El Niño winters. The statistical significance of the anomalies calculated from the sample data and the confidence intervals on the estimates for probability of occurrence were not reported. In a more geographically focused study using data from 1957 to 1990 (8 El Niño winters), Gabric et al. ([date unknown]) found that for the Ohio Valley and Southern Great Lakes region, 87.5% of El Niño winters on record had less than average precipitation, with an average decrease of 4.6 cm. They also found that 62.5% of the El Niño years had an increase in temperature, with an average increase of  $0.25^\circ\text{C}$ . The statistical significance of these sample statistics were not reported. La Niña winters were not included in their study.

The interest of the current study is in the localized impact of ENSO on winter precipitation and temperature in southwest Ohio (Fig. 2). The variability in precipitation and temperature in southwest Ohio can be important within the context

of regional planning, flood control, water quality, and agriculture. Southwest Ohio includes major metropolitan areas (Cincinnati, Dayton) as well as some of the most productive agricultural lands in the Midwest. The metropolitan areas lie along rivers, and historical flooding of those rivers has played a significant role in the history of flood control engineering (Eckert 1981; Becker and Nolan 1988). Variations in precipitation and temperature impact crop production, which is mostly without irrigation. The region includes a number of watersheds (the largest being the Great Miami River watershed) (Fig. 2) which, increasing in scale, are comprised by the Ohio River watershed, the Mississippi River watershed, and ultimately terminate in the Gulf of Mexico. Precipitation and temperature in these watersheds, and their impact on agriculture, have a role in establishing water quality across scales (e.g., nutrients from agricultural runoff in the Midwest create zones of hypoxia in the Gulf of Mexico).

The goal of the current study was to examine historical records available from southwest Ohio (Fig. 2) for the effects of ENSO on winter precipitation and temperature. The historical records for precipitation and temperature span 121 years, longer than in any of the prior studies cited above. In addition to using longer records here, the current study adds an assessment of the statistical significance of anomalies in the sample statistics.

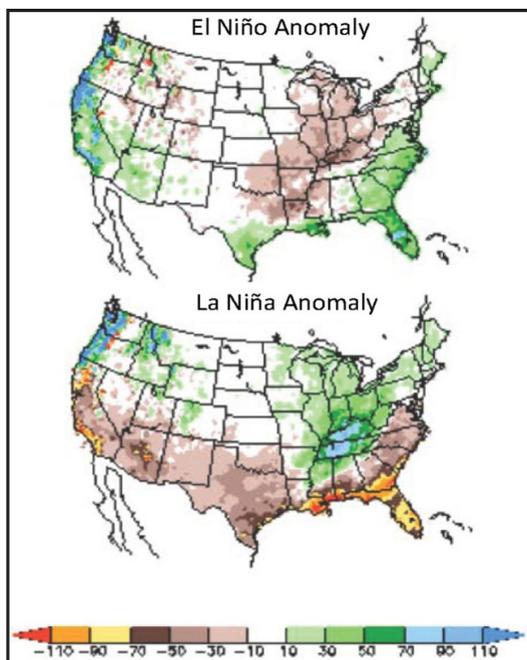


FIGURE 1. Expected precipitation anomalies (mm) in January through March as estimated by NOAA CPC (2019). (Top) El Niño. (Bottom) La Niña. Figure from NOAA CPC (2019).

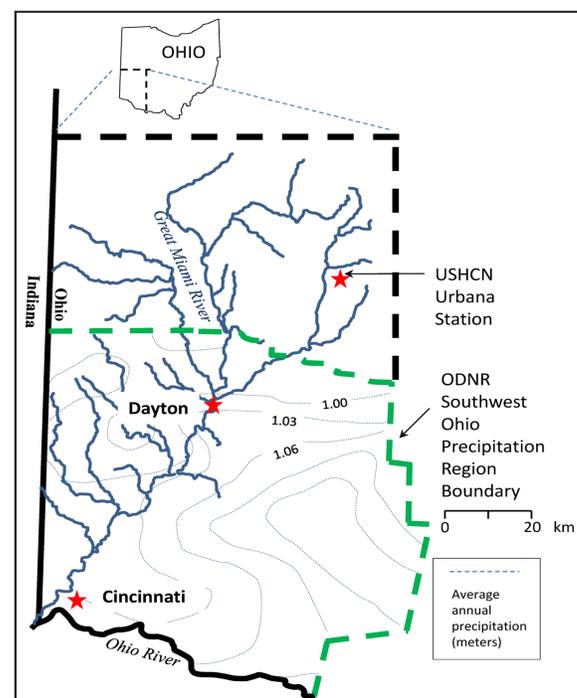


FIGURE 2. Southwest Ohio study area and data locations. Abbreviations used in figure: USHCN, U.S. Historical Climatology Network; ODNR, Ohio Department of Natural Resources.

