Relating coccidioidomycosis (valley fever) incidence to soil moisture conditions

E. J. Coopersmith1, J. E. Bell2,3,4,5, K. Benedict4, J. Shriber5, O. McCotter4, and M. H. Cosh1

1USDA-ARS-Hydrology and Remote Sensing Laboratory, Beltsville, Maryland, USA, 2Cooperative Institute for Climate and Satellites-NC, Asheville, North Carolina, USA, 3NOAA-National Centers for Environmental Information, Asheville, North Carolina, USA, 4Centers for Disease Control and Prevention, Atlanta, Georgia, USA, 5Department of Public Health, Emory University, Atlanta, Georgia, USA

Abstract Coccidioidomycosis (also called Valley fever) is caused by a soilborne fungus, Coccidioides spp., in arid regions of the southwestern United States. Though some who develop infections from this fungus remain asymptomatic, others develop respiratory disease as a consequence. Less commonly, severe illness and death can occur when the infection spreads to other regions of the body. Previous analyses have attempted to connect the incidence of coccidioidomycosis to broadly available climatic measurements, such as precipitation or temperature. However, with the limited availability of long-term, in situ soil moisture data sets, it has not been feasible to perform a direct analysis of the relationships between soil moisture levels and coccidioidomycosis incidence on a larger temporal and spatial scale. Utilizing in situ soil moisture gauges throughout the southwest from the U.S. Climate Reference Network and a model with which to extend those estimates, this work connects periods of higher and lower soil moisture in Arizona and California between 2002 and 2014 to the reported incidence of coccidioidomycosis. The results indicate that in both states, coccidioidomycosis incidence is related to soil moisture levels from previous summers and falls. Stated differently, a higher number of coccidioidomycosis cases are likely to be reported if previous bands of months have been atypically wet or dry, depending on the location.

1. Introduction

Coccidioidomycosis is caused by the fungus Coccidioides spp., which is found in the soils of the southwestern United States, south central Washington State, and regions of South America, Central America, and Mexico. This disease can cause flu-like symptoms, which can persist for weeks or even months. In a minority of cases, the infection can lead to pulmonary complications or spread from the lungs to other organ systems, leading to conditions of greater severity, such as meningitis [Rosenstein et al., 2001; Galgiani et al., 2005] or death [Kolivras et al., 2001; Huang et al., 2012]. Though inhalation of these spores does not always cause illness, those who do become ill are hospitalized in over 40% of cases, with 75% of patients unable to perform their normal daily activities for a median of 47 days [Tsang et al., 2010].

Previous research has noted relationships between climatic features for which data are widely available and the incidence of coccidioidomycosis, noting proposed hydroclimatic and biological mechanisms by which these infections occur. Kolivras and Comrie (2003), focusing their study upon Pima county in Arizona, hypothesized that a dry foresummer or fall kills other microorganisms that might compete with Coccidioides. Subsequently, winter rainfall leads to the spore formation that results in high incidence during the following year. A subsequent analysis by Comrie [2005] also addressed the seasonal patterns of precipitation and temperature as they relate to the reported cases of coccidioidomycosis. They, too, noted that precipitation during the preceding year’s summer or even the summer from 2 years previous is inversely related to reported cases of coccidioidomycosis. This “grow and blow” hypothesis, in which wetter conditions cause spore formation and drier conditions facilitate their distribution, is corroborated in Tamerius and Comrie [2011], where fall precipitation is correlated with exposures during the subsequent year. Other works attempted to locate the ecological niche for Coccidioides within the arid Southwest [Baptista-Rosas et al., 2007] using soil characteristics and other features, including moisture. Finally, Stacy et al. [2012] employed normalized difference vegetation index as a proxy for soil moisture, showing antecedent winter precipitation’s impact on incidence during the following year.

Unfortunately, in none of these cases were soil moisture data available in sufficient temporal and spatial scope to allow a more direct analysis—the effects of soil moisture on coccidioidomycosis incidence. Three...
figures from some of the works cited within the literature review are worth mentioning. Figure 5 from Kolivras et al. [2001] presents bimodal annual precipitation patterns in Arizona along with the annual pattern of valley fever incidence. This figure illustrates that the monthly precipitation pattern in Pima county, AZ, does not describe (at least in large part) the pattern of coccidioidomycosis incidence. Figures 1 and 2 from Comrie [2005] illustrate, in the same county, annual and monthly precipitation patterns that do not align with coccidioidomycosis incidence rates. As a result, soil moisture data provide an additional layer of insight to the analysis. However, in addition to precipitation gauges at U.S. Climate Reference Network (USCRN) [Bell et al., 2013; Diamond et al., 2013] locations in California and Arizona (Figure 1), an in situ record has become available after 2010. Moreover, USCRN sites contain colocated precipitation instruments. Many of these instruments predate the installation of soil moisture gauges by several years, facilitating the calibration of a precipitation driven soil moisture model (the diagnostic soil moisture equation) [Pan et al., 2003; Pan, 2012] that can be used to achieve two objectives. The first is to extend the soil moisture record backward temporally to the original installation of precipitation sensors—this was done in Coopersmith et al. [2015a]. Second, by generating such a model, gaps in the soil moisture record (e.g., a day when a sensor was damaged by ambient meteorological conditions and a period during which readings were not recorded) can be filled with the model’s estimate. As a result, a longer, more robust soil moisture record in Arizona and California is now available, enabling the types of direct comparisons not previously plausible with earlier in situ sensory resources.

2. Methodology

2.1. Defining the Coccidioidomycosis Data Set

Coccidioidomycosis is currently a reportable disease in 22 states and is nationally notifiable to the U.S. Centers for Disease Control and Prevention through the National Notifiable Diseases Surveillance System (NNDSS). We used the number of monthly coccidioidomycosis cases reported to NNDSS, by county, in Arizona and California during 2000–2014 to facilitate appropriate comparisons to determine robust relationships between soil moisture conditions and coccidioidomycosis. We normalized the numbers of reported cases by the populations of the counties in which those cases are reported. In California, 2000 and 2010 county census estimates are publically available from http://censusviewer.com/counties/CA. The 2014 population figures by county can be obtained from http://quickfacts.census.gov/qfd/maps/california_map.html. For years between 2000 and 2010 or between 2010 and 2014, a linear interpolation was performed.
The linear interpretation was performed for every year and county in California for which reported cases of coccidioidomycosis were available, and in analogous fashion for Arizona (data are available from and http://censusviewer.com/counties/AZ and http://quickfacts.census.gov/qfd/maps/arizona_map.html, respectively). From here, we converted every monthly county estimate as shown in equation (1):

\[
\text{normalized}_\text{VF}_{c,m,y} = \frac{\text{VF}_{c,m,y}}{P_y} \times 1,000,000.
\] (1)

In equation (1), \(\text{VF}_{c,m,y}\) signifies the reported cases of coccidioidomycosis in a given county during a given month of a given year, \(P_y\) denotes the estimated population during that year, and \(\text{normalized}_\text{VF}_{c,m,y}\) represents the number of cases reported per one million residents.

