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Climatic conditions linked to high PM_{10} concentration in a bi-national airshed: Nogales (Arizona, USA, and Sonora, Mexico)

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ABSTRACT: Traditional particulate matter (PM) studies focus on atmospheric transport and source identification. Focusing on a problematic airshed in southwestern North America, we analyzed atmospheric characteristics and hydroclimatic conditions leading to high concentrations of PM most representative of dust (PM_{10}). The bi-national airshed of Nogales (Arizona, USA and Sonora, Mexico), has been historically characterized by high PM_{10} concentrations, which tend to be much higher on the Sonora side. Concentrations in greater Nogales tend to be highest in fall and winter and lowest in summer, despite climatologically moister soil conditions in fall and winter. Within the fall, winter, and spring seasons, days of high and low PM_{10} concentration were primarily distinguished by the condition of the atmosphere, with less emphasis on soil moisture. However, when PM_{10} concentrations were high, soil moisture was most important in discerning days of very high concentrations on the Arizona side of the border during the most problematic seasons of fall and winter. This was not the case on the Sonora side. Furthermore, drier soil conditions were linked to anomalies in PM_{10} on the Arizona side of Nogales that were higher than the corresponding anomaly on the Sonora side. The generation of PM on the Sonora side is less reliant on dry soil than it is on the Arizona side, indicating a higher level of anthropogenic dust production on the Sonora side.

KEY WORDS: Particulate matter · Dust · Synoptic climatology · Soil moisture

1. INTRODUCTION

Small solid or liquid airborne particles of varying physical and chemical characteristics, collectively referred to as atmospheric particulate matter (PM), are introduced into the atmosphere by both natural (pollination, wind erosion, wildfire) and anthropogenic (combustion, ground traffic) processes. The importance of PM concentration lies in the potential impact the increased load of atmospheric dust can have on climate forcings (including radiation), on desertification rates in fringe areas, and foremost on human health. Size is a general determinant of the associated effects of PM on respiratory health. Coarse PM of a diameter ranging from 2.5 to 10 µm (PM_{10}) is inhaled and typically deposited in the upper portions of the respiratory system. Inhalation of PM_{10} has been associated with elevated mortality, bronchial aggravation, and alteration of pulmonary functions within children (ADEQ 2000).

Dust particles generated from dry soil are typically of a larger diameter and are therefore represented within the concentration of PM_{10} when measured with dichotomous samplers (PM_{10} vs. smaller $PM_{2.5}$). PM_{10} is predominantly dust that is introduced to the lower atmosphere by ground traffic, construction activities, and wind of a magnitude capable of producing soil erosion (generally 7.72 ms^{-1} [15 mph] or greater; Pewe 1981, ADEQ 2000). High concentrations of PM_{10} are a concern in arid climates that are often associated with a rather stagnant atmosphere, which does not promote timely evacuation of suspended particulates. This is especially so near population centers, which are typically associated with cultivation, deforestation, climate

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modification (Tegen & Fung 1995), and vehicle traffic flows (Vernath et al. 2003).

Estimates of so-called 'fugitive dust' indicate that up to half of the current global atmospheric dust load originates from anthropogenically disturbed soils (Tegen et al. 2004). However, efforts to model world dust emissions from the surface have produced varying estimates of the total load from anthropogenic sources. Sokolik & Toon (1996) estimated an amount of near 20%, while Tegen & Fung (1995) determined a contribution from anthropogenic aerosols between 30 and 50%.

In arid regions, where dry soil, a stagnant atmosphere, and population increases associated with an attractive climate can lead to an expansion of dust sources, mitigation efforts are especially important. Regional studies in arid environments have tended to focus on the impact of fugitive dust in areas surrounding road surfaces and restoration of farmland in desert locales. Etyemezian et al. (2004) analyzed the transport of fugitive dust, PM_{10} in particular, and found varying degrees of removal of sediment from unpaved road surfaces. The variability in measurements at set distances from the road surfaces were impacted by the atmospheric conditions, which controlled the amount and distance that the dust was transported. A similar study by Vernath et al. (2003) also noted the decrease in concentration of fugitive dust away from a road surface. Mitigation efforts have increasingly reduced the impact of source areas. Grantz et al. (1998) indicated that the impact of wind-driven dust emissions from anthropogenically disturbed land (tilled and overgrazed land) can be controlled by as much as 97%.