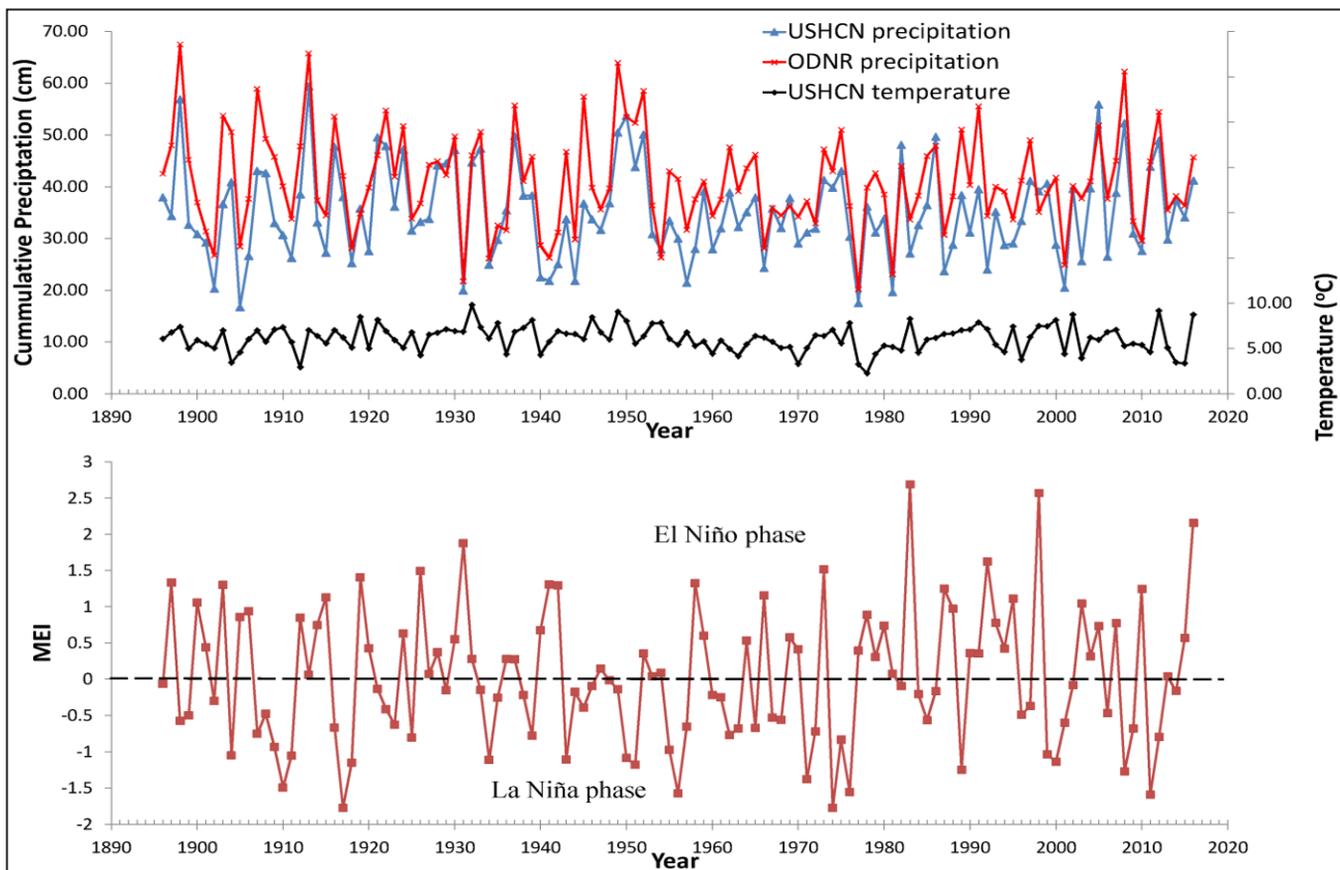
Based on the work reviewed above, the current study hypothesizes that winters during El Niño conditions most often had below-average precipitation and above-average temperatures, and that winters during La Niña conditions most often had above-average precipitation and below-average temperature (Table 1). The hypotheses are tested by statistically analyzing historical records of winter precipitation and temperature to determine if there are statistically significant anomalies during ENSO phases that are consistent with the hypotheses.

### DATA AND METHODS

The sample population data are from the 121 winters from 1896 to 2016 (Fig. 3). The data are the measured monthly-total precipitation and the monthly average of daytime high temperatures, published by the U.S. Historical Climatology Network (NOAA NCEI [date unknown a, date unknown b]), hereafter referred to as the USHCN records. The USHCN data were measured at station USH00338552 located near Urbana, Ohio (Fig. 2). The next nearest USHCN station (Kenton) is about

**Table 1**  
**Hypotheses for ENSO effects on winter precipitation and temperature in southwest Ohio**

Record	El Niño conditions	La Niña conditions
Precipitation	Below average	Above average
Temperature	Above average	Below average



**FIGURE 3.** Records for winter weather and the extended Multivariate ENSO Index (MEI). Cumulative precipitation is for November through March. Temperature is the average daily high in winter. Abbreviations used in figure: USHCN, U.S. Historical Climatology Network; ODNR, Ohio Department of Natural Resources.

100 km north and across the Gulf of Mexico/ Atlantic Ocean drainage divide. USHCN data have corrections for bias from such factors as changes in the time of observation (Karl et al. 1986), station moves, instrument changes (Karl and Williams 1987; Quayle et al. 1991), and urban bias (Karl et al. 1988).

Another historical record of monthly winter precipitation was analyzed. This second record, covering a period of time corresponding to the USHCN record, was published by the Ohio Department of Natural Resources (ODNRMWIR [date unknown]) and is hereafter referred to as the ODNR record. Each entry in this record is a monthly precipitation total that is spatially averaged from tens of stations located in their Southwest Ohio Precipitation Region, delineated in Fig. 2. The number and location of stations used in the average have varied with time, and the data do not have the adjustments for bias as applied to the USHCN data. The isohyetal contours (ODNR HAO [date unknown]) shown for the Southwest Ohio Precipitation Region in Fig. 2 exhibit only small gradients within the region, as expected given the low topographic relief and modest size of the region. The ODNR record has some limitations, as it is not adjusted for possible biases and is possibly smoothed from spatial averaging. However, it seems representative of the type of record that could be available for other study regions that lack a USHCN station with an adjusted record. Therefore, the

current report analyzed the ODNR data to see if any anomalies associated with ENSO, identified in the USHCN data set, can also be consistently identified in the unadjusted and aggregated ODNR record.