 Counties with small populations and few reported cases can skew results. For this reason, counties in which the averages of reported coccidioidomycosis cases did not exceed 10 per month were excluded from subsequent analysis. The resulting subset of data included three counties in Arizona (Pima, Pinal, and Maricopa) and six counties in California (Fresno, Kern, Kings, Los Angeles, San Diego, and Tulare).

A long-term annual trend, more specifically an overall increase in coccidioidomycosis incidence (until 2012—incidence falls thereafter), has been noted in Arizona and California during the time period in question [Centers for Disease Control and Prevention, 2003, 2009]. It is worth noting that changes in laboratory testing and reporting practices occurred during this time [Centers for Disease Control and Prevention, 2013]. In Table 1, we observe a positive annual trend in coccidioidomycosis incidence in the selected counties in both California (blue) and Arizona (red). Before performing subsequent analysis, these data are once again detrended to ensure that the changes observed in reported cases of coccidioidomycosis are related to soil moisture patterns rather than the consequence of long-term trends.

First, we present a simple, linear model for an annual trend in reported cases of coccidioidomycosis.

\[
\text{normalized}_\text{VF}_y = \beta_0 + \beta_1 y.
\] (2)

In equation (2), \(\text{normalized}_\text{VF}_y\) denotes the population-normalized number of reported cases of coccidioidomycosis in year \(y\), while \(\beta_0\) and \(\beta_1\) represent the coefficients describing intercept and slope, respectively. Two relationships were developed of this form, one for Arizona and another for California. Continuing, for each county, for each month, within a year \(y\), the number of annual reported cases was normalized as shown:

\[
\text{detrended}_\text{VF}_{c,m,y} = \frac{\text{normalized}_\text{VF}_{c,m,y} \sum_{i=2000}^{2013} \text{normalized}_\text{VF}_i}{\beta_0 + \beta_1 y}.
\] (3)

In equation (3), the detrended value for coccidioidomycosis cases reported (already normalized for population, see equation (1)) is denoted by \(\text{detrended}_\text{VF}_{c,m,y}\), obtained by dividing the population-normalized

| Year | # of Reported Cases per 1,000,000 Residents (Arizona) | # of Reported Cases per 1,000,000 Residents (California) |
|------|-----------------------------------------------------|--------------------------------------------------------|
| 2000 | 460.5306325                                         | 89.4857218                                            |
| 2001 | 503.6564143                                         | 189.9703495                                           |
| 2002 | 635.5023968                                         | 239.6480424                                           |
| 2003 | 487.4502462                                         | 309.380018                                            |
| 2004 | 723.4897709                                         | 367.8734306                                           |
| 2005 | 679.2749888                                         | 556.5844856                                           |
| 2006 | 997.392081                                          | 1045.732803                                           |
| 2007 | 914.9692501                                         | 619.8972283                                           |
| 2008 | 844.526981                                          | 700.8052481                                           |
| 2009 | 1656.425735                                         | 829.5482692                                           |
| 2010 | 1825.660079                                         | 1267.326671                                           |
| 2011 | 2420.537466                                         | 1045.615295                                           |
| 2012 | 1999.852074                                         | 775.0142713                                           |
| 2013 | 1012.168952                                         | 328.2901243                                           |
| 2014 | 982.4871174                                         | 248.2403409                                           |

Table 1. Incidence of Coccidioidomycosis per 1,000,000 Residents, Selected Counties in Arizona and California (2000–2014)
value for reported cases of coccidioidomycosis, normalized $V_{F, m,y}$, by the expected total for the year in question, subsequently multiplied by the average annual, population normalized total between 2000 and 2013, $\sum_{i=2000}^{2013} \frac{\text{normalized}_V}{\text{normalized}_F}$.}

2.2. Defining the Corresponding Soil Moisture Data Set

With soil moisture playing an increasingly important role in precision agricultural decision support [Coopersmith et al., 2014a], complex hydrologic models [e.g., Grayson et al., 1997; Bell et al., 2010], drought monitoring [e.g., Sheffield et al., 2004; Bell et al., 2015], and General Circulation Models [e.g., Koster and Milly, 1997; Belair et al., 2005; Campoy et al., 2013; De Rosnay et al., 2013; Joetzjer et al., 2013], the availability of in situ soil moisture resources has increased dramatically in the past decade. As discussed in the previous section, an in situ network, the U.S. Climate Reference Network (USCRN), formed the basis of this inquiry [Diamond et al., 2013; Bell et al., 2013]. USCRN provides quality controlled soil moisture and precipitation measurements at multiple for locations across the United States. USCRN soil moisture measurements are produced in triplicate at each recorded depth (5 cm, 10 cm, 20 cm, 50 cm, and 100 cm). For the purpose of this study, only the 5 cm soil moisture measurement was used, as this depth corresponds best with the capacity of dust particles to become airborne. Please review the descriptions in Bell et al. [2013] for more specific information about the operation, quality assurance/quality control procedures, and logistics of the USCRN soil instrumentation.

As the soil moisture gauges contain colocated precipitation instruments, it is possible to calibrate models that transform a time series of antecedent precipitation into a soil moisture time series. One such model, developed by Pan et al. [2003] and subsequently updated by Pan [2012], is the diagnostic soil moisture equation. As a simple, lumped-bucket model, this equation convolutes the antecedent precipitation series and, via six parameters that can be calibrated via a genetic algorithm [Coopersmith et al., 2014b], returns a soil moisture estimate as shown in equations (4) and (5).

$$\theta_{est} = \theta_{re} + (\phi_{e} - \theta_{re}) (1 - e^{-c_{4} \beta}) \tag{4}$$

$$\beta = \sum_{i=1}^{i=n-1} \frac{P_i}{\eta_{i}} \left(1 - e^{-\frac{\eta_{i}}{c_{4}}} e^{\sum_{i=1}^{\eta_{i}} (\frac{\eta_{i}}{c_{4}})}\right) + \frac{P_{i}}{\eta_{i}} \left(1 - e^{-\frac{\eta_{i}}{c_{4}}} \right) \tag{5}$$

In equation (4), $\theta_{est}$ represents the model’s soil moisture estimate via three parameters ($\theta_{re}$, $\phi_{e}$, and $c_{4}$). Those three parameters signify the residual soil moisture (the level below which moisture levels will not fall, even after prolonged absences of precipitation), the porosity (the maximum quantity of moisture the soil can hold when saturated), and a drainage rate (note that a soil with $c_{4} = 0$ drains infinitely rapidly, returning instantly to $\theta_{re}$ a soil where $c_{4}$ is large drains extremely slowly, remaining at $\phi_{e}$ in perpetuity). The “beta series,” $\beta$, in equation (5), convolutes an exponentially decaying series of precipitation totals, $P_{i}$ over a series of receding time stamps, $i$, from 1 to n (the maximum temporal distance at which rainfall can be considered relevant—that is, we ignore rainfall occurring farther back in time than n hours). The prediction depth is signified by $z$, and the “eta series,” $\eta_{i}$, a sinusoidal estimate with a period of 1 year defining moisture losses due to evapotranspiration and deep drainage. The eta series contains the remaining three parameters, defining the sinusoid’s amplitude, horizontal, and vertical shift (its period is known to be 1 year). For further information regarding the calibration of these models and their implementation, please review the original literature [Pan et al., 2003; Pan, 2012] or the literature describing their more recent, machine learning-based updates in Coopersmith et al. [2014b].