Along the border between Arizona, USA, and Sonora, Mexico, suspended PM is common due to the arid climate, the generally weak atmospheric dynamics, and the confining topography within which human development has occurred (Berman et al. 1995). In 1995 the Arizona Comparative Environmental Risk Project examined human exposure to all environmental risks in Arizona and ranked air quality, specifically PM, as the highest threat to the collective health of the state's inhabitants (ADEQ 2000). The study estimated that PM_{10} concentrations are responsible for >900 premature deaths annually, and that in recent years there have been increases in respiratory disease and asthma (ADEQ 2000).

PM concentrations along the Arizona–Sonora international border (Fig. 1) have been a specific concern of the Arizona Department of Environmental Quality (ADEQ) and the US Environmental Protection Agency (EPA) for years. In studying PM_{10} within Douglas, Arizona (Fig. 1), ADEQ scientists found that concentrations were 21 to 117% higher at the border than at a location 1 mile north of the border (ADEQ 1999), suggesting that the Sonora side of the border is a source of PM for the Arizona side.

In the most recent annual report from ADEQ (2000), the PM monitoring site in Nogales, Arizona (Fig. 1) recorded an annual mean PM_{10} concentration of 52.5 mg m^{-3} during 1999, which was the 8th highest among the 86 monitoring sites across the state. The highest 1 d concentration of 169 mg m^{-3} at Nogales was the 5th highest across the state of Arizona. Across the border in Sonora the annual mean concentration of PM_{10} during 1999 (59.8 mg m^{-3}) was higher than across the border in Arizona, as was the highest 1 d concentration (180 mg m^{-3}, ADEQ 2000).

High PM_{10} concentrations in Nogales may be related to the fact that the international border crossing at Nogales is the busiest in the state of Arizona. More than 4.5 million pedestrians cross the border annually, representing nearly 60% of the pedestrians that cross the Arizona–Sonora border each year. The >251 000 trucks crossing the border at Nogales each year represent nearly 75% of the total along the Arizona–Sonora border. Finally, nearly 4 million passenger cars pass through the Nogales port each year, accounting for 41% of that form of border traffic. Within the relatively high elevation Chihuahuan Desert ecoregion, semi-desert shrub is the dominant vegetation type, exposing the soil to the arid climate and further promoting the generation of airborne dust.

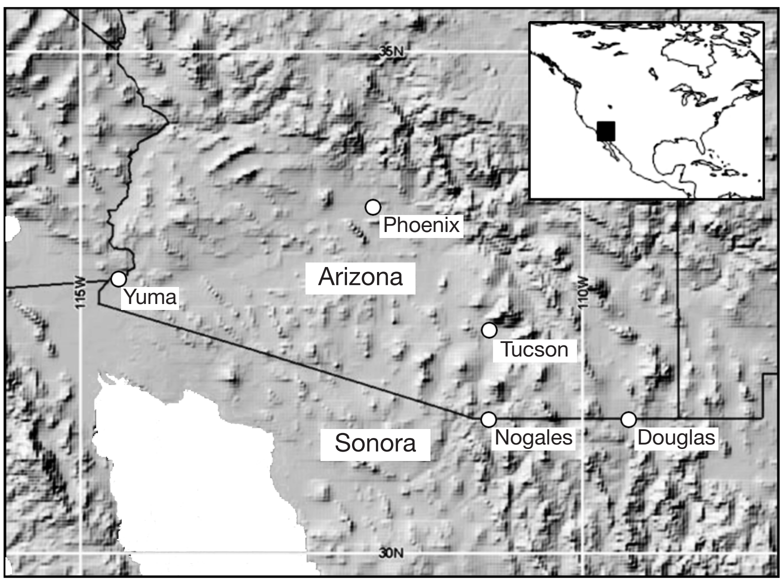

Fig. 1. Southwestern USA and northwestern Mexico region, including Nogales, Arizona/Sonora