The ENSO cycle is represented in the analyses by the extended Multivariate ENSO Index, MEI (Wolter 2011). The MEI is determined from sea level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and cloudiness using data from the International Comprehensive Ocean Atmosphere Data Set (Wolter 2018). The MEI is increasingly positive with the strength of the El Niño phase and increasingly negative with the strength of the La Niña phase. The extended MEI was chosen (among possible ENSO indices) because it has been computed for the century-long time frame corresponding to the precipitation and temperature records (Fig. 3).

Because ENSO cycles differ in their strength, coverage, and seasonality, there is subjectivity in what constitutes an ENSO “event.” According to the NOAA Physical Sciences Laboratory (PSL), however, there are “broad agreements,” and NOAA PSL ([date unknown a]) identified El Niño and La Niña events that occurred from 1896 to 2016 (hereafter referred to as El Niño and La Niña winters). These are listed in Table 2 along with “neutral” (non-event) winters. Some of the analyses below are of the data subdivided into the 3 subpopulations shown in Table 2.

**Table 2**  
**Years with ENSO winters defined by NOAA PSL<sup>a</sup>**

El Niño									
1897	1900	1903	1906	1915	1919	1926	1931	1941	1942
1958	1966	1973	1978	1980	1983	1987	1988	1992	1995
1998	2003	2007	2010	2016					
Neutral									
1896	1898-1899	1901-1902	1905	1907-1908	1912-1914	1916	1920-1924	1927-1930	1932-1933
1935-1938	1940	1944-1949	1952-1954	1957	1959-1961	1963-1965	1967-1970	1972	1975
1977	1979	1981-1982	1984-1986	1990-1991	1993-1994	1996-1997	2001-2002	2004-2006	2009
2013-2015									
La Niña									
1904	1909	1910	1911	1917	1918	1925	1934	1939	1943
1950	1951	1955	1956	1962	1971	1974	1976	1989	1999
2000	2008	2011	2012						

<sup>a</sup>Based on the strength of the MEI index (NOAA PSL [date unknown a]). Years are referenced to January.

Winter is taken to be the 5 months from November to March, consistent with NOAA PSL ([date unknown b]) and Gabric et al. ([date unknown]). Prior studies have used various metrics including the 5-month winter-mean (NOAA PSL [date unknown b]; Gabric et al. [date unknown]) and a shorter 3-month mean (NOAA CPC 2019). Here, 4 metrics were used for winter precipitation and 3 were used for winter temperature (Table 3). The precipitation metrics include (a) the cumulative-total winter precipitation and (b) the 5-month winter-mean precipitation; these metrics might show seasonal-scale anomalies due to ENSO effects. The other 2 precipitation metrics are (c) the maximum-month precipitation (i.e., the value for the month with the highest value within each season) and (d) the minimum-month precipitation; these metrics might show shorter (1 month) scale anomalies that might not be identified with the season-long metrics. The temperature metrics

included the mean monthly, the maximum-month, and the minimum-month winter temperature. Summary statistics for these metrics are listed in Table 3.

Fig. 4a shows, for example, the cumulative winter precipitation metric plotted after subdividing the data into the subpopulations of El Niño winters, La Niña winters, and neutral winters. The winters with the greatest and the least precipitation occur in neutral years, and ENSO phases do not appear to contribute any more than neutral years to the overall variation in precipitation. Note that there is no strong visual indication of a non-stationary mean or variance within each data subpopulation. Fig. 4b shows the mean monthly temperature metric utilizing the same 3 subpopulations; it has the same characteristics as Fig. 4a and similarly does not indicate that ENSO phases contribute any more than neutral years to the overall variation. This is also true for plots of all of the other metrics.

**Table 3**  
**Summary statistics for metrics on winter precipitation and temperature <sup>a</sup>**

Winter precipitation (cm)								
USHCN data	All winters		El Niño winters		Neutral winters		La Niña winters	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Cumulative	35.16	8.88	30.40	6.10	36.35	9.43	36.52	7.87
Mean monthly	7.03	1.78	6.08	1.22	7.27	1.89	7.30	1.57
Maximum-month	11.53	4.62	9.57	2.32	12.31	5.02	11.53	4.31
Minimum-month	3.20	1.55	2.68	1.34	3.27	1.55	3.54	1.64
ODNR data								
Cumulative	41.02	9.36	36.65	7.24	41.76	9.96	43.34	8.49
Mean monthly	8.20	1.87	7.33	1.45	8.35	1.99	8.67	1.70
Maximum-month	13.13	4.64	11.26	2.83	13.69	5.11	13.59	4.19
Minimum-month	3.93	1.60	3.43	1.50	4.00	1.59	4.23	1.70
Winter temperature (°C)								
USHCN data	All winters		El Niño winters		Neutral winters		La Niña winters	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Mean monthly	6.12	1.43	6.30	1.41	5.96	1.43	6.42	1.34
Maximum-month	11.68	2.06	11.92	1.39	11.50	2.19	11.95	2.17
Minimum-month	1.10	2.40	1.33	2.02	0.89	2.56	1.48	2.18

<sup>a</sup>Includes 121 winters: 25 El Niño, 24 La Niña, and 72 neutral.