Parameters calibrated in this manner are shown to be viable for modeling soil moisture in other locations, provided that those locations are hydroclimatically and texturally similar to the calibration site Coopersmith et al. [2014b]. Although the USCRN soil moisture gauges sites included in this analysis are not perfect edaphic matches for included counties, given the arid climate of the American southwest, perfunctory similarity will suffice. In turn, these models have been used to extend the soil moisture records at these sites back to the initial installation of precipitation instruments [Coopersmith et al., 2015a] or to validate the performance of remotely sensed satellite estimates [Coopersmith et al., 2015b]. For the purposes of this analysis, these modeled estimates will allow us to consider the performance of two related soil moisture time series in estimating future reported cases of coccidioidomycosis. The first series denotes the modeled estimates, using the
parameters calibrated at the location relevant location. The second series is a “merged” series, utilizing the in situ estimate when one is available and the modeled estimate when one is not.

For selected counties in Arizona and California (Figure 1) with reported coccidioidomycosis cases, a soil moisture record is selected using the most geographically proximate in situ record from USCRN (Figure 1). In Arizona, the nearest in situ record is located at the USCRN gauge near Tucson (USCRN #1011, nearest to Maricopa, Pima, and Pinal counties). In California, the nearest in situ records are located near Yosemite Village (USCRN #1508, nearest to Fresno, Kings, and Tulare counties), Fallbrook (USCRN #1528, nearest to Los Angeles and San Diego counties), and Santa Barbara (USCRN #1529, nearest to Kern county). The next section discusses the possible relationships to be explored with those soil moisture data.

Given the spatial disparity between these counties and the chosen USCRN sensors for which model estimates extend historical records, it is prudent at this stage to assess the capacity of these distant sensors to approximate the local soil moisture of interest. First, the Advanced Microwave Scanning Radiometer–EOS (AMSR-E) satellite estimates of soil moisture (available between June 2002 and October 2011) are extracted for the center of each of the counties considered. As the in situ records at these USCRN locations typically begin in 2010 or 2011, the remotely sensed soil moisture values from AMSR are compared with the model estimates produced to extend the historical records at the USCRN locations utilized for the purposes of this analysis. In Coopersmith et al. [2015b], these model estimates were compared to AMSR-E data at the USCRN locations themselves. The average accuracy reported in that analysis, after inclusion of an optimal gain and offset, was 0.047 m$^3$/m$^3$. The corresponding statistics, using AMSR-E within the county rather than at the USCRN location itself, are reported in Table 2.

Of the nine counties listed, the RMSE values between the local AMSR-E estimates and the model estimates at the nearest USCRN sensor are roughly in line with the reported RMSE values between USCRN model estimates and the local AMSR-E retrievals. Thus, these six counties are retained for further analysis. Kern, Los Angeles, and San Diego, are subsequently removed via this criterion.

2.3. Defining Relationships to Consider

With soil moisture records in place, the next step is to consider the various types of relationships for potential correlations. Analogous to the 8 day averages of soil moisture utilized in Wang et al. [2007], this analysis focuses upon the monthly average soil moisture value. As the period of record for coccidioidomycosis incidence falls between 2000 and 2014, ideally, the soil moisture record with which to compare these figures should cover the maximum proportion of these years. For this reason, the extended records at the USCRN gauges (which begin when precipitation data are first available) are preferable to the in situ records for soil moisture. In turn, just as Wang et al. [2007] utilized period averages with variable daily lags, the following monthly aggregations and lags are considered: (a) the number of months to aggregate of the independent variable (1 to 6). That is, the average soil moisture from January to March (an aggregation of 3 months), only February (an aggregation of 1 month), or the entire first half of the calendar year (an aggregation of 6 months); (b) the number of months to aggregate of the dependent variable (1 to 6, a normalized estimate of reported coccidioidomycosis cases per 1,000,000 residents, with the annual trend removed), that is, we can estimate the total in August and September (an aggregation of 2 months) or a longer/shorter window; (c) the number of months of “lag” time between the independent range and the dependent range (0 to 36 months), for example, using the total number of hours above 10% between April and June of year $X$ to forecast

| County      | USCRN | RMSE, AMSR-E, Ascending | RMSE, AMSR-E, Descending |
|-------------|-------|-------------------------|--------------------------|
| Fresno      | 1508  | 0.050                   | 0.051                    |
| Kern        | 1529  | 0.073                   | 0.074                    |
| Kings       | 1508  | 0.051                   | 0.052                    |
| Los Angeles | 1528  | 0.073                   | 0.072                    |
| Maricopa    | 1011  | 0.036                   | 0.036                    |
| Pima        | 1011  | 0.035                   | 0.035                    |
| Pinal       | 1011  | 0.035                   | 0.035                    |
| San Diego   | 1528  | 0.073                   | 0.077                    |
| Tulare      | 1508  | 0.046                   | 0.051                    |

*Bolded values are from USCRN sensors used in the subsequent analysis.*
Table 3. Soil Moisture Levels and Coccidioidomycosis Impacts in Arizona and California