Traditionally, the greatest focus in the study of PM has been on atmospheric transport and linkage to a source, to help develop means of mitigation. The present study, on the other hand, concentrates on the relative importance of atmospheric characteristics and hydroclimatic conditions in the evolution of high concentrations of lower atmospheric dust. Furthermore, the work adds a unique human dimension to the question of the relative importance of the surface and the atmosphere by studying the problematic Arizona–Sonora airshed. Nogales was deemed a suitable location for the study of PM variability on 2 sides of a busy international border crossing, since PM generation varies considerably across the border at this point.

2. DATA AND METHODOLOGY

2.1. PM data

A data set of PM_{10} concentration was created and analyzed for Nogales. $PM_{2.5}$, representing smaller particles of an anthropogenic nature, is included in the PM_{10} concentration measurement; however, it is assumed that variability in PM_{10} concentration is primarily a function of the larger sized particles, such as dust. Mean 24 h PM_{10} data for Arizona (1985–2001) and Sonora (1993–2001) were collected from ADEQ. Data underwent extensive quality assurance procedures at ADEQ prior to database assemblage, and therefore the data were taken as accurate and as complete as possible. Data measurements were taken at a 6 d interval. Beginning in 1993, the time step of the measurements from the 2 sites is coincidental. However, the 2 sites have different beginning dates (1985 vs. 1993). Once days characterized by missing data were eliminated, the result was a database of 815 observations for Arizona, 457 observations for Sonora, and 349 observations that were coincident between both.

PM data were subjected to a descriptive statistical analysis in order to characterize the concentration of PM_{10} on both sides of Nogales as well as one side relative to the other. PM_{10} data were then stratified by month and by day of the week for the full data record from each side of Nogales, and again subjected to descriptive statistical analyses. Based upon the monthly characterizations of PM concentrations (see Fig. 2c,d) and the climate of Nogales (temperature, precipitation; see Fig. 3a,b), the annual calendar was divided into seasons, where December through February is the winter season, and each season thereafter (spring, summer, and fall) is defined by the ensuing 3 mo period.

PM data for both sides of Nogales were positively skewed and with positive kurtosis (more skewed toward higher values and more clustered about a central value than the normal distribution). The data were transformed with a logarithmic function to produce 2 normally distributed data sets — one for each of the sites in Nogales. Once fitted to a normal distribution, high daily values of PM_{10} concentrations were deemed to be those in the upper quartile, low daily values were those in the lower quartile, and all values in between were considered to be non-extreme. The result was a distribution of 144 high PM days ($\geq$78.0 µg m^{-3}) and 146 low PM days ($\leq$31.3 µg m^{-3}) for Arizona, and 89 high PM days ($\geq$95.0 µg m^{-3}) and 91 low PM days ($\leq$39.0 µg m^{-3}) for Sonora.

2.2. Synoptic composites

For the seasons characterized by the highest PM_{10} concentrations (fall, winter, spring), days when — on both sides of Nogales — the PM concentration was high (upper quartile) were extracted and used to create synoptic composite maps of 500 hPa height and 850 hPa wind. The purpose was to characterize general synoptic-scale anomalies. Data for composites were extracted from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis database (Kalnay et. al 1996). Composites were based on 18 d within the fall season and 20 d from the winter season, while no composites were constructed for spring season since there was not a single occurrence of coincidental high PM days at the 2 Nogales stations. Height maps were constructed to illustrate the climatological pattern (ridge/trough) and anomalies on days of high PM concentration in order to characterize the general upper-atmospheric stagnation (upper atmospheric high pressure). Lower atmospheric (850 hPa) climatological wind vectors and composite wind vectors from high PM days were compared to illustrate the general regional stagnation well above the surface.