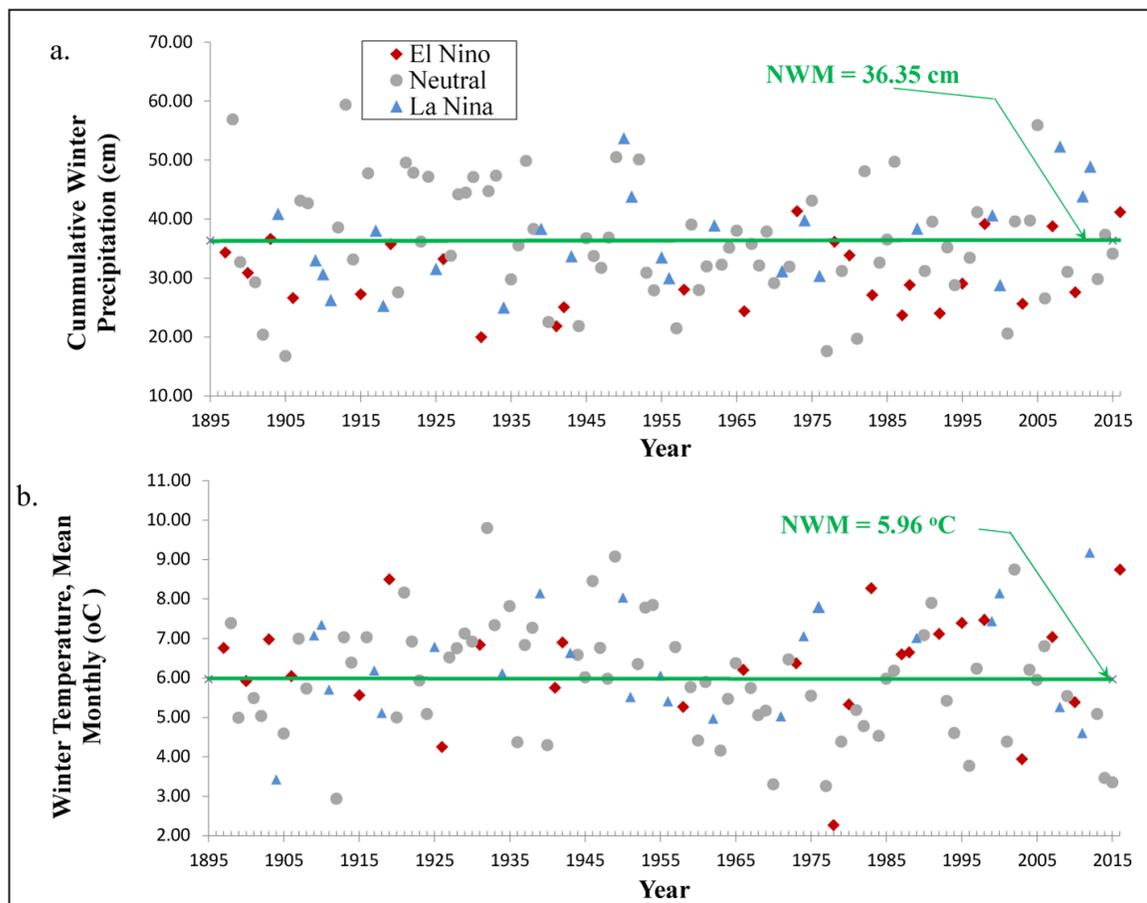


FIGURE 4. USHCN records divided into El Niño winter, La Niña winter, and neutral winter subpopulations. (a) Cumulative winter precipitation. (b) Mean monthly winter temperature (daily highs). Green horizontal line is the neutral-winter mean (NWM).

Three statistical methods were used to test the hypotheses. Two of the methods used the data subdivided into 3 subpopulations defined as El Niño winters, La Niña winters, and neutral winters, consistent with previous studies (Gabric et al. [date unknown]; NOAA CPC 2019). The first method quantified the proportion of El Niño or La Niña winters in which a metric fell above or below the mean of all neutral winters. The second method used an independent-samples  $t$ -test comparison of the mean value of a metric for all El Niño or La Niña winters against the mean of all neutral winters; this method tests whether or not the means are statistically significantly different. The third method was not based on the trinary categorization of the ENSO cycle; instead, the effect of the continuous cycle of ENSO conditions was considered by analyzing the variations in precipitation and temperature metrics as a function of the extended MEI, using linear regression.

The  $t$ -tests and regression analyses assume normality of error terms and constant variance. These assumptions were assessed via residual plots

and deemed to be satisfied for all metrics except the maximum-month precipitation. The maximum-month precipitation data were skewed, and the model assumptions were met by using a natural log transformation in the  $t$ -tests and regression for that metric. Each of these methods is described in the remainder of this section.

Note that studies such as Mitra et al. (2014) have used spectral methods to define the frequency of ENSO phases and the attenuation and phase lag in the response of hydrometeorologic processes. Such methods are relevant if there is uncertainty over when an ENSO phase occurred and if a multi-year lag is expected in the response (such as might be true with the piezometric surface in aquifers with significant storage). In the current study the years of ENSO winters are known, and any effects on precipitation and temperature are expected to occur within the winter of those years. Questions on the spectral frequency at which ENSO phases occurred and evaluation of the phase lag in hydrometeorologic responses are outside of the scope of this article, and thus spectral decomposition was not employed.

