



Regional dust storm modeling for health services: The case of valley fever



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ABSTRACT

On 5 July 2011, a massive dust storm struck Phoenix, Arizona (USA), raising concerns for increased cases of valley fever (coccidioidomycosis, or, cocci). A quasi-operational experimental airborne dust forecast system predicted the event and provides model output for continuing analysis in collaboration with public health and air quality communities. An objective of this collaboration was to see if a signal in cases of valley fever in the region could be detected and traced to the storm – an American haboob. To better understand the atmospheric life cycle of cocci spores, the DREAM dust model (also herein, NMME-DREAM) was modified to simulate spore emission, transport and deposition. Inexact knowledge of where cocci-causing fungus grows, the low resolution of cocci surveillance and an overall active period for significant dust events complicate analysis of the effect of the 5 July 2011 storm. In the larger context of monthly to annual disease surveillance, valley fever statistics, when compared against PM₁₀ observation networks and modeled airborne dust concentrations, may reveal a likely cause and effect. Details provided by models and satellites fill time and space voids in conventional approaches to air quality and disease surveillance, leading to land-atmosphere modeling and remote sensing that clearly mark a path to advance valley fever epidemiology, surveillance and risk avoidance.

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1. Introduction

A soil-dwelling fungus (*Coccidioides immitis* and *Coccidioides posadasii*) and its arthroconidia, fragments approximately 2–5 μm in length (Fisher et al., 2012a,b), cause valley fever (coccidioidomycosis) when inhaled. Humans and animals are commonly affected. While symptoms in most cases of valley fever are slight, for about a third of humans affected it may mean months of shortness of breath, exhaustion or skin rash. Coccidioidomycosis, or cocci, can be fatal (see, e.g., Smith, 1940; Ramras et al., 1970; Williams et al., 1979; Laniado-Laborin, 2007). Between 1990 and 2008 an average of 161 deaths were attributed to the illness every year in the United States (Huang et al., 2012). In 2004 approximately 3000 cases of val-

ley fever were reported in Arizona, 6000 cases nation-wide. Arizona Hospital Discharge Data show 1735 hospital visits for valley fever in 2007, resulting in \$86 million in hospital charges alone. Flaherman et al., 2007, counted in neighboring California an average of 70 deaths each year from valley fever between 1997 and 2008. Medical records for Kern County, California, attribute approximately \$45 million in direct costs for hospitalization and outpatient care for valley fever cases during the period 1991–1993 (CDC, 1994). Note: a requirement to report cocci cases first appeared in 1997; in 2009 a new laboratory procedure to confirm cocci diagnoses was initiated; in 2010, Arizona counted 11,888 cases of valley fever (Tsang et al., 2010), reflecting a change in reporting practices of a major commercial laboratory that more than doubled cocci numbers (Hector et al., 2011); and a major laboratory switched to another test for cocci in 2013 (Tsang, personal communication, 2014).

203 cases of valley fever were reported in Ventura County, California (nearly 10 times the average), following the Northridge

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earthquake of 17 January 1994. Windblown cocci spores carried from landslides triggered by the earthquake are blamed (Schneider et al., 1997).

A 1977 valley fever outbreak in California (more than 379 new cases from a single dust event) serves as a benchmark for estimating the number of valley fever cases that will follow a significant dust storm (Pappagianis and Einstein, 1978). When a massive storm struck Phoenix, Arizona (USA) and its more than 3 million people on 5 July 2011, an extrapolation from the 1977 California experience estimated 3600 excess cases of valley fever would result.

A dust storm forecast and simulation system (Nickovic et al., 2001; Sprigg et al., 2008; Vukovic et al., 2014) assembled by an international team through the University of Arizona had anticipated the storm, (Fig. 1), an American haboob, and its dimensions more than a day in advance.

These points, along with previous success in modeling dust events and indications that their airborne mineral dust plumes are characterized reasonably well (Morain et al., 2007, 2009; Yin et al., 2007; Yin and Sprigg, 2010; Huneeus et al., 2011) prompted a study to see if valley fever surveillance would reflect consequences of the haboob that moved through Phoenix in the early evening hours of 5 July 2011. The following sections borrow from that study (Sprigg et al., 2012) and benefit from updated health surveillance and air quality data, along with additional model output and the work of others (e.g. Chen and Fryrear, 2002; Takemi, 2005; Seigel and van den Heever, 2012; Harriman, 2013) that yield a reasonable understanding of dust generation and severe convective cloud systems.

The haboob of 5 July 2011 was born in the onset of the southwest monsoon, bringing moisture aloft into the dry, hot summer of southern Arizona. A thunderstorm developed just north of Tucson and moved, downhill, toward Phoenix. Severe downdrafts, powered in part by evaporating rain, hit the dry, loose soils of

the land below and pushed dust and dirt out and upward. The US National Weather Service described it as one of the most significant dust storms in the last 30 years (NWS, 2011). At a height of 1500–1800 meters, 18 km depth, along a 160 km front, the July 2011 storm appeared to be the natural, real-time experiment that would reveal, more accurately than ever before, the suspected chain of relationships between windblown dust and case reports of valley fever. However, Mother Nature did not cooperate: National Climatic Data Center Storm Data (NCDC, 2013) show over the last decade in Arizona one to three haboob-like storms every year (Raman and Arellano, 2013). Six haboobs occurred in and around Phoenix alone during the single summer of 2011 (Vukovic et al., 2014).

If a link between valley fever cases and a successfully predicted dust storm can be found, an opportunity is opened for a cocci warning and risk reduction system. It also could help locate active cocci-spore-bearing dust emission zones for mitigation.

If credible model airborne dust simulations and forecasts can be made, and health service providers are confident in the connection between elevated windblown dust and valley fever, the epidemiology and risk aversion strategies for it and many other respiratory and cardiovascular diseases may be advanced. For example, after Morain et al. (2010) found DREAM (Dust Regional Atmospheric Model, Nickovic et al., 2001) hind-casts correlated with particulate network data ($r^2 = 0.97$) in timing of peak concentrations and ($r^2 = 0.59–0.67$) for peak concentrations in a 4–6 January 2007 dust-generating weather front that swept across the American southwest, DREAM was used to sum and map April 2009 daily dust concentrations to assess potential health risks of airborne dust across the state of New Mexico for the New Mexico Environmental Public Health Tracking System.

NASA satellites and the DREAM regional dust model (Nickovic et al., 2001; Nickovic, 2005; Perez et al., 2006) form the dust storm forecast and simulation system in this study. The governing dust



Fig. 1. Looking south, 7:45PM, 5 July 2011, from the US National Weather Service Phoenix Office in Tempe, Arizona, as the dust storm approached. [Photo courtesy NWS].

mass concentration equation is embedded and driven by a non-hydrostatic atmospheric model. This equation mathematically describes all major airborne dust processes, including emission from arid soils, turbulent mixing, vertical and horizontal advection, and wet and dry deposition. Dust particles are represented by eight bins with effective radii of 0.15, 0.25, 0.45, 0.78, 1.3, 2.2, 3.8, and 7.1 μm (Tegen and Lacis, 1996). The first four bins were considered clay particles and the remaining four as silt. The basic DREAM output parameters are 3D dust concentration for each size bin, dust emission and dust wet and dry deposition. Dust sources are monitored by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite.

2. Valley fever surveillance

Interdisciplinary studies strive for comparability in detail, length and stability of time dependent data. We begin by looking at valley fever surveillance.

Coccidioidomycosis (valley fever or cocci in the remaining text) is endemic throughout the US southwest, extending along the border, well into Mexico (Fig. 2) and continues south into Central and South America with equally fuzzy boundaries (Ochoa, 1967; Hector and Laniado-Laborin, 2002; Barker et al., 2012).

Most infections due to *C. immitis* and *C. posadasii*, although causing significant illness, are self-limited and resolve over a period of weeks to months without specific treatment (Galgiani, 2012). For the United States, valley fever was not required to be reported by clinical laboratories or physicians until 1997 (ADHS, 2012). Cocci is usually diagnosed by a laboratory test, and clinical laboratories are very efficient in sending reports of patients who have positive tests. However, this is a passive reporting surveillance system and clinical illnesses are often misdiagnosed; unless a clinician orders appropriate tests the illness will not be counted. Even with surveillance, there will always be under-reporting because surveillance only captures the people who are ill enough to see a doctor. With improved ordering of cocci tests by clinicians, more people will be diagnosed for their cocci illness, but cocci cases will still be under-reported. The incubation period for coccidioid illness ranges from 1 to 4 weeks. Additional time lags occur between onset of symptoms and a medical evaluation, and between initial evaluation and diagnostic test result. Both intervals

vary in length so that divining the exact time and location of exposure at the time of diagnosis is quite uncertain. For many of these reasons, valley fever case reports accumulate as countywide statistics throughout the year. However, with justification, surveillance could be enhanced and some uncertainties of location and timing of exposure could be remedied. Arizona State case reports (Fig. 3) of the Arizona Department of Health Services show the rate of valley fever cases per 100,000 population reported in Arizona from 1990 through 2012. One contributing factor to increases in reported cocci cases may be the increase of susceptible populations to Arizona (ADHS, 2007). The nearly doubling of cases in 2009 is due to a reporting change by a major clinical laboratory rather than an actual epidemic that year (Hector et al., 2011). And, another change in cocci tests was made by a major laboratory in 2013 (Tsang, personal communication, 2014). For these reasons we examine most closely in this study only the period of record from 2010 through 2012.

Arizona makes up sixty percent of cocci cases reported in the US and they are shown, distributed by county, in Table 1 (ADHS, 2012) for 2007 through 2011.

The most recent state statistics for 2011 show an even larger increase in 2011 to 16,473 cases, 38% more than in 2010. In contrast to the earlier increase, this cannot be ascribed to changes in reporting practices. Perhaps the answer lays in the relative dustiness during the year, which is explored in section 4.3, particulate air quality.

Another explanation for the increased reported numbers of valley fever infections is that clinicians are doing a better job of accurately diagnosing valley fever in their patients. It is likely that only a minority of all patients seeking medical attention for coccidioid infections are currently accurately diagnosed by laboratory testing, either because physicians don't order the necessary tests or because the tests fail to detect the infection (Chang et al., 2008; Chen et al., 2011). The Arizona Department of Health Services, the Valley Fever Center for Excellence at the University of Arizona, and the Infectious Diseases Society of America (Galgiani et al., 2005) have all recommended that any patient with community-acquired pneumonia and endemic exposure be tested for cocci. If physicians increasingly adhere to that recommendation, it is expected that more infections will be added to the state statistics even if the actual number of infections are not greater. It is not known how much improved detection contributes to recent increases.

The goal of improved surveillance continues to challenge (C. Tsang, personal communication, 2014): In December 2012, a major laboratory switched to a new test, creating a significant decrease in reported cocci cases for the year 2013. With such inconsistencies in reporting and testing, it may take some time before cocci reporting methods stabilize.

Most reported valley fever cases occurred in Pima, Pinal and Maricopa counties, the "Valley Fever Corridor", where much of the state's population resides (Fig. 4). Eighty-two percent of Arizona's 2011 valley fever infections occurred in Maricopa County, with Phoenix its center of population. Maricopa County is the most populous county in Arizona. Furthermore, Maricopa County experienced some of the worst July dust storms in recent memory.

Little historical information exists to prove that a large dust storm will increase reports of valley fever. One very large storm in California's Central Valley occurred in December of 1977 (Pappagianis and Einstein, 1978). Dust and coccidioid spores were blown as far north as Sacramento and the San Francisco Bay, triggering primary valley fever infections. A large number of cases in Kern County were reported in the following three months when, normally, few new cases of Valley Fever would have been reported. The California storm was the result of Santa Ana winds, not the summer thunderstorm downdraft phenomenon that

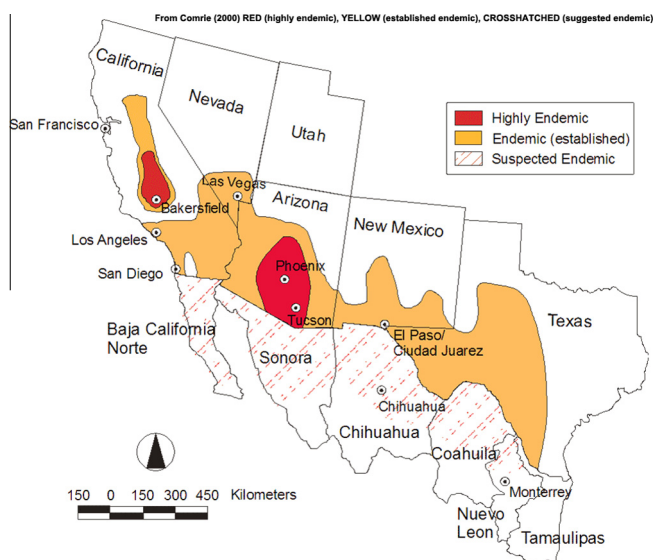


Fig. 2. Estimated Coccidioidomycosis (Valley Fever) endemic zones in North America. (From Comrie, 2012).