| Year | Month | Modeled SM (m³/m³), AZ | Detrended Cocci Incidence, AZ | Modeled SM (m³/m³), CA | Detrended Cocci Incidence, CA |
|------|-------|-------------------------|-------------------------------|-------------------------|-------------------------------|
| 2002 | 9     | 0.018688498             | 238.6835648                  | 0                       | 0                            |
| 2002 | 10    | 0.030761552             | 291.4209886                  | 0                       | 0                            |
| 2002 | 11    | 0.042590859             | 314.7253879                  | 0                       | 0                            |
| 2002 | 12    | 0.079504266             | 402.4278317                  | 0                       | 0                            |
| 2003 | 1     | 0.040706236             | 217.6314323                  | 0                       | 0                            |
| 2003 | 2     | 0.047960111             | 118.9956718                  | 0                       | 0                            |
| 2003 | 3     | 0.058734527             | 139.3982875                  | 0                       | 0                            |
| 2003 | 4     | 0.023988582             | 93.20229356                  | 0                       | 0                            |
| 2003 | 5     | 0.021576505             | 111.0593612                  | 0                       | 0                            |
| 2003 | 6     | 0.032606353             | 140.6273795                  | 0                       | 0                            |
| 2003 | 7     | 0.034824275             | 205.3632434                  | 0                       | 0                            |
| 2003 | 8     | 0.063790721             | 316.7377084                  | 0                       | 0                            |
| 2003 | 9     | 0.070075447             | 211.4483979                  | 0                       | 0                            |
| 2003 | 10    | 0.073544563             | 213.733152                   | 0                       | 0                            |
| 2003 | 11    | 0.07633426              | 195.8249965                  | 0                       | 0                            |
| 2003 | 12    | 0.077928581             | 285.6830261                  | 0                       | 0                            |
| 2004 | 1     | 0.080290731             | 211.9314125                  | 0                       | 0                            |
| 2004 | 2     | 0.086659528             | 224.0742793                  | 0                       | 0                            |
| 2004 | 3     | 0.091885505             | 178.9580231                  | 0                       | 0                            |
| 2004 | 4     | 0.076389722             | 147.1321316                  | 0                       | 0                            |
| 2004 | 5     | 0.048595993             | 249.075831                   | 0                       | 0                            |
| 2004 | 6     | 0.050074095             | 311.3864712                  | 0                       | 0                            |
| 2004 | 7     | 0.053449079             | 297.3654862                  | 0                       | 0                            |
| 2004 | 8     | 0.075714144             | 239.3006426                  | 0                       | 0                            |
| 2004 | 9     | 0.08334769              | 272.7333319                  | 0                       | 0                            |
| 2004 | 10    | 0.088344984             | 284.3028402                  | 0                       | 0                            |
| 2004 | 11    | 0.114069337             | 244.1796974                  | 0                       | 0                            |
| 2004 | 12    | 0.134465145             | 282.5061027                  | 0                       | 0                            |
| 2005 | 1     | 0.14126691              | 160.2114796                  | 0                       | 0                            |
| 2005 | 2     | 0.138735481             | 112.0010048                  | 0                       | 0                            |
| 2005 | 3     | 0.069427576             | 119.1015506                  | 0                       | 0                            |
| 2005 | 4     | 0.026501304             | 140.9278206                  | 0                       | 0                            |
| 2005 | 5     | 0.029467254             | 126.9506981                  | 0                       | 0                            |
| 2005 | 6     | 0.034264098             | 159.824663                   | 0                       | 0                            |
| 2005 | 7     | 0.047369151             | 205.4515105                  | 0                       | 0                            |
| 2005 | 8     | 0.121873645             | 271.667615                   | 0                       | 0                            |
| 2005 | 9     | 0.084187959             | 173.3887346                  | 0                       | 0                            |
| 2005 | 10    | 0.085661459             | 246.0509143                  | 0                       | 0                            |
| 2005 | 11    | 0.075487162             | 394.048302                   | 0                       | 0                            |
| 2005 | 12    | 0.049257706             | 360.4681667                  | 0                       | 0                            |
| 2006 | 1     | 0.047195764             | 223.8126685                  | 0                       | 0                            |
| 2006 | 2     | 0.046754592             | 406.0198996                  | 0                       | 0                            |
| 2006 | 3     | 0.06377237              | 321.6875436                  | 0                       | 0                            |
| 2006 | 4     | 0.02168894              | 303.6157508                  | 0                       | 0                            |
| 2006 | 5     | 0.020238768             | 250.91043                    | 0                       | 0                            |
| 2006 | 6     | 0.033135632             | 262.8592065                  | 0                       | 0                            |
| 2006 | 7     | 0.063432066             | 300.9350003                  | 0                       | 0                            |
| 2006 | 8     | 0.07439608              | 237.5421378                  | 0                       | 0                            |
| 2006 | 9     | 0.066061927             | 174.8022503                  | 0                       | 0                            |
| 2006 | 10    | 0.049548081             | 181.9017814                  | 0                       | 0                            |
| 2006 | 11    | 0.019553513             | 229.6054128                  | 0                       | 0                            |
| 2006 | 12    | 0.028981184             | 385.3860391                  | 0                       | 0                            |
| 2007 | 1     | 0.082276498             | 268.2745264                  | 0                       | 0                            |
| 2007 | 2     | 0.045748735             | 218.1070116                  | 0                       | 0                            |
| 2007 | 3     | 0.031602907             | 188.4985045                  | 0                       | 0                            |
| 2007 | 4     | 0.030831453             | 222.027718                   | 0                       | 0                            |
| 2007 | 5     | 0.01934795              | 215.5676418                  | 0                       | 0                            |
| 2007 | 6     | 0.020675259             | 208.739997                   | 0                       | 0                            |
| 2007 | 7     | 0.059385878             | 194.8453503                  | 0                       | 0                            |
| 2007 | 8     | 0.102940045             | 202.1052942                  | 0                       | 0                            |
| Year | Month | Modeled SM (m$^3$/m$^3$), AZ | Detrended Cocci Incidence, AZ | Modeled SM (m$^3$/m$^3$), CA | Detrended Cocci Incidence, CA |
|------|-------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|
| 2007 | 9     | 0.056300585                 | 154.3844403                  | 0.014422721                 | 72.2435431                   |
| 2007 | 10    | 0.019098717                 | 258.6904939                  | 0.02040912                  | 122.4520266                  |
| 2007 | 11    | 0.020181495                 | 328.867631                   | 0.033769362                 | 88.3809576                   |
| 2007 | 12    | 0.1268061                   | 284.8079076                  | 0.093992526                 | 141.1553566                  |
| 2008 | 1     | 0.058864981                 | 387.335354                   | 0.136142251                 | 84.16493733                  |
| 2008 | 2     | 0.020181495                 | 208.614782                   | 0.090723711                 | 182.5723673                  |
| 2008 | 3     | 0.0312175                   | 184.5926911                  | 0.031635149                 | 138.2376122                  |
| 2008 | 4     | 0.018939927                 | 184.5926911                  | 0.031635149                 | 138.2376122                  |
| 2008 | 5     | 0.018688498                 | 184.5926911                  | 0.031635149                 | 138.2376122                  |
| 2008 | 6     | 0.035782162                 | 169.1139229                  | 0.05040674                  | 148.2855919                  |
| 2008 | 7     | 0.0974885                   | 187.4741605                  | 0.015210755                 | 154.9923056                  |
| 2008 | 8     | 0.060875011                 | 187.4741605                  | 0.015210755                 | 154.9923056                  |
| 2008 | 9     | 0.07512169                  | 187.4741605                  | 0.015210755                 | 154.9923056                  |
| 2008 | 10    | 0.07017004                  | 258.6904939                  | 0.02040912                  | 122.4520266                  |
| 2008 | 11    | 0.073159039                 | 328.867631                   | 0.033769362                 | 88.3809576                   |
| 2008 | 12    | 0.0974885                   | 328.867631                   | 0.033769362                 | 88.3809576                   |
coccidioidomycosis in August and September and year $X + 1$ would represent a lag of 13 months; and (d) the 12 possible months (or aggregations thereof), to wit, utilizing a 3 month window for independent or dependent variables, one can consider January–March versus February–April versus March–May, etc.

The next section will outline how this analysis will refine that profusion of potential relationships into a coherent set of insights relating soil moisture estimates to reported cases of coccidioidomycosis.

2.4. Focusing the Lens

Our methods are quite similar to those of Wang et al. [2007], beginning with the removal of a long-term trend, the application of correlation analysis to lagged data, and even the usage of composites of temporal ranges by aggregating between time stamps for independent variable generation. In Table 3, we visualize the average modeled soil moisture by month and the annually detrended number of reported coccidioidomycosis cases.

In California (upper panel), we observe that soil moisture arrives in clusters of roughly 6 months, which aligns with hydroclimatic research addressing Pacific climates, where precipitation arrives primarily during the fall/winter seasons [e.g., Coopersmith et al., 2012]. In Arizona (lower panel), we observe soil moisture clusters of shorter periods of 3 months, aligning with the monsoon rainfall pattern of the arid Southwest. Thus, for California and Arizona, we will aggregate soil moisture monthly averages into clusters of six and three, respectively. In terms of the dependent variables, in California (upper panel), we notice clusters of roughly 3 months of coccidioidomycosis incidence that rise and fall in relation to the soil moisture levels observed, with lags of several months. In Arizona, cocci responses seem inversely related (drier periods are succeeded by higher coccidioidomycosis incidence), with somewhat longer lag periods.