### Proportion of El Niño or La Niña Winters with Temperature or Precipitation Above or Below the Neutral-winter Mean

The sample proportion of El Niño and La Niña winters in which a metric fell above or below the neutral-winter mean (NWM) were calculated to give an estimate of the proportion of El Niño and La Niña winters in which the metric was, relative to the NWM, consistent with the hypotheses above. For example, a result supportive of the El Niño hypothesis would be that the sample proportion of El Niño winters that had cumulative precipitation less than the NWM, and the 95% confidence interval (CI), all fall above 0.5. A result supportive of the La Niña hypothesis would be that the sample proportion of La Niña winters with cumulative precipitation greater than the NWM, and the 95% CI, are all above 0.5. All confidence intervals were calculated via the Wilson score interval methodology (Wilson 1927).

### Independent Samples t-test Comparison of the Mean Winter Values

Statistical tests for difference in the means should be constructed with a null hypothesis ( $H_0$ ) that is hoped to be rejected. Here the  $H_0$  states that the mean during El Niño or La Niña winters is the same as the NWM. Rejection of  $H_0$  was defined to be a probability of error (Type I) less than 0.05 in one-tailed tests (Walpole and Myers 1972). Rejection of  $H_0$  supports the alternative hypotheses ( $H_1$ ). For example, in considering cumulative precipitation in El Niño winters,  $H_1$  states that the mean was less than the NWM. For La Niña winters,  $H_1$  states that the mean was greater than the NWM.

### Linear Regression

An example of a result consistent with the research hypotheses would be a regression model for cumulative precipitation vs. MEI that is statistically significant (taken as a  $p$ -value less than or equal to 0.05) and has a negative slope. An  $R^2$  value above 0.25 indicates that MEI explains a meaningful proportion of the variance in precipitation (Cohen 1988), and a value below 0.25 would not support the conclusion that MEI is a significant control on the variance.

## RESULTS

### Results from Analyses of ENSO Winters

*Precipitation in El Niño winters.* The sample proportion of El Niño winters that had precipitation metrics below the NWM in the USHCN record is given in Table 4, along with the 95% CI. Of El Niño winters, 80% had cumulative winter precipitation less than the NWM; this result is consistent with Fig. 4a. Also, 80% had mean monthly precipitation less than the NWM, 92% had less precipitation than the NWM in the maximum-month of a winter, and 72% had less precipitation than the NWM in the minimum-month of a winter. The 95% CI on the sample proportions listed in Table 4 fall entirely above 0.5, and thus these results are unambiguously consistent with the research hypothesis that El Niño winters have had less precipitation. The results from the ODNR sample population are similar, except that the 95% CI for minimum-month precipitation is not entirely above 0.5.

The results of the statistical tests for difference in the means are listed in Table 5. In the USHCN record, the mean cumulative precipitation in El Niño winters was 5.96 cm less than the NWM, and the monthly average was 1.19 cm less. These anomalies are statistically significant with  $p$ -values of  $3.5E-04$ . The anomalies for the maximum-month and minimum-month precipitation metrics are also statistically significant ( $p = 2.5E-05$ ,  $p = 0.04$ , respectively). The results are similar for the ODNR record, except the  $p$ -value for the minimum-month precipitation is slightly above 0.05.

Collectively, these results show that El Niño winters in southwest Ohio have most often had less precipitation than neutral winters, with an average of 5 to 6 cm less per 5 month winter season, or about 1 cm less per month on average. The month that had the most precipitation in a season had about 3 cm less on average than neutral winters. These results were consistent between the USHCN and ODNR records. The month that had least precipitation during a winter season had 0.6 cm less in the USHCN record, a small but statistically significant anomaly. The result from the ODNR record for this metric is consistent but is equivocal with respect to its statistical significance.

**Table 4**  
**Proportion of El Niño and La Niña winters with mean above or below the neutral-winter mean (NWM) <sup>a</sup>. The 95% confidence intervals (CI) are given in parentheses.**

<b>Winter precipitation</b>		
<b>USHCN data</b>	<b>Proportion of El Niño winters below the NWM<sup>b</sup></b>	<b>Proportion of La Niña winters above the NWM<sup>b</sup></b>
Cumulative	0.80 (0.61, 0.91)	0.50 (0.31, 0.69)
Mean monthly	0.80 (0.61, 0.91)	0.50 (0.31, 0.69)
Maximum-month	0.92 (0.75, 0.98)	0.25 (0.12, 0.45)
Minimum-month	0.72 (0.52, 0.86)	0.42 (0.25, 0.61)
<b>ODNR data</b>		
Cumulative	0.80 (0.61, 0.91)	0.58 (0.39, 0.76)
Mean monthly	0.80 (0.61, 0.91)	0.58 (0.39, 0.76)
Maximum-month	0.88 (0.70, 0.96)	0.33 (0.18, 0.53)
Minimum-month	0.68 (0.48, 0.83)	0.50 (0.31, 0.69)
<b>Winter temperature</b>		
<b>USHCN data</b>	<b>Proportion of El Niño winters above the NWM<sup>b</sup></b>	<b>Proportion of La Niña winters below the NWM<sup>b</sup></b>
Mean monthly	0.64 (0.45, 0.82)	0.38 (0.22, 0.57)
Maximum-month	0.6 (0.4, 0.79)	0.50 (0.31, 0.69)
Minimum-month	0.72 (0.54, 0.89)	0.41 (0.24, 0.61)

<sup>a</sup>Includes 121 winters: 25 El Niño, 24 La Niña, and 72 neutral.

<sup>b</sup>Highlighted values color key: Green, proportion and confidence interval all above 50%. Yellow, proportion above 50% but not the 95% CI. Red, proportion not above 50%.