2.3. Daily atmospheric data

To go beyond the general composite representations of high PM days in Nogales, a set of more local daily data was constructed. Daily lower atmospheric wind data (850 hPa u and v vector components), 500 hPa height data, and lower atmospheric temperature profile data were extracted from the North American radiosonde database of the National Climatic Data Center (NCDC) and Forecast Systems Laboratory (FSL) for Tucson, Arizona, which represents the nearest radiosonde station to Nogales (Fig. 1). High resolution surface wind data for Nogales would have desirable, but instrumentation exists for only a single site. Furthermore, the instrumentation at Nogales, Arizona, was established in 1996, resulting in <6 yr of data that are not continuous and have not been quality controlled. Therefore, wind data for Tucson at the 850 hPa level were taken to represent the general flow in the lower atmosphere across the region. However, the general stagnation of the lower atmosphere influences the degree to which the wind data at Tucson are representative of the region and not just the local thermally driven circulation. Data representing the 500 hPa height level at Tucson were used to capture the general intensity of the typical middle-atmospheric high pressure area across the region, while lower atmospheric temperature data were used to calculate the morning (05:00 h LST) inversion height and strength. The inversion height was determined to be the point in the lower atmosphere where the temperature last increased from the previous reading when moving upward through the profile data. The strength of the inversion was represented as the mean increase in temperature (°C km^{-1}) across the inversion layer. If no morning surface temperature inversion existed, the inversion height and strength were quantitatively represented as zero.

Daily maximum and minimum temperature (Tmax and Tmin, respectively) data for Nogales, Arizona, were extracted from NCDC's Summary of the Day database, while climatological (1971–2000) daily mean values of Tmax and Tmin for the station were taken from the database of the Western Regional Climate Center. The 2 daily data sets were combined to calculate daily Tmax and Tmin anomalies for Nogales. These data were used to characterize the daily climatic condition at Nogales.

2.4. Daily soil moisture data

Also extracted from the NCDC database were daily precipitation data for Nogales, from which several variables were calculated to help characterize the general dryness of the soil. First, the number of days since the last precipitation event was calculated for each day of the PM concentration record (1985–2001). Second, monthly precipitation and mean temperature (calculated from Tmax and Tmin described above) were employed in a climatic water budget model to simulate the monthly soil moisture at Nogales. The Thornthwaite-Mather water budget model (Thornthwaite & Mather 1955) is a mass conservation technique that balances estimated inputs of water to the soil (precipitation, P) with water loss (evaporation plus plant transpiration or evapotranspiration). The climatic water budget employs empirical techniques to estimate the potential evapotranspiration (PE), or atmospheric demand given ample soil moisture, and the actual evapotranspiration (AE). PE is calculated based upon mean temperature, while the equal or lesser amount of AE is calculated from a function that is based upon PE and the level of soil moisture relative to field capacity. Monitoring the input to the soil (P) against the loss (AE) allows for estimation of the soil moisture on daily-to-monthly time scales. The Thornthwaite-Mather method of PE calculation is generally accepted as the simplest yet most accurate method available (Leathers et al. 2000), especially on a monthly time resolution. Using the climatic water budget, monthly values of P – PE and soil moisture were produced for Nogales. To some extent, the accuracy of the soil moisture amount, although historically accurate when using this method, is irrelevant here, as the greatest interest is in relative amounts of moisture associated with episodes of high and low PM concentrations rather than specific levels of soil moisture (i.e. thresholds).

Lastly, as another indicator of the dryness of the soil, monthly values of the Palmer Drought Severity Index (PDSI) for the climatic region encompassing Nogales were extracted from the PDSI database of the Climate Diagnostics Center (CDC) of the National Oceanic and Atmospheric Administration. The PDSI (Palmer 1965, Alley 1984) is the most widely used index for monitoring soil moisture conditions across the USA. The method is very similar to that associated with the climatic water budget, whereby inputs (P) are compared to soil moisture outputs (PE and AE). Monthly PDSI values are produced by the CDC for US climate divisions, which are climatically homogeneous regions that are largely defined by clusters of counties. Positive values indicate moist soil conditions while negative values indicate dry soil moisture conditions. Here, the gross monthly values from Arizona climate division number 7 (southeastern Arizona) were matched with the daily PM concentrations for Nogales.