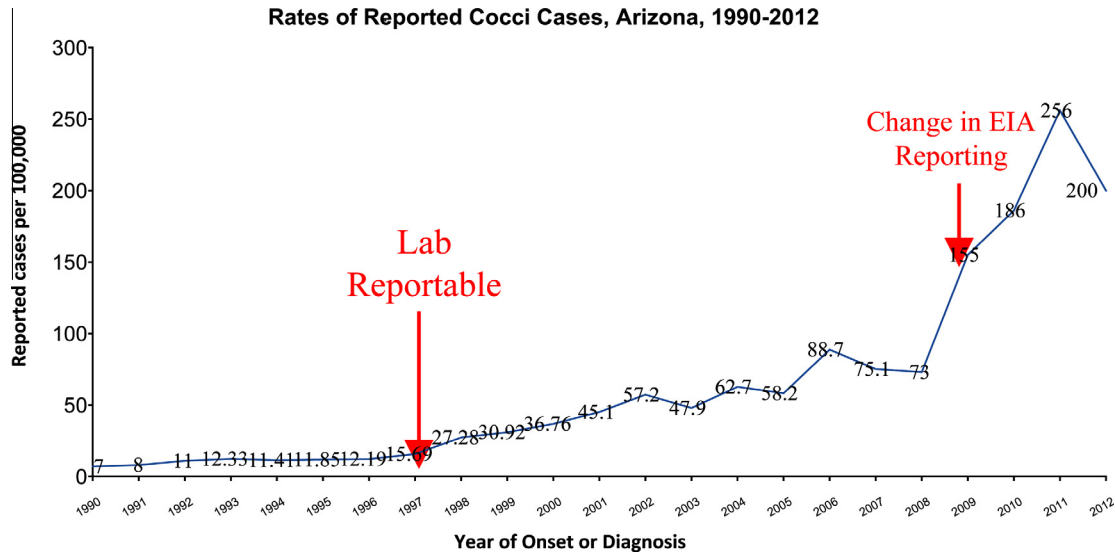


Fig. 3. Rate of valley fever cases in Arizona per 100,000 population; 1990–2012 (Arizona Department of Health Services, Valley Fever Report 2007–2011); Enzyme-linked immunoassay (EIA). Update courtesy C. Tsang, Arizona Department of Public Health Services.

Table 1
Reported valley fever cases by county in Arizona for 2007–2012. (Arizona Department of Health Services, Valley Fever Report 2007–2011); update courtesy C. Tsang and M. Kahn, Arizona Department of Health Services.

County	Coccidioidomycosis case counts by county, 2007–2012						
	2007	2008	2009	2010	2011	2012	
APACHE	5	7	11	23	19	17	
COCHISE	32	17	39	48	71	48	
COCONINO	13	6	25	41	57	48	
GILA	15	16	31	46	50	49	
GRAHAM	24	12	13	24	35	33	
GREENLEE	2	1	2	1	1	2	
LAPAZ	15	7	21	26	45	25	
MARICOPA	3450	3525	8078	9456	13,405	10,116	
MOHAVE	47	59	77	118	140	109	
NAVAJO	11	11	31	34	56	39	
PIMA	901	816	1320	1430	1665	1555	
PINAL	254	255	509	563	820	774	
SANTA CRUZ	7	6	14	14	20	19	
YAVAPAI	26	23	50	39	59	53	
YUMA	13	7	12	21	30	33	

caused the 5 July 2011 Phoenix haboob. However, both produced very dusty conditions. If the findings in Kern County could be extrapolated to the population of Maricopa County, one could easily expect three thousand or more excess valley fever infections to appear in the Maricopa County statistics in the following months.

However, Arizona state surveillance statistics show only a hint of connection between the 5 July storm and the 2011 increase in cases of cocci. This is at least in part due to a second haboob that struck Phoenix two weeks later on 18 July that added residents' risk of exposure to the fungus and to valley fever – the disease incubation period overlapped with the two storms. Weekly cocci reports, accumulated through 2011 are shown (Figs. 5a,b) for the three individual counties of Maricopa, Pima and Pinal, and for all other Arizona Counties combined. The accumulated weekly values fail to show a significant increase immediately following the haboobs in July 2011 (ADHS, 2012; *Coccidioidomycosis Study Group, 2012*), but month-by-month data do show a peak in Maricopa County reports within the incubation period following the two big storms (Fig. 7).

Combined with generic, considerable uncertainties in valley fever surveillance statistics, cause and effect correlation between

either of the two storms and valley fever cases become quite problematic.

Note the difference in graph scales. Maricopa County case counts are significantly larger than the other counties. Despite the week-to-week variation, what is most apparent is that the statewide increase in cases is fairly constant throughout the year, not just temporally after the July storms. Not so apparent in this figure is that during the year the reported numbers for the three Valley Fever Corridor Counties tended to rise and fall in synchrony. Fig. 6 shows the weekly change of 2011 county numbers as a percentage of 2010 numbers. At the beginning of the year there are very few cases, so relatively small differences are accentuated.

As the year progresses, Maricopa values trend downward in late summer and early fall, but the trend lags those of Pima and Pinal Counties. This loss of synchrony may be due to excess cases from the July storms.

Month-to-month Maricopa County cocci reports for 2010, 2011 and 2012 are compared in Fig. 7. Cocci reports for 2011 generally exceed those of 2010 and 2012 throughout the year. We shall see later in 4.3 that 2011 was an exceedingly dusty time. It is tempting to blame the jump in the 2011 curve on the July storms, but what

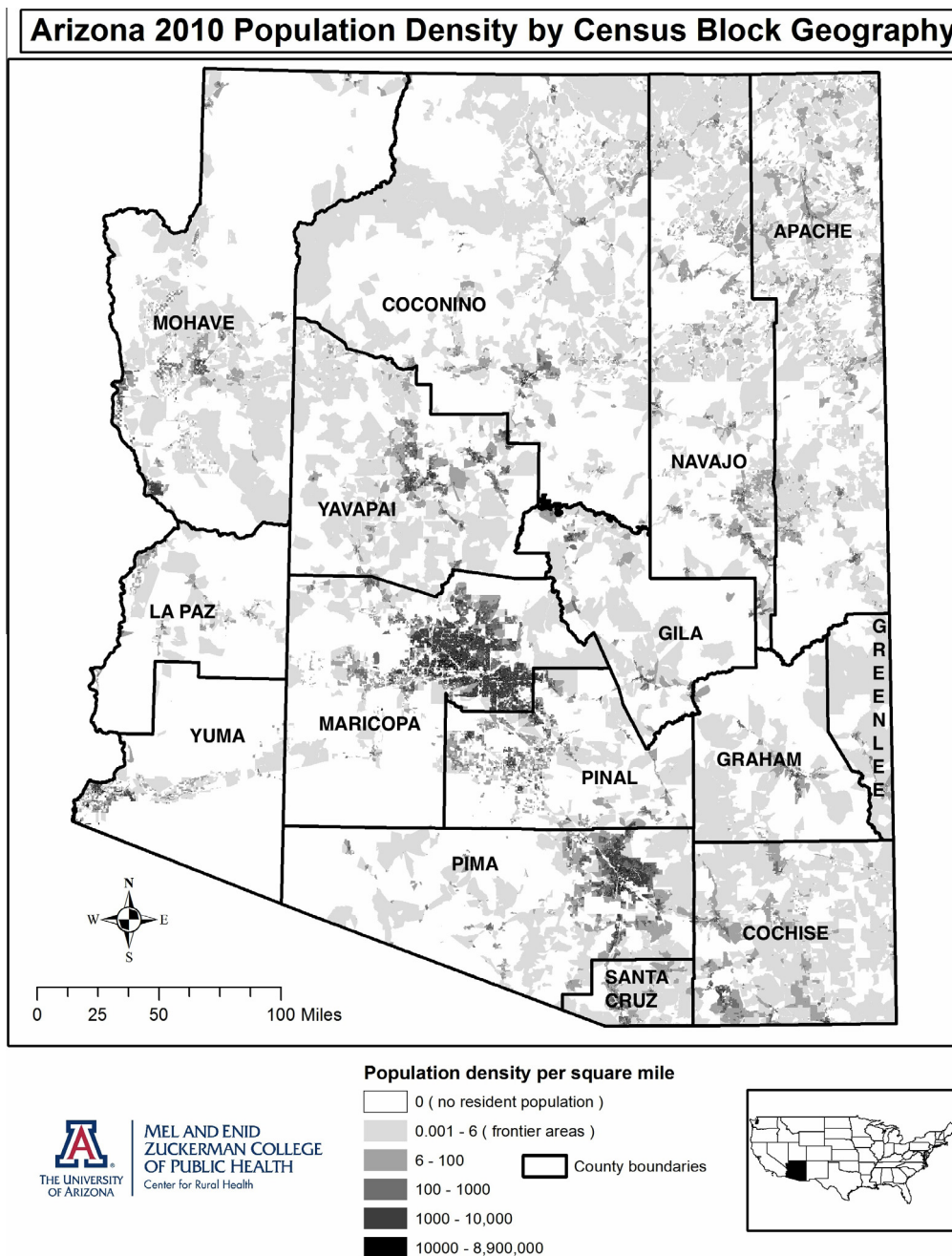


Fig. 4. Arizona's Valley Fever Corridor runs, south to northwest, through Pima, Pinal and Maricopa Counties, coinciding with population density.

would explain the high counts of November and December in 2010? Are they a residual effect of the change in reporting depicted in Fig. 3? Particulate air quality deteriorated toward year-end, but not remarkably so (see Fig. 10).

3. The dust model system (a proxy for *C. immitis* and *C. posadasii arthroconidia*) and the 5 July 2011 Phoenix haboob

The 5 July 2011 dust storm was anticipated nearly two days in advance using the coupled atmosphere-land/dust model NMME-DREAM (Non-hydrostatic Mesoscale Model, E-grid, Dust Regional Atmospheric Model) at 20 km horizontal resolution; but the higher spatial resolution of 3.5 km was necessary to reveal details of the storm.

NMME-DREAM runs concurrently on redundant systems in the University of Arizona's High Performance Computing Center and in the South East European Virtual Climate Change Center, Belgrade, Serbia. Hind-cast analyses of the haboob are described herein at 3.5 km resolution. The smaller, 18 July haboob went undetected on the quasi-operational 20 km resolution system. Potential dust productive regions (Fig. 8) were identified in the land cover and Normalized Difference Vegetation Index (NDVI) 16-day composites from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) (e.g. Kim et al., 2013). MODIS land cover data set types of barren, sparsely vegetated and agricultural lands were singled out and combined with information on non-vegetated areas from NDVI every 16 days. The resulting database is called a dust mask and marks non-vegetated land fractions, while the actual dust emission calculated in the model further depends on the soil

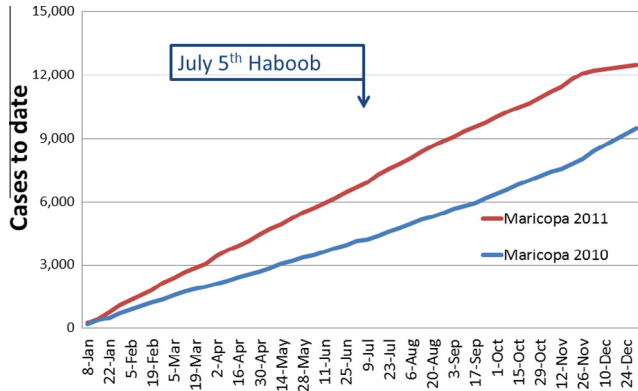


Fig. 5a. 2010 and 2011 weekly cumulative valley fever cases in Maricopa County, Arizona.

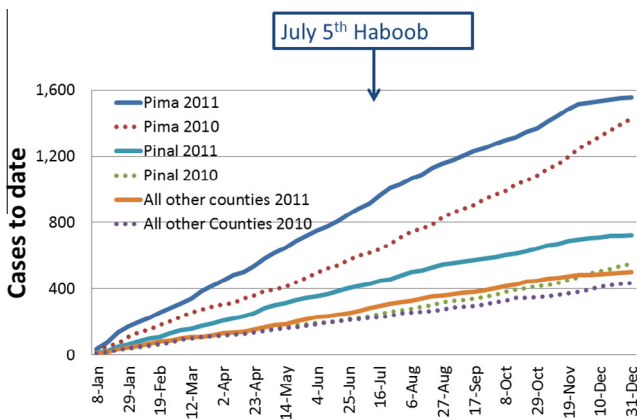


Fig. 5b. 2010 and 2011 weekly cumulative valley fever cases in Pima, Pinal and all other Arizona Counties except Maricopa County (note change in scale from Fig. 5a).

texture, soil moisture and wind near the surface (Morain et al., 2009, 2007).

A description of the NMME-DREAM, along with characterization of dust sources and model verification relevant to the 5 July storm are presented in Vukovic et al., 2014. US National Weather Service radar and meteorological observations, NASA satellite-based images, and the Arizona Department of Environmental Quality PM₁₀ monitoring stations provided data against which model results were compared.

Model verification in the 5 July 2011 study included comparisons with meteorological parameters to confirm integrity of the modeled atmosphere – and with MODIS aerosol optical depth (AOD) with deep blue (DB) algorithm (NASA, 2014; Mahler et al., 2006) for aerosol loading and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) to see the dust profile and its vertical structure.

The NMME-DREAM successfully hind-casted the position of the front and the rapid uptake of dust and high values of the storm’s dust concentration in space and time, with approximately 16 h lead time. The modeled arrival of the dust front in Phoenix was approximately 1-h late. Fig. 9 shows, in 1-h time steps (GMT), observed PM₁₀ (μg m⁻³) and the modeled entrance of the dust plume into the Phoenix area.

In proximity to rural source regions the model PM₁₀ surface dust concentration reached ~2500 μg m⁻³ (where monitoring stations do not exist for comparison). The model under-estimated values compared to PM₁₀ stations within the city. Dust sources (the proxy for valley fever fungal spore sources) used in these model runs do not include city sources such as construction sites, roadways and gardens. Yet, evidence from veterinary reports of cocci in household pets shows that the fungus, *C. immitis* and *C. posadasii*, exists in city and suburban environs (Valley Fever Center for Excellence, VFCE, 2013).

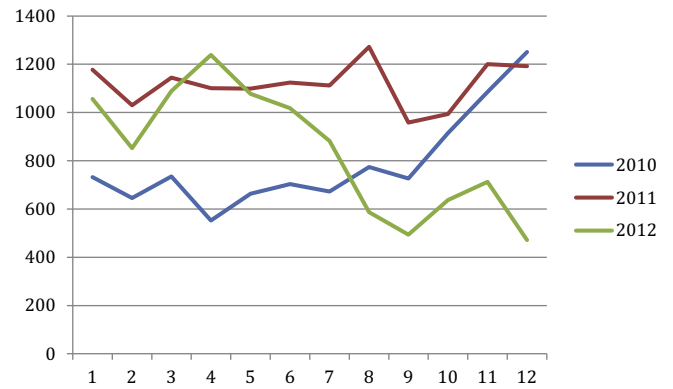


Fig. 7. Number of reported cocci cases by month, Maricopa County, 2010–2012 (Courtesy C. Tsang and M. Kahn, Arizona Department of Health Services).