**Precipitation in La Niña winters.** In both the USHCN and ODNR records, for all the metrics, the proportion of the La Niña winters with precipitation above the NWM and the low end of the 95% CI were not above 0.5 (Table 4). In the results of the statistical tests for difference in the means, listed in Table 5, the  $p$ -values are all well above 0.05, and thus none of the anomalies in La Niña winters are statistically significant. The results for all the precipitation metrics, collectively, do not support the hypothesis that La Niña winters more often had above average precipitation.

**Temperature in El Niño winters.** The sample proportion of El Niño winters that had temperature metrics above the NWM in the USHCN record is given in Table 4. The values are above 0.5 for the mean monthly, the maximum-month, and

the minimum-month metrics. However, the low end of the 95% CI was above 0.5 only for the minimum-month metric. The anomalies listed in Table 5 are positive for all the temperature metrics, consistent with the hypothesis. However,  $p$ -values in all cases are above 0.05 and so the differences are not statistically significant. The null hypothesis of zero difference in mean temperature during El Niño winters cannot be rejected for any metric. Thus, the results do not collectively support the hypothesis that El Niño winters were warmer on average.

**Temperature in La Niña winters.** The sample proportion of La Niña winters that had temperature metrics below the NWM in the USHCN record is given in Table 4. The results are not above 0.5 for any of the metrics. The results in Table 5 show all the mean temperature metrics were above the

Table 5

## Results from hypothesis testing on differences in the mean with unknown and unequal variances

Precipitation: El Niño					
<u>USHCN data</u>	<u>Anomaly (difference from NWM) (cm)</u>	<u>Null hypothesis</u>	<u>Alternate hypothesis</u>	<u>Result<sup>a</sup></u>	<u>p-value</u>
Cumulative	-5.96	Equals NWM	<NWM	Reject null	3.5E-04
Mean monthly	-1.19	Equals NWM	<NWM	Reject null	3.5E-04
Maximum-month	-2.74 <sup>b</sup>	Equals NWM	<NWM	Reject null	2.5E-05
Minimum-month	-0.59	Equals NWM	<NWM	Reject null	0.040
<u>ODNR data</u>					
Cumulative	-5.12	Equals NWM	<NWM	Reject null	0.004
Mean monthly	-1.02	Equals NWM	<NWM	Reject null	0.004
Maximum-month	-2.44 <sup>b</sup>	Equals NWM	<NWM	Reject null	0.001
Minimum-month	-0.57	Equals NWM	<NWM	Cannot reject null	0.056
Precipitation: La Niña					
<u>USHCN data</u>	<u>Anomaly (difference from NWM) (cm)</u>	<u>Null hypothesis</u>	<u>Alternate hypothesis</u>	<u>Result<sup>a</sup></u>	<u>p-value</u>
Cumulative	0.17	Equals NWM	>NWM	Cannot reject null	0.466
Mean monthly	0.03	Equals NWM	>NWM	Cannot reject null	0.466
Maximum-month	-0.78 <sup>b</sup>	Equals NWM	>NWM	Cannot reject null	0.171
Minimum-month	0.27	Equals NWM	>NWM	Cannot reject null	0.248
<u>ODNR data</u>					
Cumulative	1.58	Equals NWM	>NWM	Cannot reject null	0.227
Mean monthly	0.32	Equals NWM	>NWM	Cannot reject null	0.227
Maximum-month	-0.10 <sup>b</sup>	Equals NWM	>NWM	Cannot reject null	0.372
Minimum-month	0.23	Equals NWM	>NWM	Cannot reject null	0.283
Temperature: El Niño					
<u>USHCN data</u>	<u>Anomaly (difference from NWM) ( °C)</u>	<u>Null hypothesis</u>	<u>Alternate hypothesis</u>	<u>Result<sup>a</sup></u>	<u>p-value</u>
Mean monthly	0.34	Equals NWM	>NWM	Cannot reject null	0.160
Maximum-month	0.42	Equals NWM	>NWM	Cannot reject null	0.142
Minimum-month	0.44	Equals NWM	>NWM	Cannot reject null	0.198
Temperature: La Niña					
<u>USHCN data</u>	<u>Anomaly (difference from NWM) ( °C)</u>	<u>Null hypothesis</u>	<u>Alternate hypothesis</u>	<u>Result<sup>a</sup></u>	<u>p-value</u>
Mean monthly	0.45	Equals NWM	<NWM	Cannot reject null	0.086
Maximum-month	0.45	Equals NWM	<NWM	Cannot reject null	0.199
Minimum-month	0.59	Equals NWM	<NWM	Cannot reject null	0.145

<sup>a</sup> Highlighted values color key: Green, reject the null hypothesis with  $p$ -value less than 0.05. Yellow, cannot reject the null hypothesis at the 0.05 level but  $p$ -value is close. Red, cannot reject the null hypothesis.

<sup>b</sup> The hypothesis test used the natural-log transform and the anomaly is stated as the difference in the geometric means.

NWM. Thus, the hypothesis that La Niña winters are more often cooler is contradicted by the sample proportions and means. Furthermore, the 95% CI on estimates of proportion all span the threshold of 0.5, and the differences in the means from neutral winters all have  $p$ -values above 0.05. Therefore, statistically significant anomalies (positive or negative) in the metrics are not present. These results do not support the hypothesis that La Niña winters were more often cooler with mean temperature below the NWM.