To distill a large number of comparisons, we focus on those that show the more significant, consistent, robust relationships. If fewer than 18 comparisons are available, the comparison cannot be considered for use in the study. A threshold of 18 has now been adopted to ensure at least one pair of independent and dependent

### Table 3. (continued)

| Year | Month | Modeled SM (m$^3$/m$^3$), AZ | Detrended Cocci Incidence, AZ | Modeled SM (m$^3$/m$^3$), CA | Detrended Cocci Incidence, CA |
|------|-------|-------------------------------|------------------------------|-------------------------------|-------------------------------|
| 2012 | 9     | 0.059601122                  | 204.2646714                  | 0.014742877                  | 111.4972694                  |
| 2012 | 10    | 0.018797563                  | 296.1976982                  | 0.035070406                  | 87.6140127                   |
| 2012 | 11    | 0.031084186                  | 320.5746086                  | 0.094424432                  | 88.1042566                   |
| 2012 | 12    | 0.074000038                  | 200.897139                   | 0.157289468                  | 93.2495163                   |
| 2013 | 1     | 0.061580616                  | 215.8309765                  | 0.079910734                  | 60.3781933                   |
| 2013 | 2     | 0.097161785                  | 189.9210826                  | 0.06503031                   | 74.8473953                   |
| 2013 | 3     | 0.043805947                  | 103.0214633                  | 0.099472384                  | 69.0089907                   |
| 2013 | 4     | 0.023682717                  | 102.1139398                  | 0.102119484                  | 65.2375778                   |
| 2013 | 5     | 0.018688498                  | 134.5468404                  | 0.029101883                  | 71.3297316                   |
| 2013 | 6     | 0.018688498                  | 180.7191826                  | 0.032773113                  | 88.6652104                   |
| 2013 | 7     | 0.057232007                  | 131.1258734                  | 0.02314116                   | 46.8858209                   |
| 2013 | 8     | 0.04777314                   | 197.0633332                  | 0.014627682                  | 47.7767745                   |
| 2013 | 9     | 0.044216847                  | 137.3913779                  | 0.032197353                  | 28.8794820                   |
| 2013 | 10    | 0.018684898                  | 129.1651728                  | 0.036543682                  | 35.1306167                   |
| 2013 | 11    | 0.055693437                  | 248.1182123                  | 0.055573595                  | 47.9089913                   |
| 2013 | 12    | 0.089243157                  | 222.1762911                  | 0.056617057                  | 47.2744033                   |
| 2014 | 1     | 0.026467379                  | 190.936132                   | 0.020561535                  | 42.6064306                   |
| 2014 | 2     | 0.022966894                  | 170.9610033                  | 0.13219354                   | 79.9685889                   |
| 2014 | 3     | 0.034498843                  | 223.239164                   | 0.119463294                  | 34.3209332                   |
| 2014 | 4     | 0.019020564                  | 157.5879583                  | 0.11920279                   | 32.9753581                   |
| 2014 | 5     | 0.018920864                  | 232.531611                   | 0.090978637                  | 55.4608898                   |
| 2014 | 6     | 0.018684988                  | 161.9626934                  | 0.025230896                  | 43.3914334                   |
| 2014 | 7     | 0.093122684                  | 93.5987799                   | 0.03509858                   | 58.1591900                   |
| 2014 | 8     | 0.06704296                   | 146.0930835                  | 0.016512132                  | 45.6021486                   |
| 2014 | 9     | 0.078068763                  | 109.0883894                  | 0.030480576                  | 49.3091126                   |
| 2014 | 10    | 0.070803184                  | 91.14695079                  | 0.037730295                  | 30.0848426                   |
| 2014 | 11    | 0.020658284                  | 132.0806601                  | 0.077829588                  | 25.8910817                   |
| 2014 | 12    | 0.095039508                  | 118.7038301                  | 0.12214687                   | 13.8985843                   |
ranges per county per year, from 2007 (the year at which precipitation data become available in California) and 2014 (when the incidence data set concludes). For example, if we are considering comparisons of coccidioidomycosis incidence from February to March with the average in situ soil moisture estimate from June to August of the preceding summer, over all counties in California, a single data point is valid if, and only if, coccidioidomycosis estimates are available in that county in February and March, and in situ soil moisture estimates are available within that same county in June, July, and August of the previous year. As stated, 18 such points are required before comparisons can be further considered.

Finally, the statistically significant relationships that remain are examined in greater detail. Relationships that “recur” or show higher rates of significance/correlation between the independent variable (a soil moisture measurement metric) and the dependent variable (reported cases of coccidioidomycosis) become the relationships concluded to be most robust. Note a relationship “recurr” if the same independent variable demonstrates strong, statistically significant relationships between numerous temporal windows of the subsequent year.

3. Results

In this section, the results of the correlation analysis are deployed to evaluate the performance of those comparisons for the two states in question.

3.1. California

In Tables 4 and 5, we observe the positive correlation between average modeled soil moisture levels over a specific 6 month period (December-to-May) and the number of reported cases of coccidioidomycosis in the subsequent 3 month bands covering the summer and fall. Table 5 demonstrates the relationship between summer/fall incidence of coccidioidomycosis and the average soil moisture the preceding winter and spring. The results of these relationships are summarized in Table 1, all of which are statistically significant at the $\alpha = 0.05$ level.

It is worth noting that all of these relationships illustrate summer/fall periods of coccidioidomycosis incidence responding to the same 6 month band beginning during the fall of the preceding year. Interestingly, while the “wetter” 6 month bands do not necessarily cause a higher number of reported cases, the “drier” bands are fairly consistent with respect to their lower number of cases reported. It is also important to note that, in Southern California, a disproportionate quantity of rainfall is observed during the fall/winter/early-spring

| Table 4. Annually Detrended Cases of Coccidioidomycosis (July–September) Versus 6 Month Average Soil Moisture (December–May), California |
|---|
| Modeled SM | Reported Cases |
| 0.115 | 115.5262 |
| 0.128 | 298.9765 |
| 0.122 | 227.4943 |
| 0.089 | 56.39648 |
| 0.089 | 12.70564 |
| 0.091 | 25.9088 |
| 0.089 | 41.74433 |
| 0.115 | 46.81051 |
| 0.128 | 36.58167 |
| 0.122 | 27.86085 |
| 0.089 | 21.22929 |
| 0.089 | 13.19565 |
| 0.091 | 13.49517 |
| 0.089 | 32.53876 |
| 0.115 | 36.6503 |
| 0.128 | 83.92622 |
| 0.122 | 56.03302 |
| 0.089 | 18.30164 |
| 0.089 | 15.2794 |
| 0.091 | 11.61712 |

| Table 5. Statistically Significant Relationship Displaying Recurrent Patterns, California |
| Ind_var Range | Ind_var Type | Dep_var Range | $\rho$ | $p$ Value | n |
|---|---|---|---|---|---|
| Dec–May (y $^{-1}$) | Average Soil Moisture (m$^3$/m$^3$) | Jun–Aug | 0.503 | 0.020 | 21 |
| Dec–May (y $^{-1}$) | Average Soil Moisture (m$^3$/m$^3$) | Jul–Sep | 0.539 | 0.012 | 21 |
| Dec–May (y $^{-1}$) | Average Soil Moisture (m$^3$/m$^3$) | Aug–Oct | 0.535 | 0.013 | 21 |
| Dec–May (y $^{-1}$) | Average Soil Moisture (m$^3$/m$^3$) | Sep–Nov | 0.529 | 0.014 | 21 |
| Dec–May (y $^{-1}$) | Average Soil Moisture (m$^3$/m$^3$) | Oct–Dec | 0.501 | 0.021 | 21 |
months, which would, in turn, suggest the greatest variability of soil moisture between December and May, which, in turn, displays consistent relationships with respect to coccidioidomycosis incidence during the summer and fall thereafter.