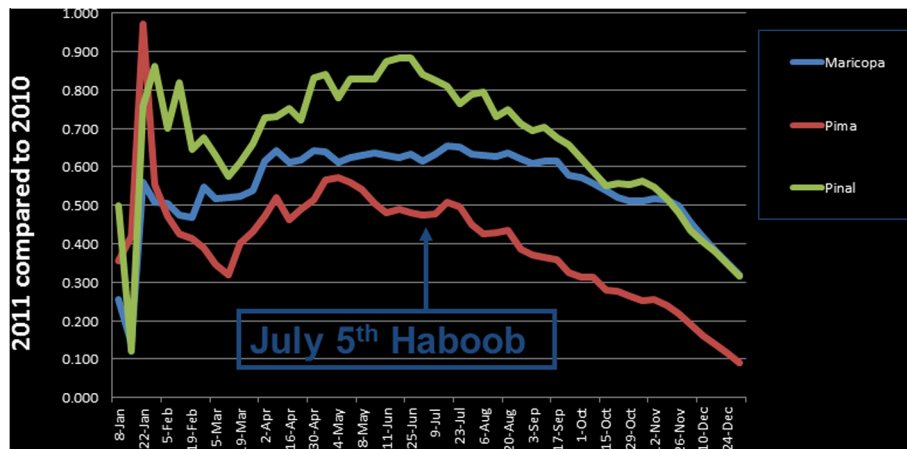


Fig. 6. Weekly% increases for 2011 vs 2010 in cases of valley fever reported to the Arizona Department of Health Services. Before the number of cases begin to accumulate during the year, small differences between 2011 and 2010 are accentuated.

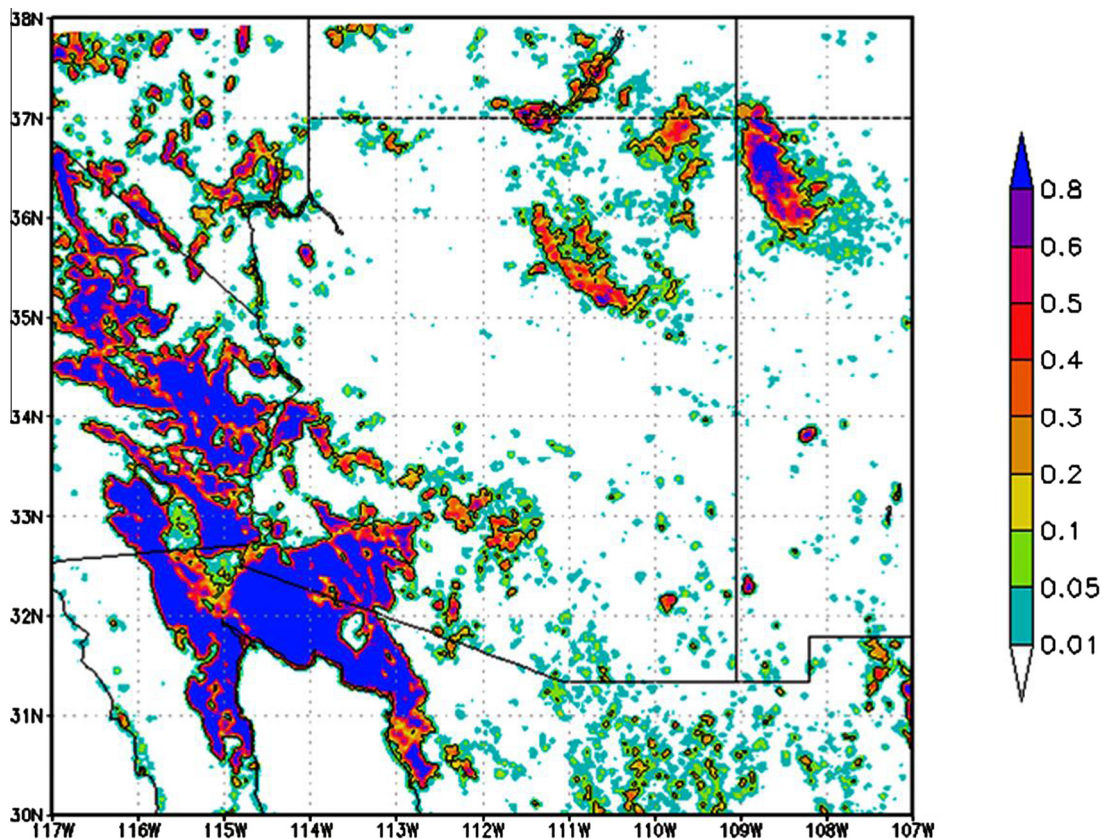


Fig. 8. Potential dust sources are identified from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) to create a mask on 3.5 km model resolution. The mask includes barren, sparsely vegetated and farmland areas that are currently without vegetation.

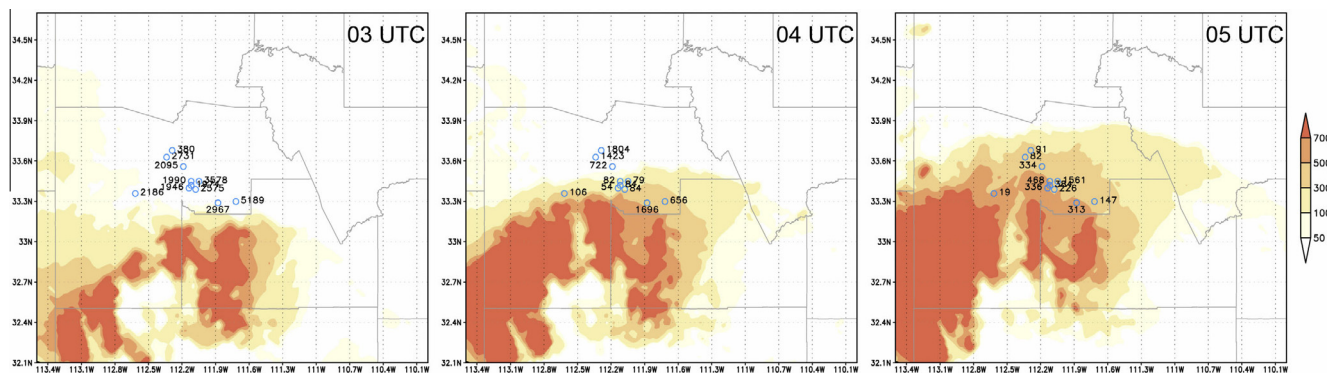


Fig. 9. NMME-DREAM PM_{10} ($\mu g m^{-3}$) surface dust concentration (orange) and observed (blue dots) values of PM_{10} ($\mu g m^{-3}$) at 03, 04 and 05 UTC on 6 July 2011 for Maricopa County, Arizona (from Vukovic et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

An analysis of why measured and computed concentrations will not exactly match must take into account several factors. While DREAM can assume a large array of characteristics for dust sources and airborne particles (Olson, 1994a, 1994b), for the purposes of these experiments particles larger than PM_{10} are omitted in the assumption that they will drop quickly from the air and that larger particles are of less interest for health implications (see Section 4.3).

We also assume the sources are rural, including active and abandoned cropland, which are known sources for windblown particles or “dust.”

We have masked out cities as dust sources, partly because this environment is its own generator of PM_{10} , and Environmental

Quality offices move quickly to mitigate causes of deteriorating air quality. Due to the efforts of these offices, the amount and character of urban particulates are well known and regulated. The largely unknown part of airborne particulates that affect air quality comes from beyond city limits. We address this.

The PM_{10} measurements, against which DREAM outputs are compared, are made largely within and very near urban areas. We know PM_{10} from these city sources is different, both in what causes particles to be launched into the atmosphere (e.g. road construction and highway traffic) and their makeup (e.g. some combustion). While a few rural-like PM_{10} measurement sites are available, they are too few for meaningful, statistical analysis.

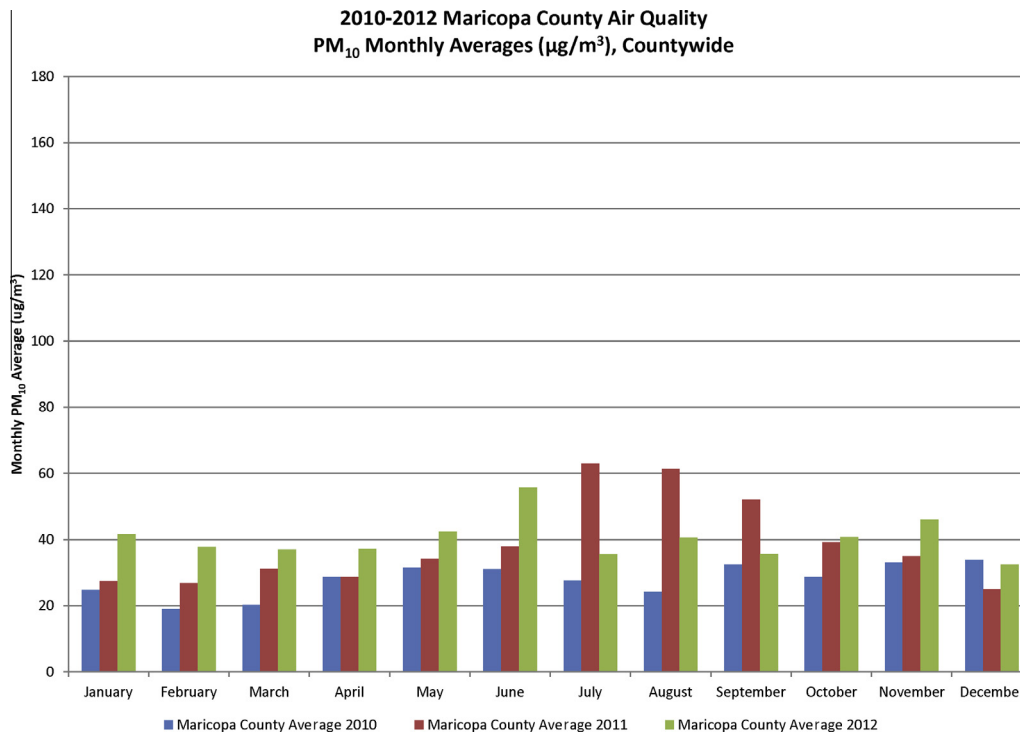


Fig. 10. 2010–2012 Maricopa County Air Quality PM₁₀ Monthly Average ($\mu\text{g m}^{-3}$), Countywide from 15 continuous monitoring stations.

For these reasons, and the “double penalty” problem (Rossa, 2008) when verifying model simulations of small-scale, highly changeable features, such as precipitation, wind gusts and airborne dust, a direct comparison today of available PM₁₀ measurements with model output is problematic.

4. The 5 July 2011 haboob in context: real world conditions of 2011

Exposure to cocci arthroconidia may happen for many reasons. We shall try to distinguish the risks of exposure posed by weather and climate conditions, i.e., wind-generated dust events, from the largely elective risk-taking activities of, for example, farming, landscaping, construction and off-road recreation.

In order to better understand and later predict mechanisms of emission and transport of cocci spores, knowledge of the geographic distribution of cocci fungus is critical. In 4.1 we show that source regions are poorly defined, so we must look for the climate (see Section 4.2) and soil conditions in Arizona and the region extant that favor *C. immitis* and *C. posadasii* growth; this will yield a first-guess map of cocci source regions and a mask for model use.

In the first approximation of risk of exposure to airborne cocci spores (arthroconidia) in the period encompassing the July 2011 storms, we assess the general dust conditions (particulate PM₁₀) across the landscape for June through October, 2011, derived from air quality monitoring networks (see Section 4.3) and mapped, model-generated, hind-casts, which (beneficially) fill gaps between PM₁₀ stations (Section 4.4). The assumption is that cocci arthroconidia are part of the airborne particulates. Most reports of valley fever from the July haboobs should appear in this time period. But, can the general dustiness of the period overwhelm the comparatively short-lived but massive dust entrainment generated by the haboobs?

Finally, in Section 4.5, we compare model runs using the two source masks, one from known dust sources and another where only dust sources believed to be conducive to the cocci fungus are developed. This experiment demonstrates how a cocci-source mask may sharpen our knowledge of where and when risk of expo-

sure to windblown cocci arthroconidia may have been greater – or lesser. It is a first approximation and an indicator for further study.

4.1. *C. immitis* and *C. posadasii* sources

Exact locations of *C. immitis* and *C. posadasii* arthroconidia are poorly known (Fisher et al., 2012a; Castanon-Olivares et al., 2012). Cocci is believed to be endemic only in the Americas (Tabor et al., 2010; Barker et al., 2012). But, dust travels great distances, over hundreds of kilometers, across continents, oceans and around the world (Griffin et al., 2001; Prospero and Lamb, 2003; Lee and Liu, 2004; Kellogg and Griffin, 2006; Perez et al., 2008; Sandstrom and Forsberg, 2008; Marx et al., 2009; Kimura, 2012; Prospero and Mayol-Bracero, in press). Viable cocci arthroconidia is being transported along with the mineral dust, evidenced in outbreaks of valley fever quite distant from known or suspected source regions and the storms that entrained them (Pappagianis and Einstein, 1978; Flynn et al., 1979; Fisher et al., 2012b). Yin and Sprigg (2010) show that significant amounts of mineral dust cross the US–Mexico border regions during typical dust events.