### Regression Analyses of Winter Precipitation and Temperature as a Function of the MEI

A regression of cumulative winter precipitation as a function of MEI, using the USHCN record, is shown in Fig. 5a. The slope of the model is negative, consistent with the research hypothesis, and gives a mean decrease of 1.9 cm in winter per unit increase in the MEI (a decrease of 0.38 cm in mean monthly precipitation). Table 6 shows that the  $p$ -values for the cumulative winter precipitation and the mean monthly precipitation metrics are both less than 0.05, a result also consistent with the hypothesis.

Table 6 shows the results of the regression analyses of the other precipitation metrics, for both data sets. The slopes for all the precipitation metrics using either data record are negative and thus

consistent with the hypothesis. The  $p$ -value for the  $\ln(\text{maximum-month})$  and the minimum-month metrics are less than 0.05 for the ODNR record, but not for the USHCN record though it is close for the  $\ln(\text{maximum-month})$  metric.

The results from both records, for both the cumulative and the mean monthly winter precipitation, indicate that under stronger El Niño conditions winters have had less precipitation. However, the adjusted  $R^2$  values for the results with all metrics, using either record, range from 0.05 to much smaller values (all well below 0.25). Thus, these models account for a very small amount of the overall variability in winter precipitation, and the results do not support MEI being a significant control on the variance.

The results of the regression analysis of the winter temperature metrics as a function of MEI are also listed in Table 6. Fig. 5b shows one example for mean monthly temperature. In all cases the slopes are negative, which is inconsistent with the hypothesis. In all cases the magnitudes of the slopes are negligible, the  $p$ -values greatly exceed 0.05, and the adjusted  $R^2$  values are negligible. These results do not support the hypothesis that past winter temperatures were affected by ENSO, and do not support the specific hypotheses that El Niño winters have been warmer and La Niña winters have been colder in this region.

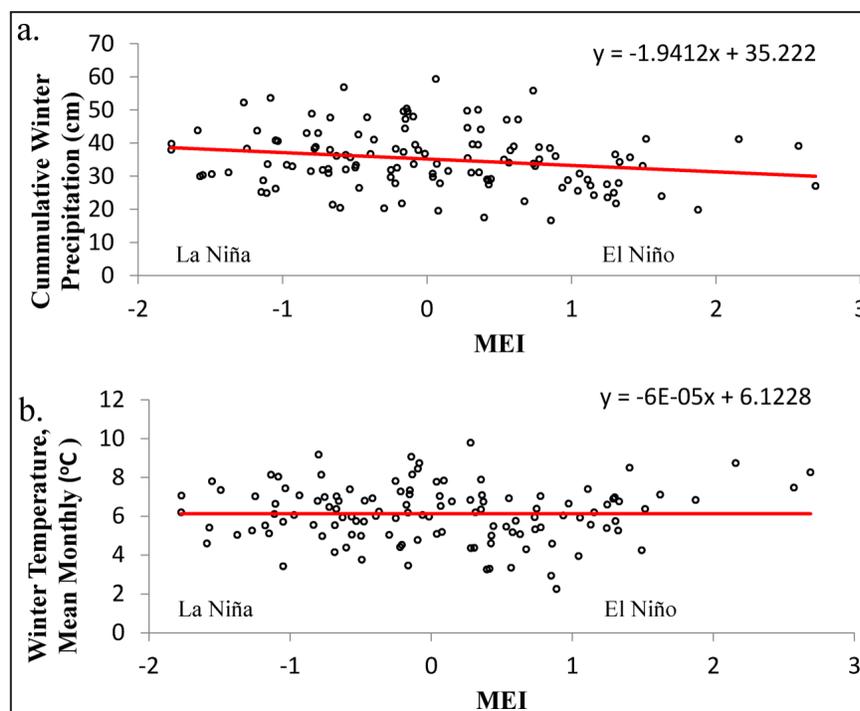


FIGURE 5. Examples of linear regression for (a) cumulative winter precipitation and (b) mean monthly winter temperature (daily highs) vs. the extended Multivariate ENSO Index (MEI)

**Table 6**  
**Results from linear regression <sup>a</sup>**

<b>Winter precipitation (cm)</b>			
<b>USHCN data</b>	<b>Slope</b>	<b><i>p</i>-value</b>	<b>Adjusted <i>R</i><sup>2</sup></b>
Cumulative	-1.94115	0.025658	0.033087
Mean monthly	-0.38823	0.025658	0.033087
ln(maximum-month)	-0.06129	0.054971	0.022455
Minimum-month	-0.18779	0.220535	0.004288
<b>ODNR data</b>			
Cumulative	-2.46393	0.006946	0.051736
Mean monthly	-0.49279	0.006946	0.051736
ln(maximum-month)	-0.06158	0.040065	0.026835
Minimum-month	-0.31319	0.045867	0.024955
<b>Winter temperature ( °C)</b>			
<b>USHCN data</b>	<b>Slope</b>	<b><i>p</i>-value</b>	<b>Adjusted <i>R</i><sup>2</sup></b>
Mean monthly	-6.5E-05	0.999633	<1E-9
Maximum-month	-0.07855	0.699445	<1E-3
Minimum-month	-0.05143	0.828637	<1E-4

<sup>a</sup> Highlighted values color key: Green, slope is consistent with hypotheses or *p*-value is less than 0.05. Yellow, *p*-value is close to 0.05 but slightly above. Red, slope is inconsistent with hypotheses or *p*-value is greater than 0.05 or adjusted *R*<sup>2</sup> value is less than 0.25.