### 3.2. Arizona

In Tables 6 and 7, we observe analogous examples in Arizona, albeit with an inverted statistical relationship. Once again, we note that one particular band of average soil moisture values during the summer season when much of the Arizona rain falls presents statistically significant relationships with respect to coccidioidomycosis incidence in each month between January and May. All of these relationships are statistically significant at the $\alpha = 0.01$ level. Though the correlation is inverted, this would seem to corroborate the grow and blow hypothesis proposed by Tamerius and Comrie [2011], in which drier periods allow spores to travel freely.

Additionally, much like the Californian results, in which wetter periods may or may not yield subsequent periods of higher incidence, but drier periods were consistently succeeded by lower number of reported cases of coccidioidomycosis, a similar pattern emerges in Arizona. To wit, in Table 6, an extremely dry summer may or may not cause the highest levels of coccidioidomycosis incidence in the subsequent winter and spring, but an atypically wet summer produces consistently low incidence rates. In California and Arizona, wet and dry conditions, respectively, are necessary, but not sufficient conditions for heightened incidence rates.

### Table 6. Annually Detrended Cases of Coccidioidomycosis (February) Versus 6 Month Average Soil Moisture (May–July), Arizona

| Modeled SM | Reported Cases |
|------------|---------------|
| 0.030      | 90.0965       |
| 0.051      | 35.88342      |
| 0.037      | 144.1528      |
| 0.039      | 74.286        |
| 0.033      | 66.92434      |
| 0.051      | 55.48029      |
| 0.034      | 144.2103      |
| 0.022      | 194.4925      |
| 0.030      | 157.8867      |
| 0.035      | 64.43757      |
| 0.032      | 65.09426      |
| 0.030      | 70.94503      |
| 0.051      | 41.20407      |
| 0.037      | 125.5012      |
| 0.039      | 64.94447      |
| 0.033      | 58.86291      |
| 0.051      | 41.38267      |
| 0.034      | 80.80375      |
| 0.022      | 79.60832      |
| 0.030      | 98.13995      |
| 0.035      | 55.82523      |
| 0.032      | 54.94693      |
| 0.030      | 63.03275      |
| 0.051      | 34.91351      |
| 0.037      | 136.3659      |
| 0.039      | 78.87655      |
| 0.033      | 57.37626      |
| 0.051      | 45.40144      |
| 0.034      | 88.53221      |
| 0.032      | 127.8806      |
| 0.030      | 119.867       |
| 0.035      | 69.65828      |
| 0.032      | 50.91981      |
| 0.030      | 90.0965       |
| 0.051      | 35.88342      |
| 0.037      | 144.1528      |
| 0.039      | 74.286        |
| 0.033      | 66.92434      |
| 0.051      | 41.20407      |
| 0.034      | 125.5012      |
| 0.039      | 64.94447      |
| 0.033      | 58.86291      |
| 0.051      | 41.38267      |
| 0.034      | 80.80375      |
| 0.022      | 79.60832      |
| 0.030      | 98.13995      |

### Table 7. Statistically Significant Relationship Displaying Recurrent Patterns, Arizona

| Ind_var Range | Ind_var Type | Dep_var Range | $\rho$       | $p$ Value | n |
|---------------|--------------|---------------|--------------|-----------|---|
| May–Jul ($y^{-1}$) | Average Soil Moisture ($m^3/m^3$) | Jan | −0.521 | 0.002 | 33 |
| May–Jul ($y^{-1}$) | Average Soil Moisture ($m^3/m^3$) | Feb | −0.521 | 0.002 | 33 |
| May–Jul ($y^{-1}$) | Average Soil Moisture ($m^3/m^3$) | Mar | −0.523 | 0.001 | 33 |
| May–Jul ($y^{-1}$) | Average Soil Moisture ($m^3/m^3$) | Apr | −0.449 | 0.009 | 33 |
| May–Jul ($y^{-1}$) | Average Soil Moisture ($m^3/m^3$) | May | −0.501 | 0.003 | 33 |
4. Discussion

4.1. The 21st Century Precipitation

Utilizing publically available California monthly precipitation data NOAA’s monthly data from appropriately located gauges in Arizona (http://w2.weather.gov/climate/xmacis.php?wfo=psr) and California (http://w2.weather.gov/climate/xmacis.php?wfo=lox), one can observe qualitatively, some of the climatic patterns in play during the time periods in question. With the USCRN precipitation record in California beginning in 2007 at most installation sites, Table 8 presents the precipitation observed during each year from Southern California (near Los Angeles) and Arizona (near Phoenix). In Table 3, we noted a gradual increase in the incidence of coccidioidomycosis, observing a spike in cases reported in 2011 (followed by a sharp decrease in 2012 and 2013). In California, as our previous analysis would suggest, an atypically wet year in 2011 may have (at least temporarily) slowed a long-standing positive trend. Table 8 presents the rainfall during each year. However, the increase in 2011 (Table 9) may be exacerbated by an exceptionally wet 2010 followed by a drier summer in central Arizona (though not in the south), perhaps facilitating wider spreading of spores by wind, as hypothesized in Kolivras and Comrie [2003]. The steep dropoff thereafter may be, perhaps, partially explained by the extremely wet 2012. Changes in surveillance methodologies, including changes in testing and reporting practices, may also have partially contributed to the 2011 peak [Centers for Disease Control and Prevention, 2013]. For example, California transitioned to a laboratory-based reporting system during 2010, though some jurisdictions such as Kern county had already been implementing such a reporting system [Centers for Disease Control and Prevention, 2013].