Fisher et al. (2012b) summarize conditions conducive to coccidioides growth, including rain after a dry period, fine grained (mostly quartz) sand or silt soils, moist but not saturated and subject to temperatures $>50\text{ }^{\circ}\text{C}$ in the upper (3 cm) surface strata. How these characteristics can be incorporated into environmental models to estimate risk of exposure to cocci is discussed in the following sections. Unfortunately it is prohibitively expensive to sample soils sufficiently to find and map coccidioides precisely over the suspected areas of infection using current methods (e.g. Barker et al., 2012). New methods are under evaluation that may lower the cost from $>\$2000$ to less than $\$50$ per soil sample (Tabor, 2012, personal communication).

4.2. Climate factors for *C. immitis* and *C. posadasii*

Tamerius and Comrie (2011) and Comrie (2012) show that the number of Valley Fever cases reported in Pima and Maricopa

Counties are correlated with antecedent precipitation on seasonal and inter-annual climate scales. An hypothesis consistent with these findings is that rain results in a fungal bloom in the soil and if followed by a hot, arid season, the soil dries out, spores become brittle and fracture, which leads to more cocci arthroconidia spores in the air. Risk of exposure and reported infections result. Comrie (2012) did not see an improvement in correlations between Valley Fever cases and rainfall when PM₁₀ data were included in the analysis. The study herein includes soil wetness as a factor to control dust or cocci spore emissions on a synoptic scale, but does not reach back for antecedent conditions that influence the phenology of *C. immitis* or *C. posadasii* growth, desiccation and fragmentation.

4.3. Particulate air quality

Particulate Matter 10 (PM₁₀) refers to particles having an aerodynamic diameter of 10 microns and less. This size range covers most of the respiratory health issues, as larger particles become trapped in the nasal passage and nose hair follicles. Of all available air quality sampling devices against which we can compare model results, the greatest number by far measure PM₁₀.

South central Arizona PM₁₀, specifically in Pinal and Maricopa counties, was significantly worse in 2011 than in 2010 and 2012 (Figs. 10–12). Pinal County's countywide averages exclude the Cowtown monitoring site (one of six continuous monitoring stations in the county) where its unique situation produces dust emissions that dominate the other five County monitoring sites, exaggerating a very local effect.

Summer 2011 PM₁₀ readings in Maricopa and Pinal Counties were significantly higher than in the summers of 2010 and 2012. Airborne fungal spores are part of the dust, which may help explain why cases of valley fever follow similar year-to-year, 2010–2012 variability (Fig. 3).

Maricopa County PM₁₀ concentrations for July through September 2011 and Pinal County PM₁₀ values for July through October 2011 were particularly high. The Maricopa countywide monthly

average PM₁₀ concentrations for July 2011 were nearly double those for July 2010 and 2012. The August 2011 Maricopa County monthly average PM₁₀ concentrations were more than double those measured in 2010 and approximately 50% higher than in August 2012. In Pinal County, monthly average PM₁₀ concentration in July 2011 was more than two and a half times higher than those of July 2010 and July 2012. A similar trend continued in Pinal County in August 2011 (two times higher than 2010, approximately 40% higher than 2012), September 2011 (approximately 30% higher than 2010 and 2012) and October (approximately 50% higher than 2010 and approximately 15% higher than 2012). Relatively small monthly averages and year-to-year or month-to-month variances in PM₁₀ for Pima County reflect in large part that the major dust sources lie northeast or some distance west of Tucson (Fig. 8), reached by synoptic and monsoon circulations after passing the mostly green Santa Rita Mountains and Tucson to the south (Raman and Arellano, 2013; Vukovic et al., 2014; Shoemaker and Davis, 2008).

The significantly higher PM₁₀ concentrations during the summer months in 2011 were due to several factors including strong winds associated with monsoon-generated storms and below normal precipitation. Annual rainfall in Pinal County recorded at Arizona Meteorological Network (AZMET) locations for 2011 was significantly lower than long-term averages. For example, the city of Maricopa in northwestern Pinal County recorded 8.9 cm of precipitation in 2011, compared to the 1988–2011 average of 16.4 cm. The Coolidge AZMET station 2011 rainfall total was 11.7 cm compared to the 1987–2011 average of 17.1 cm. The Phoenix National Weather Service (NWS) location at Sky Harbor Airport in Maricopa County measured 11.8 cm of rain in 2011 compared to the long term average of 21.1 cm. Further south, in Pima County, the National Weather Service recorded the second driest January–June period on record at Tucson International Airport in 2011 with only 1.5 cm of precipitation. Tucson International Airport had recorded the fourth longest period on record of no rain in 2011 with 81 straight days.

Dry conditions prior to and during the 2011 monsoon season (usually from early July to mid-September) reduced vegetation

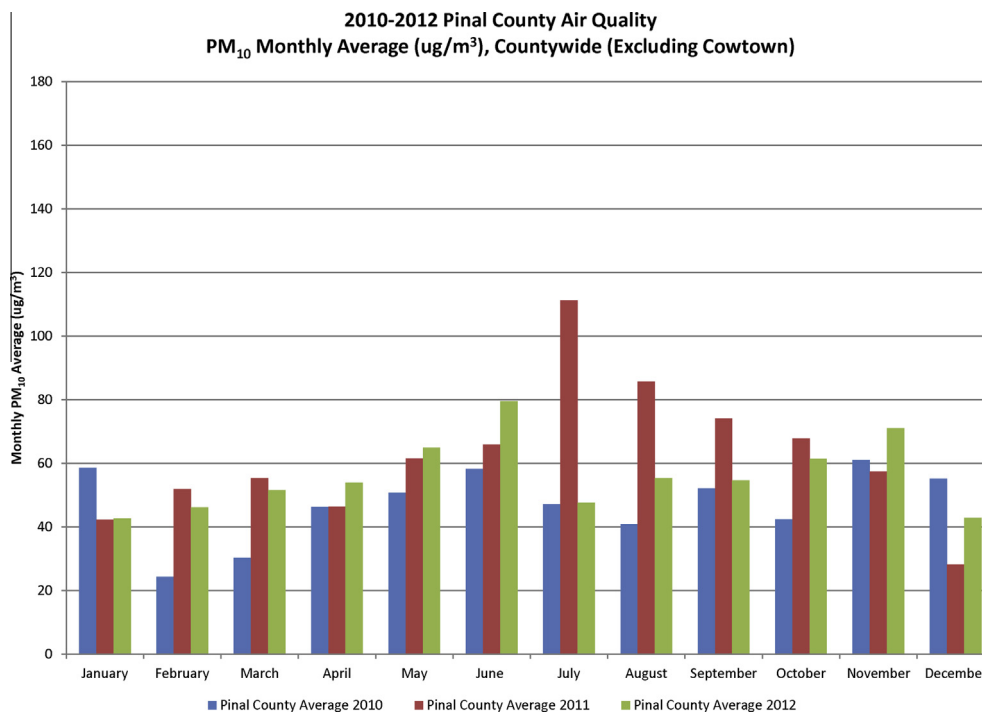


Fig. 11. 2010–2012 Pinal County Air Quality PM₁₀ Monthly Average (μg m⁻³), Countywide from 5 continuous monitoring stations.

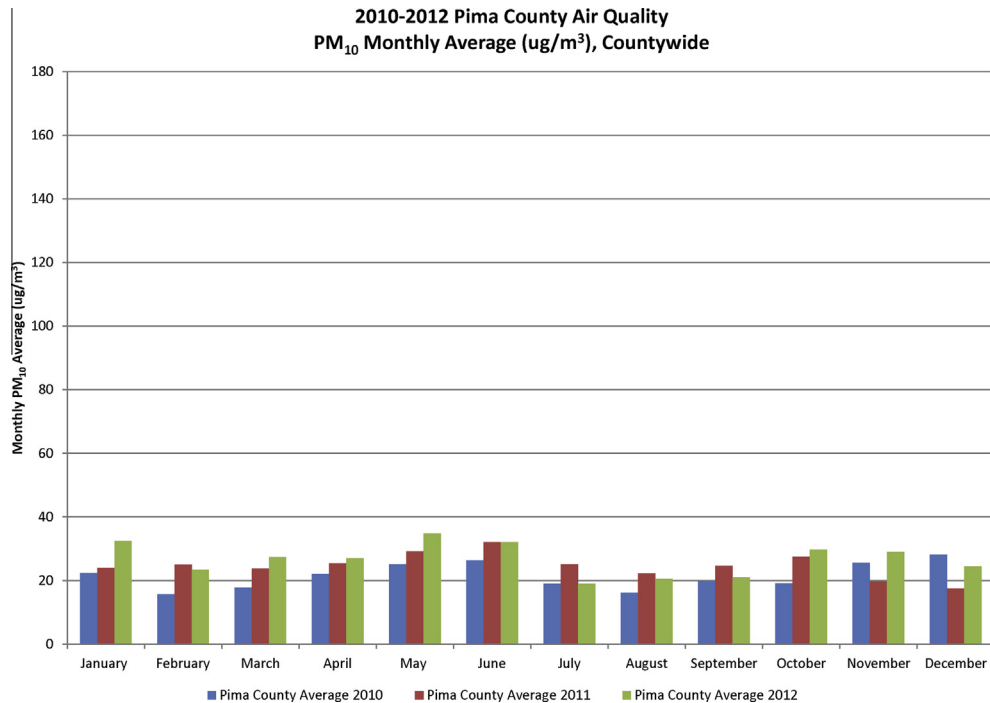


Fig. 12. 2010–2012 Pima County Air Quality PM₁₀ Monthly Average ($\mu\text{g m}^{-3}$), Countywide from 8 continuous monitoring stations.

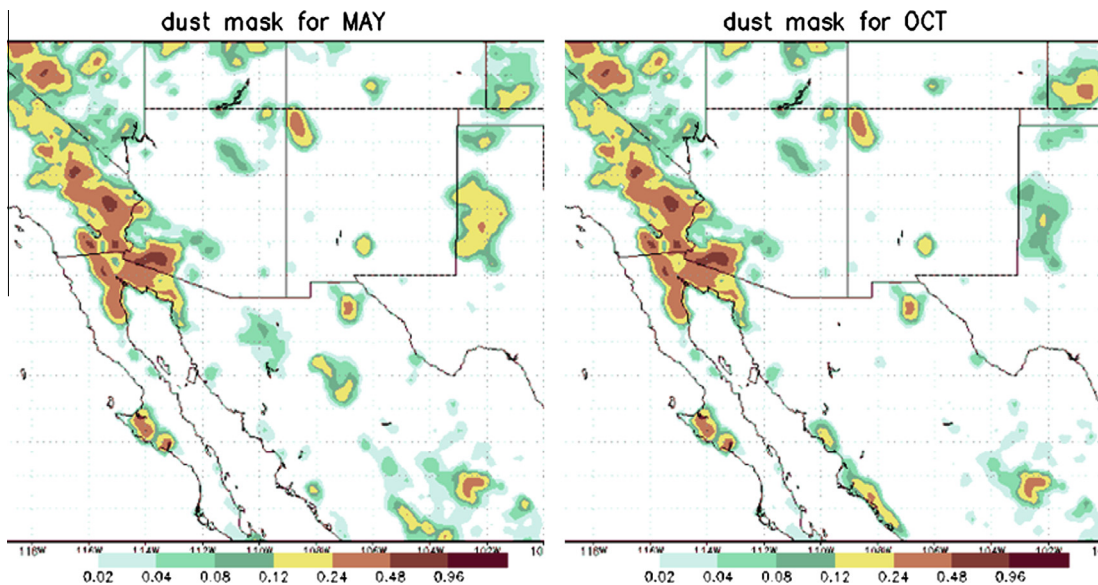


Fig. 13. Potential dust sources masks derived from NASA MODIS are redrawn every 16 days and included in NMME-DREAM; shown here are sample masks for (L) May and (R) October 2011.

and exposed soil for atmospheric entrainment. The long dry period in the region contributed to significant amounts of blowing dust and resulted in a number of Pinal County violations of PM₁₀ air quality standards. The summer of 2010 in Pinal County produced six monsoon related PM₁₀ air quality violations and Maricopa County experienced none. In summer of 2012 there were fifteen monsoon related PM₁₀ events that exceeded air quality standards in Pinal County. Maricopa County had eight. The 2011 summer was significantly higher than either 2010 or 2012 for monsoon related PM₁₀ violations in Pinal County (twenty-seven violations) and Maricopa County (seventeen violations).

The highest 24-h average PM₁₀ concentration in Pinal County during the summer of 2011 was $2316 \mu\text{g m}^{-3}$ at the Cowtown monitor on July 5, 2011. The health-based standard for PM₁₀ is a 24-h average of $150 \mu\text{g m}^{-3}$. The July 5, 2011 PM₁₀ measurement at the Cowtown monitor was more than fifteen times higher than the health standard! There were four other monitors on three separate days in summer of 2011 where PM₁₀ 24-h average concentration exceeded $1000 \mu\text{g m}^{-3}$ in Pinal County. Nothing such as this occurred in Pinal County in either 2010 or 2012. In Maricopa County during the summer of 2011 the maximum-recorded PM₁₀ concentration was $559 \mu\text{g m}^{-3}$, which was over three times the

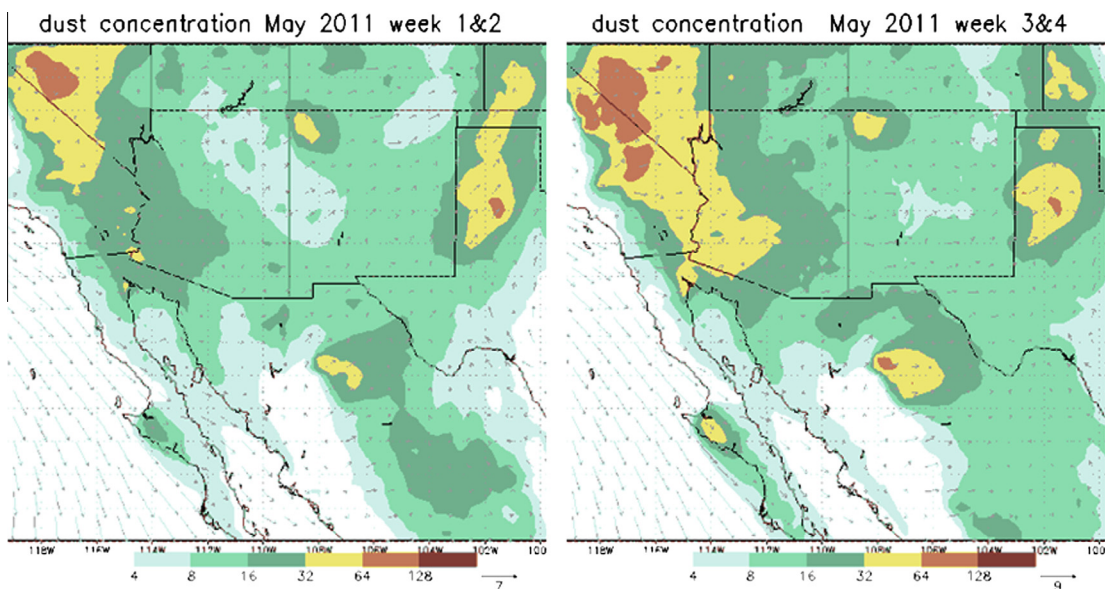


Fig. 14a. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over (L) the first two weeks and (R) the last two weeks of May 2011.