## **DISCUSSION AND SUMMARY**

### **El Niño Winters have Commonly had Less Precipitation**

The century-long historical records in southwest Ohio support the hypothesis that El Niño winters have more often had less precipitation. The record indicates an 80% probability (+11%, -19%) of lower precipitation in the winter months of November through March. Mean monthly precipitation in those months was on the order of a centimeter lower than the mean in neutral winters. Cumulative winter precipitation was on average 5 cm lower. These results are generally consistent with those of Gabric et al. ([date unknown]) and NOAA CPC (2019), and are consistent with the research hypothesis. Furthermore, while the prior studies had identified an anomaly in mean precipitation during El Niño winters, it was shown in the current study (with a longer data record)

that the anomaly is statistically significant beyond the *p*=0.05 level. Stronger El Niño conditions produced drier winters, with 2 cm less precipitation per unit increase in the MEI metric for El Niño strength. Variation in the MEI, however, only explains about 3% of the overall variability in winter precipitation. Many of the drier winters, including the driest on record, have occurred in neutral years. Therefore, while an El Niño condition was an indicator for a drier than average winter, variations in winter precipitation were large—with very dry conditions in neutral winters.

### **The Record Does Not Support that El Niño Winters have been Warmer**

The historical record does not support the hypothesis that El Niño winters were warmer than average. Although more than half of the El Niño winters had a temperature above the neutral-winter

mean, the 95% CI on the proportion statistics are not above 0.5 for the majority of the temperature metrics. Importantly, for any of the 3 metrics, the difference in the mean temperature between El Niño and neutral years was not statistically significant. Regression analyses do not show a significant relationship between winter temperature and MEI.

### **The Record Does Not Support that La Niña Winters have been Cooler with More Precipitation**

The historical record does not support the hypothesis that La Niña conditions have affected winter precipitation or temperature. The results of the analysis of proportions of winters where the temperature metrics fell above or below the neutral-winter mean were ambiguous. Also, the mean differences in precipitation and temperature from the neutral-winter mean were not statistically significant.

### **Relationship of these Results to those from Prior Studies**

The results of the current study represent the southwest Ohio region only, and should not be taken to represent the broader region of Ohio or the Midwest. For example, winter weather in northern Ohio is strongly influenced by Lake Erie; an analysis of data from this region, such as included in Gabric et al. ([date unknown]), may show different relationships to ENSO phenomena. Indeed, studies at a local scale complement broader studies at the regional or continental scale. For example, the difference in conclusions between the current study and the broader studies by Gabric et al. ([date unknown]) and NOAA CPC (2019) may indicate that southwest Ohio comprises a relatively neutral area lying between regions, to the north and south, that are more strongly impacted by ENSO cycles.

Alternatively, the differences in results may simply arise from the longer data record used in the current study, or from the requirement that differences must be statistically significant to be accepted. Local-region studies should be encouraged, especially if there are more extensive data records available that allow for reducing the uncertainty in sample statistics within the context of estimation and testing the hypotheses

about anomalies. Ultimately, these additional studies could be useful in characterizing the influence of ENSO, if existent, on more local hydrometeorological processes.

The results of analyses using the USHCN record and the ODNR record for precipitation were generally consistent. The El Niño anomaly could still be identified in the ODNR record, despite that record being spatially averaged and lacking the adjustments for bias applied to the USHCN record. This provides optimism for the success of similar local studies in other regions that lack a nearby USHCN station and have only unadjusted records to analyze.

### **Relationship of these Results to Societal Concerns**

These results indicate that as the ENSO cycle in the eastern Pacific trends toward an El Niño condition, less winter precipitation can be anticipated in southwest Ohio. This result was previously indicated by NOAA CPC (2019) for the larger Midwest. The confirmation here, using local data and with an assessment of the statistical significance of the anomaly, adds weight to this conclusion. This knowledge is societally relevant when considering activities that might be affected by deficits in winter precipitation, such as agriculture and outdoor winter recreation. Farmers might plan for drier soil conditions at the start of spring planting season. Alpine skiing venues might plan for additional snowmaking.

These results do not indicate that La Niña winters should be colder with more precipitation in southwest Ohio. The development of a La Niña phase should therefore not engender concern, such as about a higher probability for increased spring runoff and associated flood risk. For example, in anticipating the development of a La Niña condition in late fall of 2017, one Dayton, Ohio, meteorologist reported “if we are indeed entering a La Niña pattern, then we can expect a wet winter” (Elwell 2017). Such a forecast is contraindicated by our analysis of the historical record for the local region. Furthermore, we found no indication that El Niño or La Niña conditions in the eastern Pacific should be used to forecast warmer or colder winters in southwest Ohio.

## Conclusions

Records over the last century of winter precipitation and temperature in southwest Ohio support the hypothesis that El Niño conditions, occurring in the eastern Pacific, decrease winter precipitation in the southwest Ohio region. Eighty percent of El Niño winters had below-average winter precipitation. The average anomaly in precipitation for the winter season (November through March) was of the order of  $-5$  cm, and the average anomaly in the driest month of winter was of the order of  $-3$  cm. Precipitation decreased with the increase in the MEI measure of El Niño strength. These results were statistically significant beyond the  $p = 0.05$  level. However, departures from average were large in neutral winters, and El Niño winters only explain about 3% of the variance in winter precipitation. Many of the driest winters, including the driest on record, have occurred in neutral winters. Therefore, while the El Niño condition has been associated with drier winters, variations in winter precipitation were large and very dry winters have occurred independent of El Niño conditions. The historical records do not support the hypothesis that winter precipitation has been statistically significantly different from neutral winters during La Niña conditions. The historical records, furthermore, do not support the hypothesis that winter temperature has been statistically significantly different during El Niño or La Niña winters relative to neutral winters.

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