The Pacific Decadal Oscillation (PDO) is known to influence the variability of precipitation in the Southwest, specifically during Arizona winters [Sheppard et al., 2002]. An image of the PDO from 1870 through the time period under inspection in this study can be located at https://www.ncdc.noaa.gov/teleconnections/pdo/. The time period during which the spike in reported cases of coccidioidomycosis is observed in Arizona and California corresponds with the nadir of the Pacific Decadal Oscillation (PDO). Shortly thereafter, as the sign of the PDO switches, a sharp decrease in coccidioidomycosis incidence is observed (Table 1). The PDO’s connection to historical outbreaks of coccidioidomycosis could be researched by, in addition to removing a long-term annual trend as shown in equations (2) and (3), fitting a relationship between the PDO and coccidioidomycosis incidence. “Sequential normalization” specifies that multiple superimposed trends can be removed in order of the longest repeating period; see Coopersmith et al. [2011], leveraging a method from Maidment and Parzen [1984]. This would allow coccidioidomycosis incidence to explore in terms of moisture and anthropogenic features, in the absence of climatic trends.

| Table 8. Precipitation During the California and Arizona Calendar Years |
|---|---|
| Year | Annual Precipitation (mm), AZ | Annual Precipitation (mm), CA |
| 2003 | 173.228 | 242.57 |
| 2004 | 202.692 | 414.528 |
| 2005 | 178.816 | 477.774 |
| 2006 | 138.43 | 233.172 |
| 2007 | 128.27 | 124.206 |
| 2008 | 243.332 | 279.908 |
| 2009 | 82.804 | 189.738 |
| 2010 | 232.156 | 509.27 |
| 2011 | 118.364 | 250.698 |
| 2012 | 108.712 | 225.806 |
| 2013 | 213.868 | 92.71 |
| 2014 | 212.598 | 242.57 |

| Table 9. Monthly Incidence of Coccidioidomycosis per 1,000,000 Residents, Selected Counties in Arizona and California (2000–2014) |
|---|---|
| Month | # of Reported Cases per 1,000,000 Residents (Arizona) | # of Reported Cases per 1,000,000 Residents (California) |
| 1 | 92.95431443 | 45.85162106 |
| 2 | 81.63523957 | 38.46853154 |
| 3 | 78.20629274 | 37.23905642 |
| 4 | 79.10389713 | 33.56534757 |
| 5 | 81.45724761 | 32.31102624 |
| 6 | 87.14588194 | 41.04605894 |
| 7 | 93.0145815 | 36.92932236 |
| 8 | 89.63543347 | 53.02804748 |
| 9 | 75.26866006 | 58.9060512 |
| 10 | 88.80439084 | 64.11905656 |
| 11 | 110.4812564 | 59.41757467 |
| 12 | 110.9498537 | 56.3356386 |

4.2. Limitations

Limitations of coccidioidomycosis surveillance data include the passive nature of the surveillance system, which almost certainly underestimates the true number of cases. In addition to the incubation period, some patients report experiencing substantial delays.
between seeking care as well as coccidioidomycosis diagnosis [Tsang et al., 2010], and further delays may occur between diagnosis and case reporting to public health. Therefore, the month to which cases are assigned may not necessarily reflect the month that he or she was infected with Coccidioides. Earlier analyses utilized time lags in their attempts to account for the time between exposure and symptom onset [e.g., Park et al., 2005], though a subsequent analysis of model sensitivity quality control determined that employing case data “as is” did not cause significant deterioration of results [Comrie and Glueck, 2005]. Future analyses may allow for more comprehensive linkage between environmental conditions for Coccidioides growth and observed incidence by incorporating factors that account for dispersal and human exposure, ideally with methods to detect Coccidioides in air. Currently, laboratory detection of airborne Coccidioides DNA has only been successful with artificially created dust clouds [Chow et al., 2016]. However, future research is needed to enable this technology to be used for routine monitoring of Coccidioides in ambient air and to quantify spore count.

5. Conclusions

Ultimately, despite the differing hydroclimates presented by the data in Arizona and California, in both states, robust, significant, recurring relationships do emerge. In both states, drought tends to correlate with higher incidence of reported coccidioidomycosis in the following year, whether that be a drier foreshadowing monsoon season in Arizona or a drier winter/spring in California. In Arizona, these impacts tend to be noticed earlier in the subsequent year, whereas in California, these impacts are noted later in the year. While other research challenges the impact of climatic factors in Kern county, CA [Talamantes et al., 2007], this analysis reveals relationships in California and Arizona using climatic data to produce a time series of soil moisture.

With the descriptive capacity of soil moisture verified by statistical significance tests and demonstrated over periods between several months and over 2 years, it is possible that future predictive models could enable public health officials to prospectively identify periods of expected increased coccidioidomycosis incidence and notify healthcare providers and the public to remain vigilant for identification of this infection, potentially minimizing delays in diagnosis. We are hopeful that this analysis, in cooperation with subsequent research and stakeholders, will form the basis to do just that.

Acknowledgments

This work was supported by the NASA Terrestrial Hydrology Program (NNH10ZDA001N-THP) and USDA Agricultural Research Service (ARS 88-8042-5-077), USDA is an equal opportunity provider and employer. This work was also supported by NOAA through the Cooperative Institute for Climate and Satellites-North Carolina under Cooperative Agreement NA14NES432003. The reported cases of coccidioidomycosis were obtained from National Notifiable Diseases Surveillance System (NNDSS) available (https://www.cdc.gov/nndss/data-and-statistics.html). The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

References

Baptista-Rosas, R. C., A. Hinjosa, and M. Riquelme (2007), Ecological niche modeling of Coccidioides spp. in western North American deserts, Ann. N. Y. Acad. Sci., 1115(1), 35–46, doi:10.1196/annals.1406.003.

Belair, S., G. Balsamo, J.-F. Mahfouf, and G. Deblonde (2005), Towards the inclusion of hydros soil moisture measurements in forecasting systems of the meteorological service of Canada, IGARSS '05, 4th, Art. 1525624, 2741–2743.

Bell, J. E., E. Weng, and Y. Luo (2010), Ecohydrological responses to multifactor global change in a tallgrass prairie: A modeling analysis, J. Geophys. Res., 115, G04042, doi:10.1029/2009JG001120.

Bell, J. E., et al. (2013), U.S. Climate Reference Network soil moisture and temperature observations, J. Hydrometeorol., 14, 977–988, doi:10.1175/JHM-D-12-0146.1.

Bell, J. E., R. D. Leeper, M. A. Palecki, E. J. Coopersmith, T. Wilson, R. Bilotta, and S. Embler (2015), Evaluation of the 2012 drought with a newly established soil monitoring network, Vadose Zone J., 14(11), doi:10.2136/vzj2015.02.0023.

Campoy, A., A. Duchame, F. Cheruy, F. Houdrin, J. Polcher, and J. C. Dupont (2013), Response of land surface fluxes and precipitation to different soil bottom hydrological conditions in a general circulation model, J. Geophys. Res. Atmos., 118, 10725–10739, doi:10.1002/jgrd.50627.

Centers for Disease Control and Prevention (2003), Increase in coccidioidomycosis—Arizona, 1998–2001, Morb. Mortal. Wkly. Rep., 52(6), 109–112.

Centers for Disease Control and Prevention (2009), Increase in coccidioidomycosis—California, 2000–2007, Morb. Mortal. Wkly. Rep., 58(5), 105–109.

Centers for Disease Control and Prevention (2013), Increase in reported coccidioidomycosis—United States, 1998–2011, Morb. Mortal. Wkly. Rep., 62(12), 217–221.

Chow, N. A., D. W. Griffin, B. M. Barker, V. N. Loparev, and A. P. Livintseva (2016), Molecular detection of airborne Coccidioides in Tucson, Arizona, Med. Mycol., 54(6), 584–92, doi:10.1093/mycol/myw022.

Comrie, A. C. (2005), Climate factors influencing coccidioidomycosis seasonality and outbreaks, Environ. Health Perspect., 113(6), 688–692, doi:10.1289/ehp.7786.