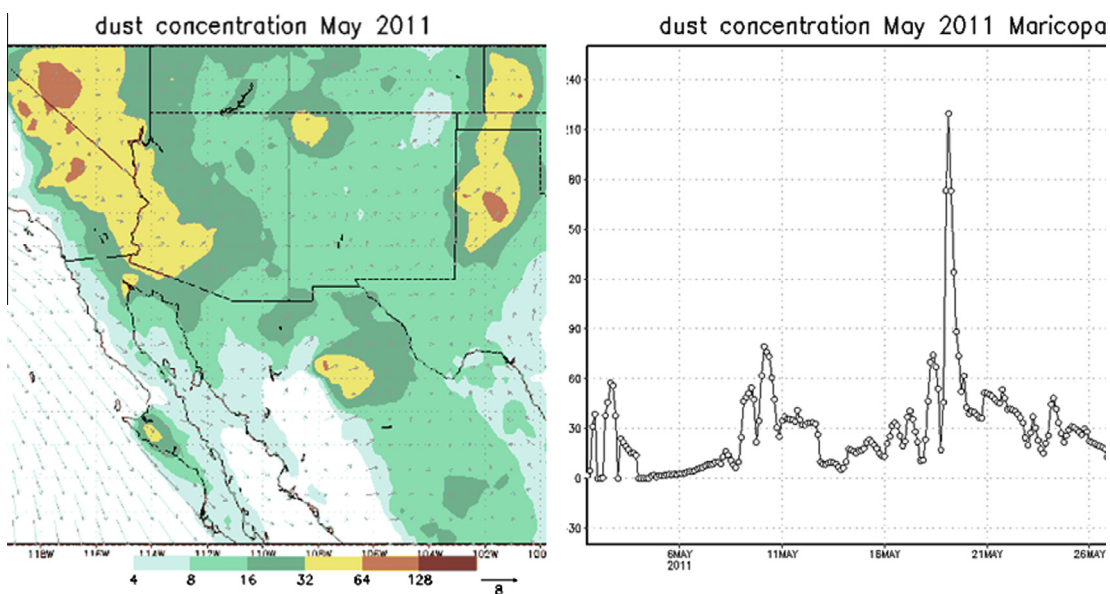


Fig. 14b. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) (L) averaged over the month of May 2011 and (R) the May 2011 evolution of dust concentration ($\mu\text{g m}^{-3}$) in Maricopa County, Arizona.

health standard. The summer of 2012 in Maricopa County had a high PM_{10} concentration of $344 \mu\text{g m}^{-3}$, more than two times the health standard. No PM_{10} violations occurred in Maricopa County during the summer of 2010. Finally, for comparison, Pima County had one PM_{10} event that exceeded the health standard during the summer of 2010. During the summer of 2011 Pima County exceeded PM_{10} standards four times; the highest concentration reached $213 \mu\text{g m}^{-3}$. Pima County did not violate the PM_{10} standard in the summer of 2012.

Summer PM_{10} standards' violations associated with wind-blown dust in 2011 were high in frequency, areal extent and overall PM_{10} concentrations. These characteristics are reflected in the modeled and mapped dust concentration described in Section 4.4. This made 2011 an outlier compared to 2010 and 2012, reflected as

well in the case counts of valley fever, higher in 2011 than in either 2010 or 2012 (Table 1).

PM_{10} averaged over the time scales depicted in Figs. 10–12, are not considered a health risk. Air quality regulations address shorter time-periods. EPA National Ambient Air Quality Standards (EPA, 2014a) specify a 24-h maximum of $150 \mu\text{g m}^{-3}$ should not be exceeded, for either health or general public welfare. Pinal County's average PM_{10} concentration for the period 1999–2012 for the same monitoring locations used to compile the 2010–2012 PM_{10} is $52.4 \mu\text{g m}^{-3}$. Maricopa County's 1999–2012 PM_{10} average is $42.2 \mu\text{g m}^{-3}$. Pima County's PM_{10} average for the same period is $27.7 \mu\text{g m}^{-3}$ (EPA, 2014b).

Compare the 2010 and 2011 slopes of the weekly cumulative cocci cases (Fig. 5a) and the month-by-month PM_{10} values

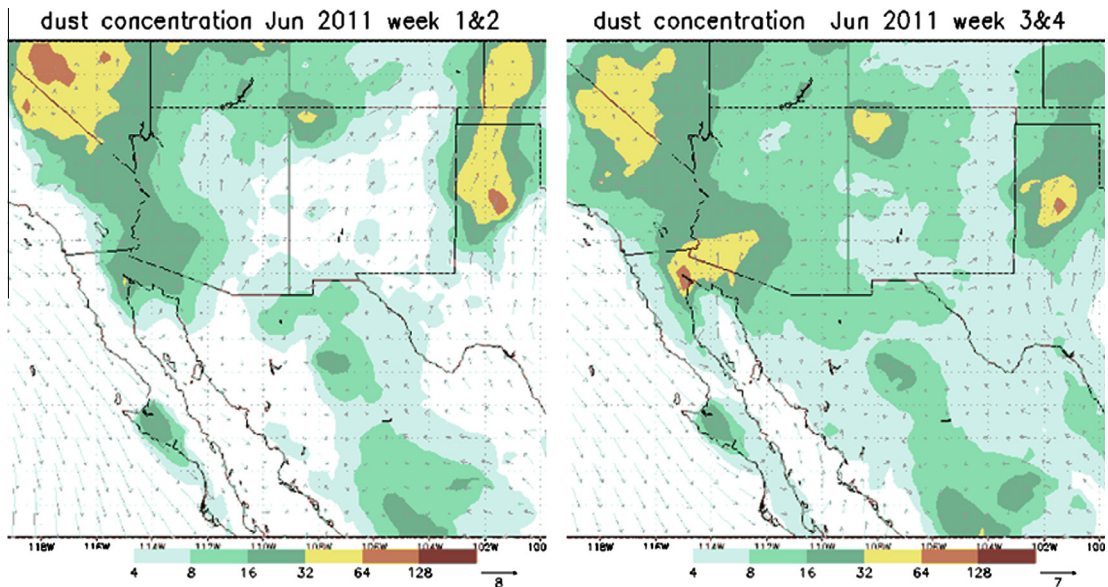


Fig. 15a. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over (L) the first two weeks and (R) the last two weeks of June 2011.

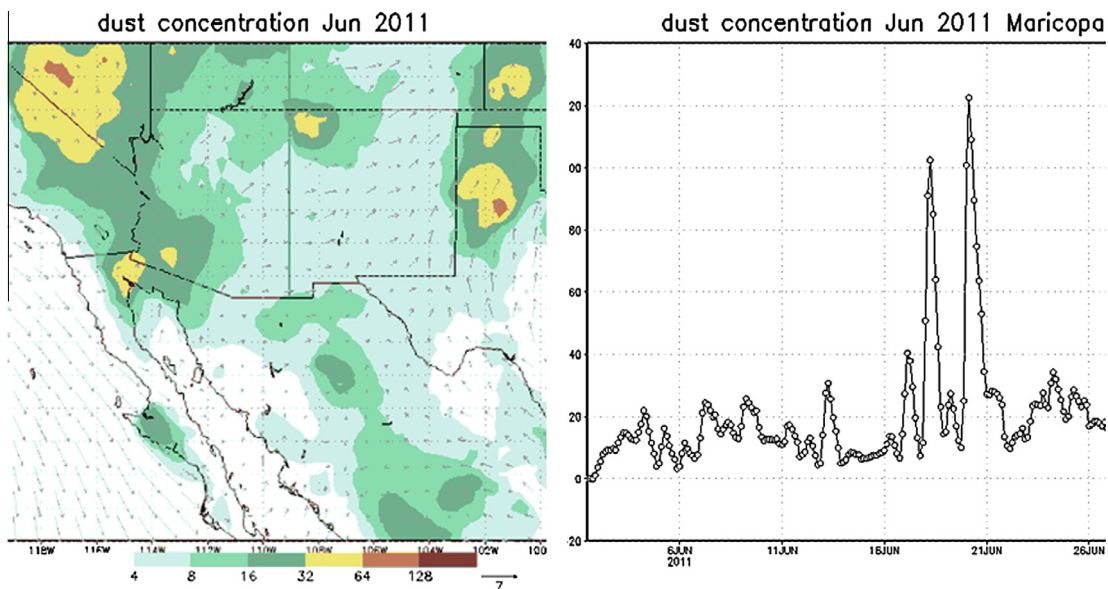


Fig. 15b. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) (L) averaged over the month of June 2011 and (R) the June 2011 evolution of dust concentration ($\mu\text{g m}^{-3}$) in Maricopa County, Arizona.

(Fig. 10) for Maricopa County. In 2010, cocci cases accumulate rather steadily through the year and PM_{10} changes only slightly from month to month. In 2011, cocci cases accumulate more rapidly in summer, coinciding with very high PM_{10} levels. While not as pronounced in Pinal County, with its lower population than either Maricopa or Pima Counties, the month-by-month PM_{10} (Fig. 11) and weekly cumulative cocci cases (Fig. 5b) follow a path similar to Maricopa County's through 2010 and 2011. Countywide accumulation figures for cocci in Pima and Maricopa are very similar in shape, if not in magnitude (Figs. 5a and 5b), including the downturn at the end of 2011. Pima County month-to-month PM_{10} follows a similar pattern and comparison of 2010, 2011 and 2012, albeit slight, at one-third the levels recorded in Maricopa County.

Month-by-month cocci reports for Maricopa County (Fig. 7) follow airborne dust levels (Fig. 10) fairly consistently in 2010 except

for the unexplained increase in cocci at the end of the year. Monthly cocci reports for 2011 follow monthly PM_{10} reasonably well, including the pronounced peak in cocci following the July storms. Cocci and PM_{10} track rather closely in 2012.

Longer, comparable surveillance records are necessary for a more quantitative assessment. For the time being we point to these qualitative analyses as evidence of the link between airborne dust events and cocci case counts.

Section 4.4 tests a low spatial resolution airborne dust forecast and simulation system to validate the “dustiness” of the region and fill gaps in the PM_{10} monitoring network.

4.4. Model hind-cast: regional windborne dust June–October 2011

Running at 3.5 km spatial resolution, NMME-DREAM predicts the 5 July 2011 American haboob (Vukovic et al., 2014), with all

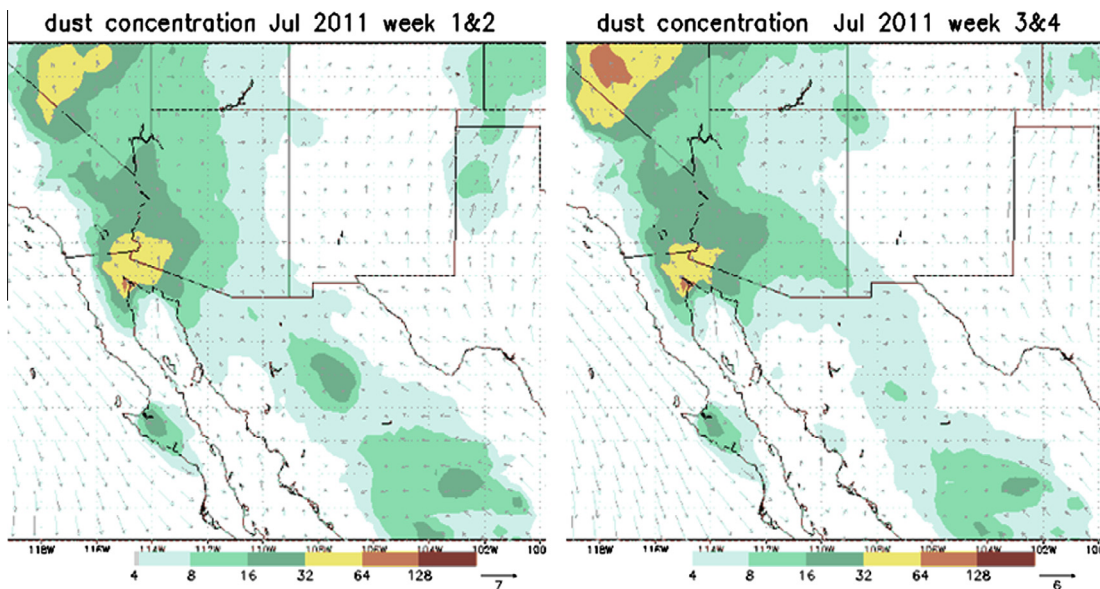


Fig. 16a. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over (L) the first two weeks and (R) the last two weeks of July 2011.

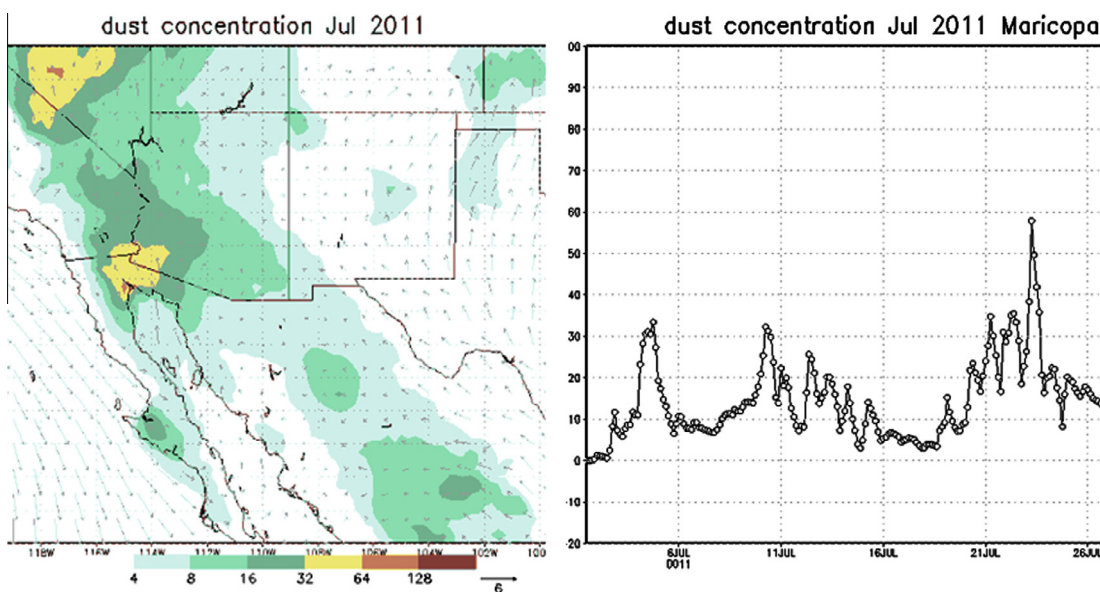


Fig. 16b. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) (L) averaged over the month of July 2011 and (R) the July 2011 evolution of dust concentration ($\mu\text{g m}^{-3}$) in Maricopa County, Arizona.

its verifiable features of meteorology and dimensions and movement of the dust wall. Computer resources generally limit how large an area can be covered at this high a resolution. An operational dust forecast system might cover a large region with lower resolution, yet, when haboob-scale conditions requiring cloud-resolving spatial resolutions are anticipated, as in the case of 5 July 2011, the forecast system can embed, or nest, a smaller domain over the region of concern running at higher resolution to pick up details of the developing storm. The following analysis of dust loading for the period June–October 2011, depicted in Figs. 14–19, shows an operationally-manageable resolution of 20 km, conserving computer demands over a large area, yet simulating and predicting the synoptic meteorological conditions conducive to windblown dust generation most common in the region. Currently

under development are automated mechanisms to combine haboob-generated dust on a 3.5 km grid, nested within the large area sourced dust, for a complete picture of exposure.

The following discussion uses NMME-DREAM to evaluate a population's risk of exposure to windblown dust from sources near and far over several consecutive seasons. The experiment focuses on Arizona. Simulated parameters are surface concentrations of dust (assumed to contain cocci spores – thus, a proxy for cocci – since large areas identified as potential dust sources overlap cocci-endemic areas, shown in Fig. 2).

Since the fungi fragments (arthroconidia) are approximately 2–5 microns in size (Fig. 20), they fall within the same PM_{10} range used in the dust forecast experiment. The assumption is that the spores will fly with, and behave similarly to, dust in the wind.

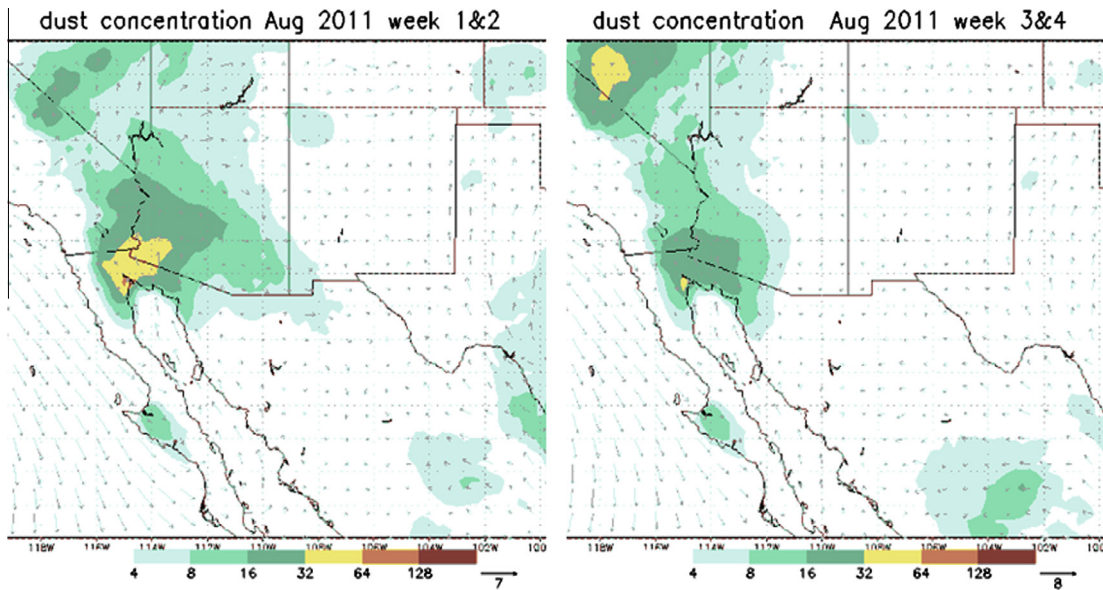


Fig. 17a. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over (L) the first two weeks and (R) the last two weeks of August 2011.

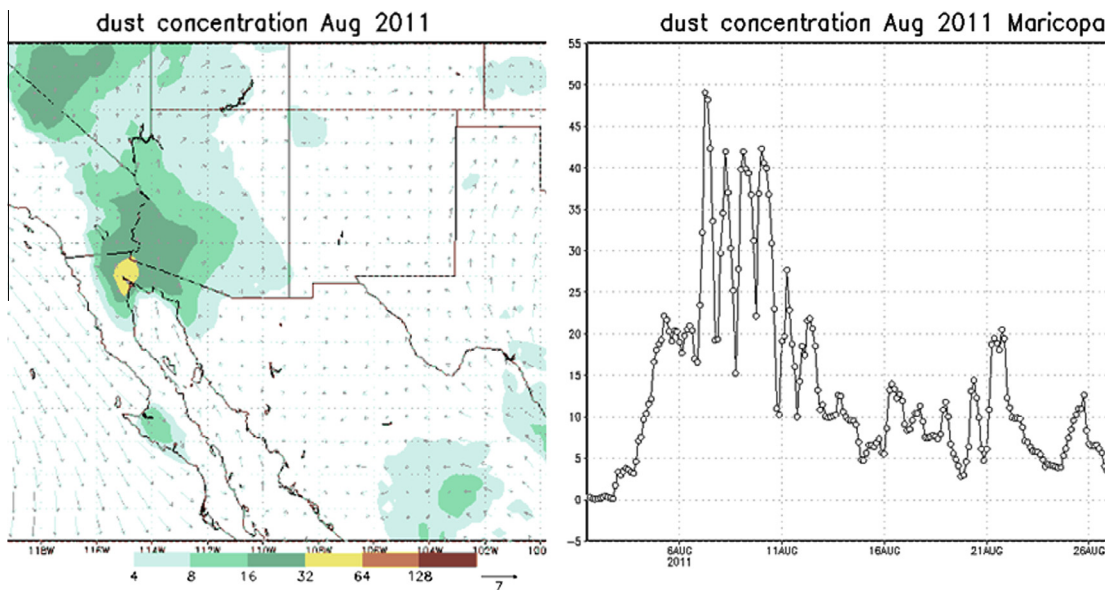


Fig. 17b. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) (L) averaged over the month of August 2011 and (R) the August 2011 evolution of dust concentration ($\mu\text{g m}^{-3}$) in Maricopa County, Arizona.

Dusty environmental conditions are averaged over periods of two weeks, one month and over six months. The evolution of dust concentration for a particular site – Maricopa, Arizona – is plotted partly to show the versatility offered by models to provide data for epidemiology of airborne dust related disease. Another objective is to demonstrate model-generated data that may be compared usefully with high-resolution disease surveillance data – should they become available – for the epidemiology of valley fever as well as for other dust-aggravated issues such as eye infections and cardiovascular and respiratory diseases.

For these experimental runs, model horizontal resolution is specified at approximately 20 km. This resolution will not detect the haboobs of July 2011, yet we see in this experiment how spatially large wind patterns contribute to overall dust loading, overall

risk for exposure, and perhaps provide another explanation as to why valley fever surveillance statistics do not reflect a dramatic reaction to a single storm such as the 5 July 2011 haboob. This is the background dust emission upon which the small-scale but intense storms add dust, cocci arthroconidia and risk.

The model domain covers much of the southwest US, including all of Arizona and New Mexico and significant parts of Northern Mexico, Southern California and Western Texas. The MODIS dust masks described previously, based on shrubland, cropland, cropland/natural vegetation and barren or sparsely vegetated, are updated every 16 days. Although little difference exists when masks for May and October are visually compared (Fig. 13), changes that do appear in the vegetation cycle could play an essential role in dust emission if combined with strong surface

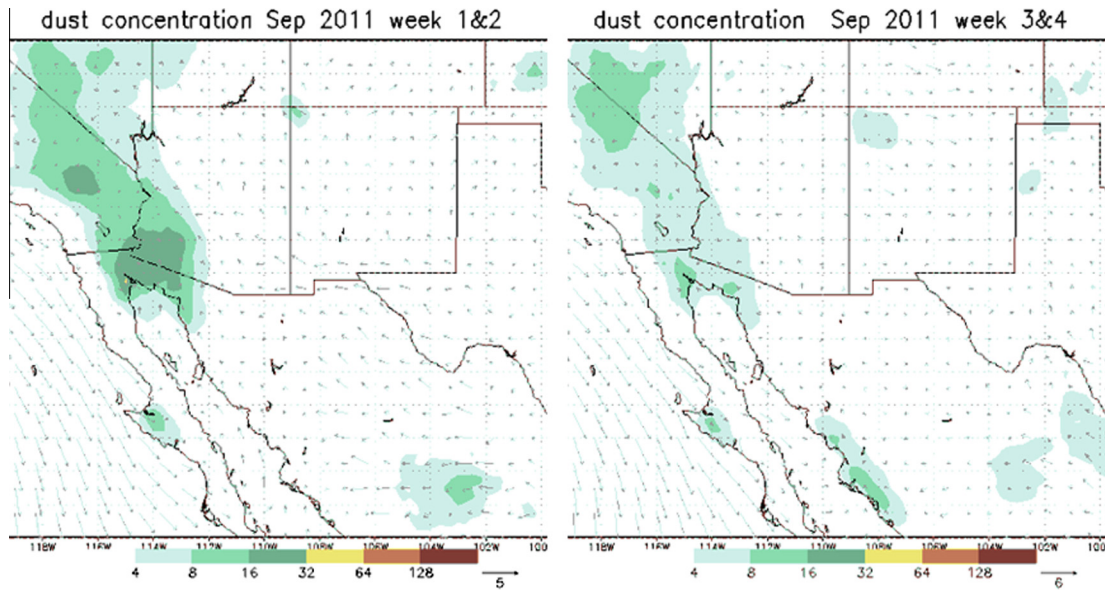


Fig. 18a. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over (L) the first two weeks and (R) the last two weeks of September 2011.

wind patterns. Similar conclusions hold when cocci spore masks, described in Section 4.5, are constructed.

In this experiment, the model simultaneously simulates atmospheric conditions and dust concentration and includes our assumption that the cocci spore cycle – emission, transport and deposition – follows that of atmospheric dust.

Biweekly and monthly averages of airborne dust (w/cocci) concentration

In May 2011 (Fig. 14a,b), most dust-laden regions were along the border of California and Nevada and in north Texas. Some sources in Mexico were more pronounced in the second half of the month. In Maricopa County, the absolute maxima (above $200 \mu\text{g m}^{-3}$) with respect to the whole 6-month period were achieved in the 3rd and 4th weeks of the month.

In June (Fig. 15a,b) the first two weeks were characterized by dust patterns similar to those simulated for May, but somewhat weaker. The north Texas pattern reduced its size and intensity in the second part of the month. Maricopa County received two pronounced peaks of dust in the second part of the period, but of lesser intensity than the county received in May.

July (Figs. 16a,b) and August (Figs. 17a,b) were characterized by smaller concentrations, in general, and with dust patterns mostly located over California, Nevada and Arizona. Further weakening of the dust process could be noticed. A series of dust intrusions were simulated in the first half of the period, although not so intense. Note that with the much lower spatial resolution of 20 km in this hind-cast experiment (compared to the 3.5 km resolution that resolved and predicted the 5 July haboob that struck Maricopa County) the model fails to detect the short, intense bursts of dust from the two haboobs in July.

In September (Figs. 18a,b), dust processes were weak and located in the western part of the southwest US. Similar simulated dust patterns could be observed in October (Figs. 19a,b), although dust in the bordering regions of Mexico and Nebraska appears again due to seasonal intensification of agricultural dust sources in Nebraska. Over this month, there are three weak dust intrusions simulated in Maricopa County.