Comrie, A. C., and M. F. Glueck (2007), Assessment of climate-coccidioidomycosis model, Ann. N. Y. Acad. Sci., 1115(1), 83–95.

Coopersmith, E. J., B. S. Minsker, and P. Montagna (2011), Understanding and forecasting hypoxia using machine learning algorithms, J. Hydroinfr., 13(1), 64–80, doi:10.2166/hydro.2010.015.

Coopersmith, E. J., M. A. Yaeger, S. Ye, L. Cheng, and M. Sivapalan (2012), Exploring the physical controls of regional patterns of flow duration curves—Part 3: A catchment classification system based on regime curve indicators, HydroL. Earth Syst. Sci., doi:10.5194/hess-16-4467-2012.

Coopersmith, E. J., B. S. Minsker, C. E. Wenzel, and B. J. Gilmore (2014a), Machine learning assessments of soil drying for agricultural planning, Comput. Electron. Agric., 104, 93–104.

Coopersmith, E. J., M. A. Yaeger, S. Ye, L. Cheng, and M. Sivapalan (2012), Exploring the physical controls of regional patterns of flow duration curves—Part 3: A catchment classification system based on regime curve indicators, HydroL. Earth Syst. Sci., doi:10.5194/hess-16-4467-2012.

Coopersmith, E. J., B. S. Minsker, C. E. Wenzel, and B. J. Gilmore (2014a), Machine learning assessments of soil drying for agricultural planning, Comput. Electron. Agric., 104, 93–104.
Coopersmith, E. J., B. S. Minsker, and M. Siyapalan (2014b), Using similarity of soil texture and hydroclimate to enhance soil moisture estimation, Hydrol. Earth Syst. Sci., 18, 3095–3107, doi:10.5194/hess-18-3095-2014.

Coopersmith, E. J., M. H. Cosh, and J. E. Bell (2015a), Extending the soil moisture data record of the Climate Reference Network (CRN) and Soil Climate Analysis Network (SCAN), Adv. Water Resour., 79, 80–90, doi:10.1016/j.adwres.2015.02.002.

Coopersmith, E. J., M. H. Cosh, R. Bindlish, and J. E. Bell (2015b), Comparing AMSR-E soil moisture estimates to the extended record of the U.S. Climate Reference Network (USCRN), Adv. Water Resour., 85, 79–85, doi:10.1016/j.adwres.2015.09.003.

De Rosnay, P., M. Drusch, D. Vasiljevic, G. Balsamo, C. Albergel, and L. Isaksen (2013), A simplified extended Kalman filter for the global operational soil moisture analysis at ECMWF, Q. J. R. Meteorol. Soc., 139(674), 1199–1213.

Diamond, H. J., et al. (2013), U.S. Climate Reference Network after one decade of observations: Status and assessment, Bull. Am. Meteorol. Soc., doi:10.1175/BAMS-D-12-00170.1.

Galigani, J., N. M. Ampel, J. E. Blair, A. Cantanzaro, R. H. Johnson, D. A. Stevens, and P. L. Williams (2005), Coccidioidomycosis, Clin. Infect. Dis., 41(9), 1217–1223, doi:10.1086/469991.

Grayson, R. B., A. W. Western, F. H. S. Chiew, and G. Bloschl (1997), Preferred states in spatial soil moisture patterns: Local and nonlocal controls, Water Resour. Res., 33(12), 2897–2908, doi:10.1029/97WR02174.

Huang, J. Y., B. Bristow, S. Shafrir, and F. Sorvillo (2012), Coccidioidomycosis-associated deaths, United States, 1990–2008, Emerg. Infect. Dis., 18(11), 1723–1728, doi:10.3201/eid1811.120752.

Joetzjer, E., H. Douville, C. Delire, P. Ciais, B. Decharme, and S. Tyteca (2013), Hydrologic benchmarking of meteorological drought indices at interannual to climate change timescales: A case study over the Amazon and Mississippi river basins, Hydrol. Earth Syst. Sci., 17, 4885–4895, doi:10.5194/hess-17-4885-2013.

Kollivras, K., and A. C. Comrie (2003), Modeling valley fever incidence based on climate conditions, Int. J. Biometeorol., 47, 87–101, doi:10.1007/s00484-002-0155-x.

Kollivras, K., P. Johnson, A. C. Comrie, and S. Yool (2001), Environmental variability and coccidioidomycosis (valley fever), Aerobiologia, 17(1), 31–42, doi:10.1023/A:1007619813435.

Koster, R. D., and P. C. D. Milly (1997), The interplay between transpiration and runoff formulations in land surface schemes used with atmospheric models, J. Clim., 10(7), 1578–1591.

Maidment, D., and E. Parzen (1984), Time patterns of water usage in six Texas cities, J. Water Resour. Plan. Manag., 110, 90–106.

Pan, F., C. D. Peters-Lidard, and M. I. Sale (2003), An analytical method for predicting surface soil moisture from rainfall observations, Water Resour. Res., 39(11), 1314.

Park, B., et al. (2005), An epidemic and coccidioidomycosis in Arizona associated with climatic changes, 1998–2001, J. Infect. Dis., 191(11), 1981–1987, doi:10.1086/430092.

Rosenstein, N. E., et al. (2001), Risk factors for severe pulmonary and disseminated coccidioidomycosis: Kern county, California, 1995–1996, Clin. Infect. Dis., 32(5), 708–715.

Sheffield, J., G. Gotei, F. Wen, and E. F. Wood (2004), A simulated soil moisture based drought analysis for the United States, J. Geophys. Res., 109, D24108, doi:10.1029/2004JD005182.

Sheppard, P., A. Comrie, G. Packin, K. Angersbach, and M. Hughes (2002), The climate of the US Southwest, Climate Res., 21, 219–238, doi:10.3354/cr021219.

Stacy, P. R., R. A. Comrie, and S. R. Yool (2012), Modeling valley fever incidence in Arizona using a satellite-derived soil moisture proxy, GeScience Remote Sens., 49(2), 299–316, doi:10.2747/1548-1603.49.2.299.

Talantantes, J. S., Behseta, and C. S. Zender (2007), Fluctuations in climate and incidence of coccidioidomycosis in Kern county, California: A review, Ann. N. Y. Acad. Sci., 1111, 73–82, doi:10.1196/annals.1406.028.

Tamerius, J. D., and A. C. Comrie (2011), Coccidioidomycosis incidence in Arizona predicted by seasonal precipitation, PLoS One, 6(6), e21009, doi:10.1371/journal.pone.0021009.

Tsang, C. A., S. M. Anderson, S. B. Imholte, L. M. Erhart, S. Chen, B. J. Park, C. Christ, K. K. Komatsu, T. Chiller, and R. H. Sunenshine (2010), Enhanced surveillance of coccidioidomycosis, Emerg. Infect. Dis., 16(11), 1738–1744, doi:10.3201/eid1611.100475.

Wang, X., H. Xie, H. Guan, and X. Zhou (2007), Different responses of MODIS-derived NDVI to root-zone soil moisture in semi-arid and humid regions, J. Hydrol., 340(1–2), 12–23, doi:10.1016/j.jhydrol.2007.03.022.