These low-resolution model runs demonstrate the important role of short, intense dust events that contribute significant amounts of airborne PM_{10} . For example, while the 3.5 km resolution NMME-DREAM picked up the 5 July 2011 dust intrusion into Phoenix, these 20 km-resolution NMME-DREAM runs did not,

and therefore underestimated dust loading for the month. Compare Fig. 17b with the July dust concentrations reported by PM_{10} monitors in Fig. 10.

4.5. Cocci as a tracer

If the sources of *C. immitis* and *C. posadasii* arthroconidia (Fig. 20) in soil are known, and assumptions of entrainment and dispersal being similar to mineral dust and other soil components in the NMME-DREAM system, instead of dust as a proxy for cocci, we may take steps to simulate or predict directly the transport and deposition of the cocci aerosol. This would create a better estimate of risk in geographical locations most affected by valley fever.

Since exact cocci source regions are unknown, we combine what is roughly known, the endemic regions shown in Fig. 2, and what Fisher et al. (2012a,b) tell us, that Silicon (Si) is believed to be a favorite soil component for cocci fungus. This area is “masked” (Fig. 22) for the following NMME-DREAM run, Figs. 23 and 24. We hope this demonstration stimulates research for more accurate locations of *C. immitis* and *C. posadasii*.

The method is based on extension of NMME-DREAM, adding a tracer equation for *C. immitis* and *C. posadasii* arthroconidia to simulate or predict the 3-dimensional structure of the cocci arthroconidia downwind concentration:

$$\frac{\partial C}{\partial t} \Delta[C] = \left(\frac{\partial C}{\partial t} \right)_{\text{source}}$$

where

$$\Delta[C] = \bar{V} \cdot \nabla_h C + (w - w_g) \frac{\partial C}{\partial z} + \nabla_h \cdot (K_h \nabla_h C) + \frac{\partial}{\partial z} \left(K_z \frac{\partial C}{\partial z} \right)$$

Here, C is the dust (or cocci fraction in dust) concentration; $\bar{V} = [u, v]$ is the horizontal velocity vector; w is the vertical velocity; w_g is the gravitation settling velocity; K_h and K_z are the horizontal and vertical turbulent mixing coefficients; ∇_h is the horizontal nabla operator. The numerical schemes of Nickovic et al. (2001), including the aerosol emission parameterization, are applied to the above equation.

The cocci source term, the component critical for forecast accuracy

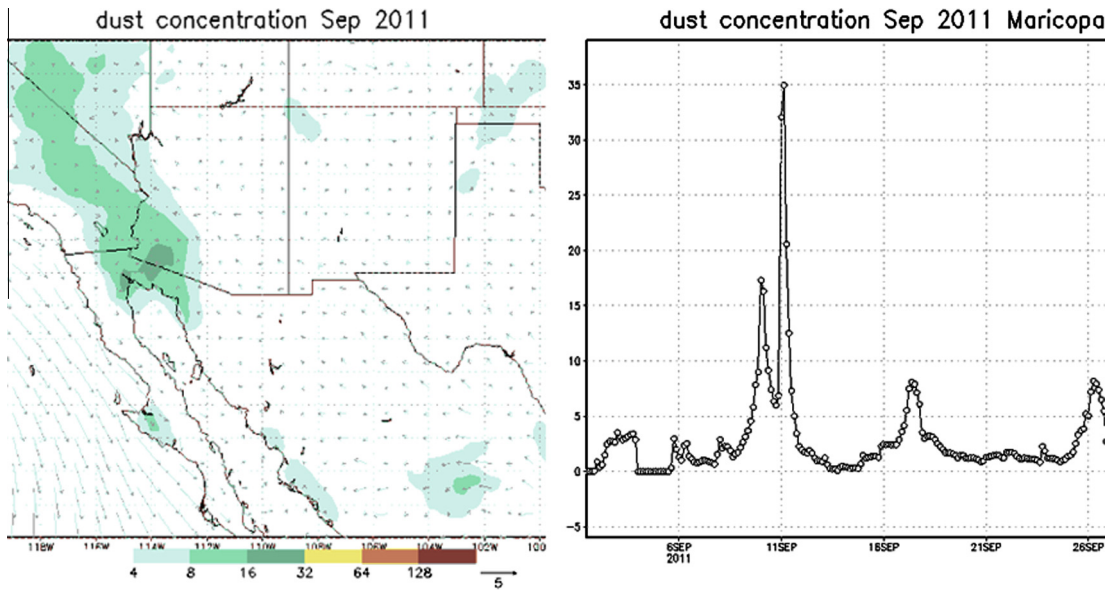


Fig. 18b. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) (L) averaged over the month of September 2011 and (R) the September 2011 evolution of dust concentration ($\mu\text{g m}^{-3}$) in Maricopa County, Arizona.

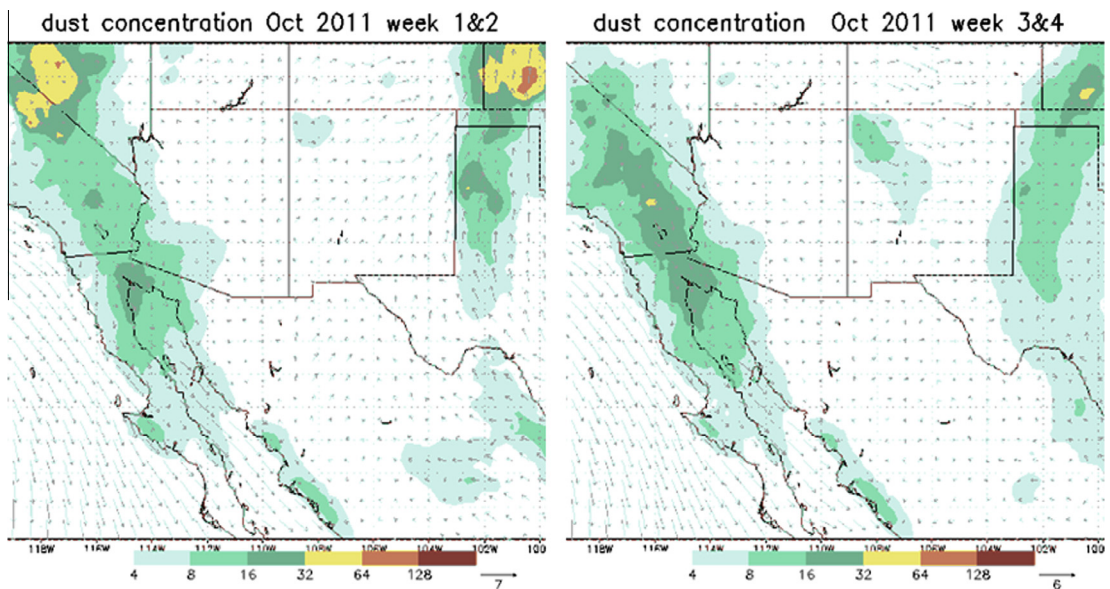


Fig. 19a. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over (L) the first two weeks and (R) the last two weeks of October 2011.

$\left(\frac{\partial C}{\partial T}\right)_{\text{source}}$ is the most uncertain information in the modeling system, as we discussed earlier.

Different environmental conditions appear to favor cocci inhabitation (Fisher et al., 2012b):

- (a) Hyperthermic and thermic soil climate zones.
- (b) Clay and silt soils as originators of emissions of particles with radii between 1–10 μm (within loamy sand and sandy loam soil textures).
- (c) Mineralogy composition of soil (quartz).
- (d) Sufficiently strong wind.
- (e) Viability time in atmosphere.
- (f) Animal/Insect vectors (carriers).
- (g) Moisture in upper 30 cm.
- (h) pH (6.1 to 8.2).
- (i) Relative high salinity.

(j) Rain after drought or dry spells that may promote growth.

In a first approximation of a cocci tracer, we take into account only the effects of (a), (b), (c), and (d). Namely, hyperthermic and thermic soil conditions are implicitly taken into account, having the source areas defined within the two thermic characteristics. Clay and silt soil populations are principal components of the mineral dust aerosol with aerodynamic sizes in the range of 1–10 μm , which includes the range in size of the arthroconidia (2–5 μm). This is also a size range in the particle bins of the DREAM model. The requirement that the near-surface wind is sufficient to erode the soil surface is incorporated in the DREAM emission parameterization numeric (Nickovic et al., 2001). The remaining conditions not used in this study are (e), (f), (g), and (h) and will be a matter of future consideration.

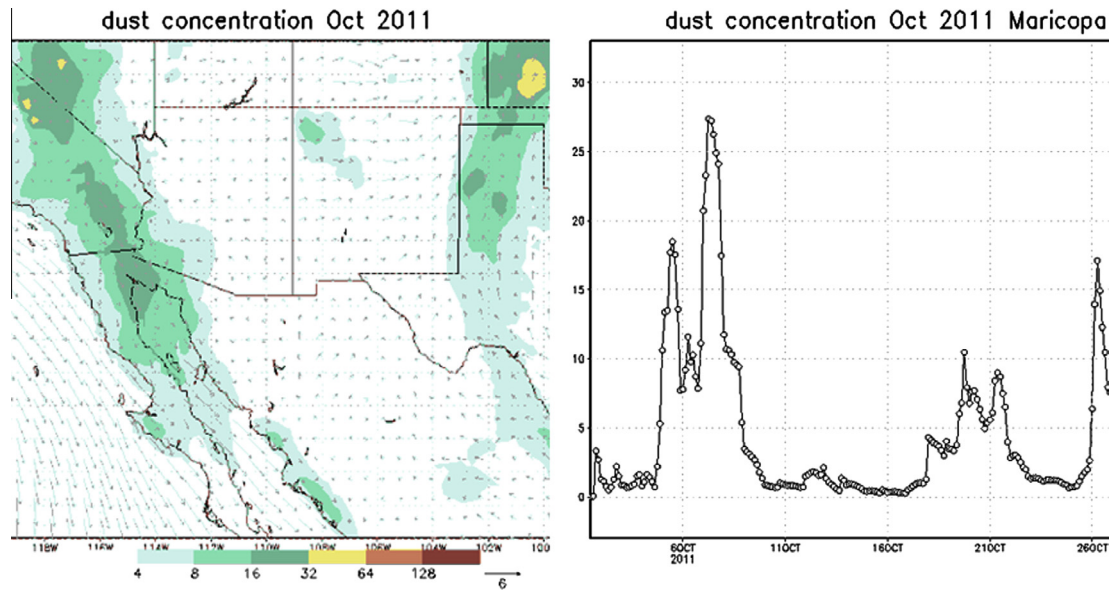


Fig. 19b. Model hindcast of surface dust concentrations ($\mu\text{g m}^{-3}$) (L) averaged over the month of October 2011 and (R) the October 2011 evolution of dust concentration ($\mu\text{g m}^{-3}$) in Maricopa County, Arizona.

In order to specify source areas most favorable for the cocci spore emission, we define these areas as intersection of the following three data sets:

- MODIS dust mask (shown earlier).
- Mask of endemic areas (Fig. 2), and
- Mask of quartz/silicon.

A mask of cocci fungus spore sources was developed first by digitizing Comrie's map in Fig. 2, the estimated cocci endemic area, with resolution of 0.1 degree, following Comrie's (2012) prescribed valley fever endemic zone. Assuming the fungus typically does not extend its geographic range via airborne transport (Fisher et al., 2012a,b), a first approximation is made that the identified endemic zones are most probably the sources of *coccidioides* arthroconidia in soil.

Cocci-preferred soils were then introduced to effect the "cocci source mask". Fungal diseases such as coccidioidomycosis are linked to Si exposure. In our experiment, we therefore specify a geographic distribution of Si fractions, as proxy for cocci favorable habitats, derived from the global mineral database of Nickovic et al., 2012. The database contains 1 km resolution data on 9 minerals typical for arid soils, with Si-rich minerals including Illite, kaolinite, smectite and quartz. Fig. 21 depicts the Arizona-affected distribution of Si from that database. Silicon is one of the largest constituents of soil-derived mineral aerosol. Estimates of crustal Si content range between 26% and 44 wt%, where most Si is present in the form of quartz (SiO_2). In this study, we allowed Si to contribute with 27% in the four minerals identified.

The assumed cocci-laden-dust, a mask updated every two weeks with exposed soils assessed from MODIS surveys, confined to estimated cocci-endemic areas with *C. immitis* and *C. posadasii* in preferred Si-rich soils appears in Fig. 22.

The modeled distribution of surface dust concentrations ($\mu\text{g m}^{-3}$) averaged over May–October 2011 is shown in Fig. 23 next to modeled surface concentrations of cocci spores (arbitrary units) for the same period. Fig. 24 shows modeled near-surface concentration of dust and cocci spores for the same period at one site, the city of Maricopa.

While peaks in concentration appear at the time of the 5 July 2011 haboob in both the dust and cocci spore plots, they are not



Fig. 20. *Coccidioides immitis* spores (arthroconidia segments) are 2–5 μm in size (courtesy J. Galgiani).

very pronounced. With low (20 km) spatial resolution, the model failed to replicate the cloud and haboob features under the experiment (Fig. 25).

4.6. Conclusions

Model simulated or hind-casted dust plume characteristics at spatial resolutions of 3.5 km compare favorably with air quality

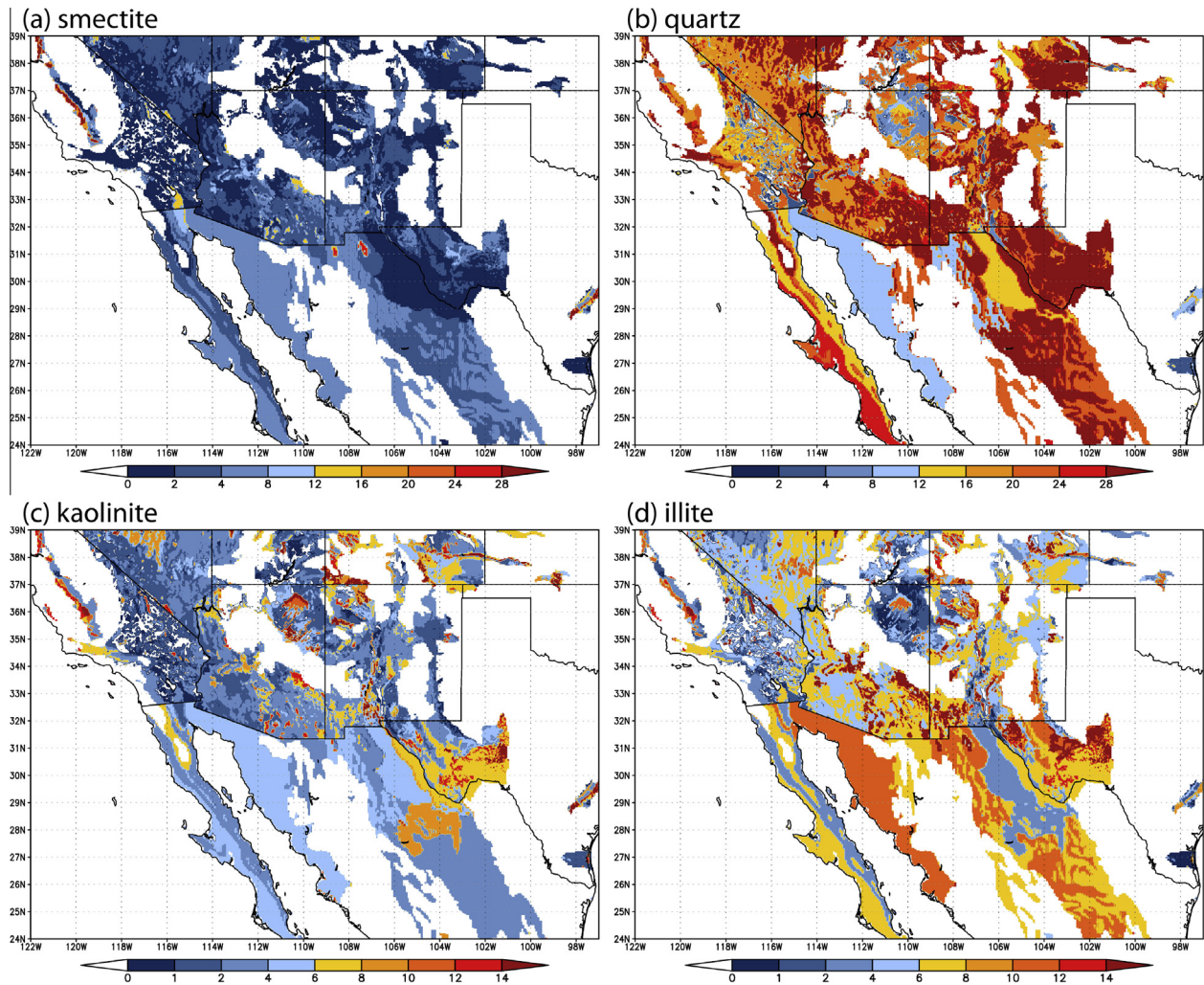


Fig. 21. Geographic distribution of (a) smectite, (b) quartz, (c) kaolinite, (d) illite as Si-rich minerals. Expressed as % content. [Nickovic et al. \(2012\)](#) Si-rich soils are believed especially hospitable to coccidioides fungus. High resolution data are available for the US

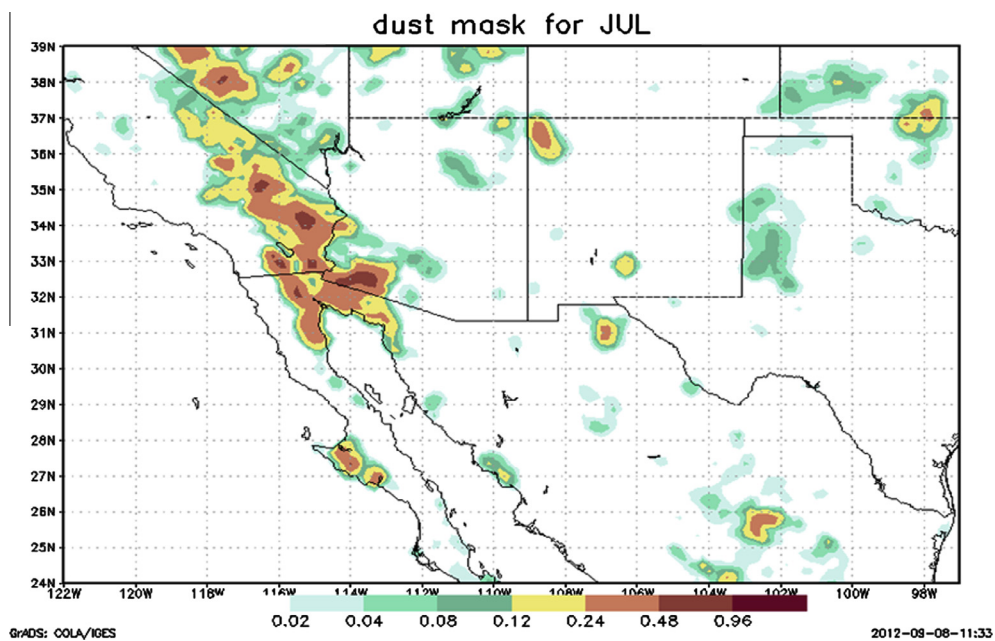


Fig. 22. A proxy for cocci fungal spore source mask, valid for July 2011, is constructed where all but Silicon (Si) enriched soil (from [Fig. 21](#)) remain in the available, erode-able dust sources ([Fig. 13](#)) within the cocci-endemic regions marked by [Comrie](#) in [Fig. 2](#).

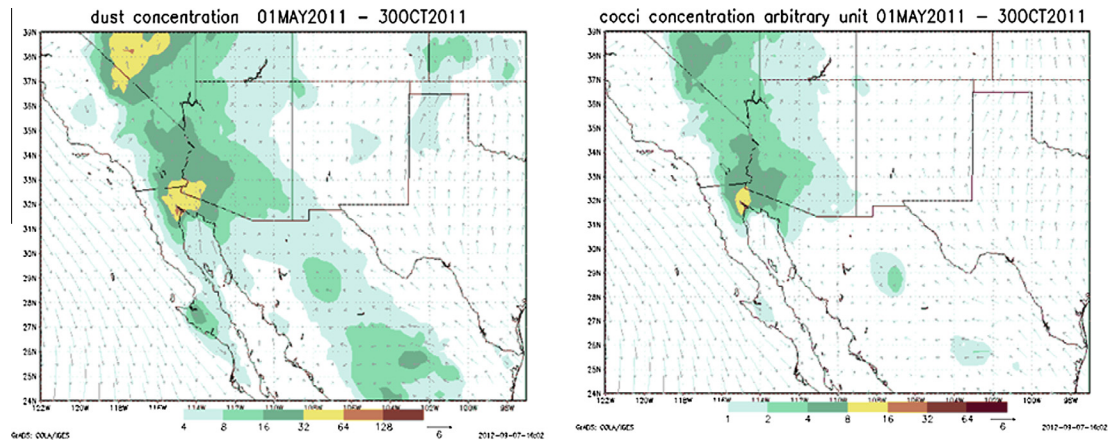


Fig. 23. Surface (L) dust ($\mu\text{g m}^{-3}$) and (R) cocci-spore-laden dust (arbitrary units) concentrations averaged over May–October 2011.

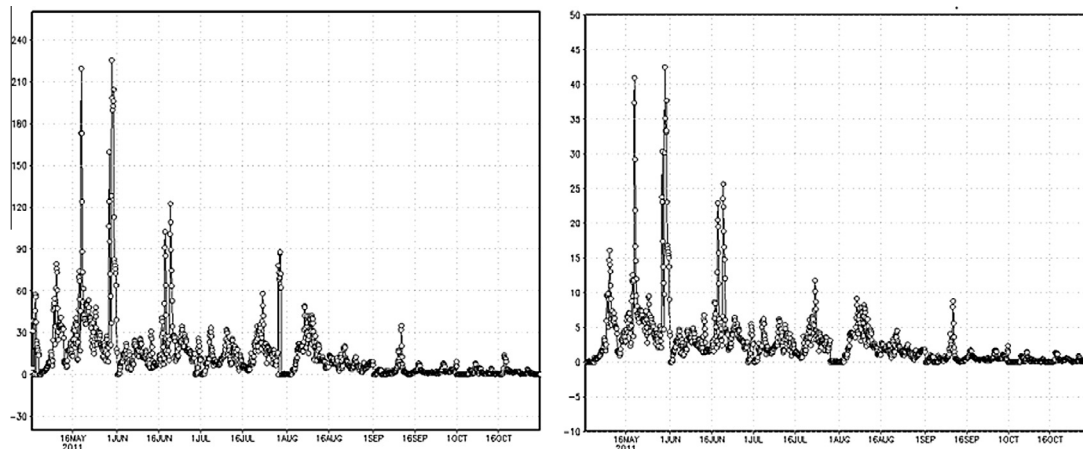


Fig. 24. Surface (L) dust ($\mu\text{g m}^{-3}$) and (R) cocci-spore-laden dust (arbitrary units) concentrations in the city of Maricopa, Arizona, 1 May–30 October 2011.

(PM_{10}) data from continuous monitoring sites. Resolutions of 20 km are too coarse to identify short, intense dust events that contribute significantly to the general dustiness of the region, whereas 3.5 km resolution can.

Active dust emission areas that pose health risks in Arizona are identified, targeting high priority areas for emission control. When costs are lowered in detecting cocci-spore-bearing dust, identification of the active dust emission zones by models and satellites will allow cost-effective mitigation of the fungus responsible for valley fever.

The year 2011 in Arizona, especially in summer, was significantly more affected by airborne PM_{10} than either 2010 or 2012. Reported cases of valley fever were also significantly higher in 2011 than in either 2010 or 2012. For the foreseeable future, in studies of the environment and valley fever epidemiology, mineral dust can serve as the “proxy for cocci,” for both source and airborne concentration.

Comparison of year-to-date differences in reported county-by-county cocci cases between 2010 and 2011 saw higher numbers of cocci infections reported in the haboob and active dust source areas affecting Maricopa and Pinal Counties than were seen in the largely unaffected Pima County. Weekly accumulated reports of cocci hint at, but generally inconclusively, their relationship with PM_{10} , with many factors responsible, from generally elevated levels of dust to an illness with a variable period of incubation and time leading to correct diagnosis and reporting.

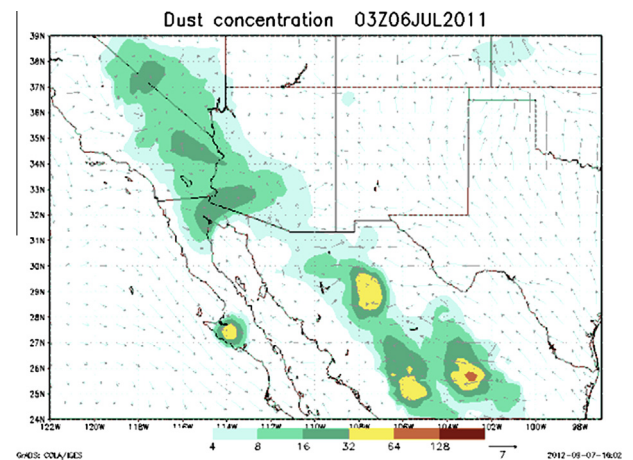


Fig. 25. Surface dust concentrations ($\mu\text{g m}^{-3}$) with the NMME-DREAM at 20 km spatial resolution at the time of the most intense haboob development, 0300 UTC 6 July 2011.

Definitive evidence of the 5 July 2011 Phoenix storm having caused a greater number of valley fever cases, or how many, or where, is problematic. The monthly reports of cocci may smooth

out some of the complicating factors of comparison with airborne dust and tend to reveal correlation with overall dust conditions. *Post-hoc* analysis clearly raises the possibility of a link with the storm, but complications include: inadequate detail and potential error in the passive public surveillance of valley fever; virtually unknown demarcation of *C. immitis*- and *C. posadasii*-infected regions; a particularly active 2011 in significant but brief dust events and very high summer PM10 concentrations compared with 2010 and 2012; and the likely reaction of people to seek shelter when seeing an approaching haboob, but allowing oneself to be exposed in a “minor” dust event.

This study bolsters the belief that most valley fever cases do not require an extreme weather event such as an haboob to cause infection; increased numbers of valley fever cases that may arise from an haboob can be swamped by the windblown dust risk that occurs all year long. Too, fungal spores are likely to become airborne with other soil disturbance, as from agriculture and construction, or from lesser wind events, including dust devil vortices that occur in generally clear skies, usually a few meters in diameter carrying dust aloft, yet sometimes to 100 meters and more with wind speeds of 100 km/hr. (Lutgens and Tarbuck, 1998; Ludlum, 1997).

The high space and time resolutions available in numerical, dynamical atmospheric models and satellite-based Earth observations provide both challenge and invitation for health and soil ecology communities. Routine cocci surveillance can be enhanced. The question can be addressed of how seasonal precipitation pattern and fungi growth cycle are related and determine populations of arthroconidia available for airborne emission.

An extended, operational period of dust forecasts and disease surveillance is needed in order to attain statistical confidence in which routine forecasts (or simulated histories), air quality and disease surveillance are evaluated together.

For the vulnerable, in health as well as highway safety, an opportunity opens for an operational warning and risk reduction system. Previous quasi-operational simulations and forecasts using DREAM in the US Southwest and the successful simulation of the 5 July 2011 haboob across Pinal and Maricopa Counties show how they can become integral to public health and safety services. This July 2011 storm and the spatial and temporal characteristics of airborne dust throughout the period beginning 2010, when valley fever reporting in Arizona became stabilized, provide a continuing test case for health and environmental sciences and services.

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