2.5. High/low PM analysis

The atmospheric and surface data were combined with the PM data to create a matrix for analyzing the relationships between PM and the characteristics of the atmosphere and surface. Initially, the data for both of the PM stations in Nogales were stratified into groups of days of high and low PM concentrations as determined from the normalized PM data for each station. The stratification was done for each season, but the summer season was omitted due to few occurrences of high PM. A 2 sample *t*-test was used to perform a hypothesis test of the difference between the populations for high and low PM days. A significance level of $p \leq 0.05$ was used. Additionally, simple linear correlation analysis was performed to assess the nature and significance of the PM_{10}-independent variable relationships.

In an attempt to highlight the independent variables that explained the greatest variability in PM concentration and to assess its predictability, stepwise multiple regression analysis was employed. Variables were only added to the regression model if they were normally distributed, had regression coefficients that were statistically significant ($p \leq 0.05$), and did not possess a significant collinear relationship with previously added variables. The result was a combination of independent variables for each season and for each side of Nogales that explained at least part of the variance in PM concentration.

2.6. Atmosphere–soil analysis

To assess the relative importance of the associations of the different variables with categorical levels of PM_{10} concentrations, separate groupings of variables were employed in linear discriminant analyses. Groupings of variables represented surface conditions (PDSI, soil moisture, P – PE, days since last precipitation), temperature (Tmax and Tmin anomalies), wind (05:00 h and 17:00 h LST 850 hPa wind components), and stagnation (500 hPa height, inversion height and inversion strength). Each set of variables was used to discriminate populations of low and high PM_{10} concentration days, and the relative importance of each set was measured by the percentage of days categorized correctly using those variables. To place a finer point on the analysis, the procedure was repeated using populations of days with PM_{10} concentrations between the 50th and 75th percentile in comparison to the populations of high concentration days (i.e. >75th percentile). While the former analysis revealed the variables closely associated with dramatic differences in PM_{10} concentrations, the latter identified the variables associated with the more subtle difference between days of high PM_{10} concentration and days that did not attain the threshold.

2.7. Arizona vs. Sonora analysis

Lastly, in an attempt to differentiate the relative importance of the conditions of the atmosphere and the surface to PM concentrations on one side of Nogales vs. the other, the different sets of variables were used to discriminate between populations of days for which the standardized concentration on one side was greater than the corresponding standardized concentration on the other side. To standardize the data, each daily concentration was converted to a *Z*-score by subtracting the mean and dividing by the standard deviation of the population. The difference in the Z-score for daily PM concentration at each site in Nogales was calculated as that on the Sonora side minus that on the Arizona side. Taking the difference in raw PM concentrations from each side of Nogales would simply result in an illustration of the fact that concentrations on the Sonora side are most often greater than on the Arizona side. However, *Z*-scores indicate the magnitude of the PM concentrations at each site relative to the mean and variability at that site, and therefore the difference between these indicates the difference in the anomalies at each site. The differences were stratified into 2 categories (+ and –), representing a greater anomaly on one side of the border than on the other. The sets of variables described previously were used to discriminate between the 2 categories, and their relative importance was revealed in the percentage of correct classifications produced by the linear discriminant analysis.

3. RESULTS

3.1. Descriptive analysis

Daily concentrations on both sides of Nogales significantly covary ($r = 0.68$), but values on the Sonora side are considerably higher regardless of the measure of the distribution (minimum, maximum, mean, median; Fig. 2a). Both the median and the mean PM_{10} concentrations at Sonora are greater than the annual US federal standard of 50 $\mu g\ m^{-3}$. On the Arizona side, the overall mean concentration is greater than the annual standard, while the median is lower. However, the value of the 95th percentile on both the Arizona and Sonora sides of Nogales is below the 24 h standard of 150 $\mu g m^{-3}$. Mean daily concentrations of PM_{10} were higher on the Sonora side than on the Arizona side for 86% of the record of coincidental data.

The arid steppe climate of Nogales is associated with high temperatures (Fig. 3a) and 2 wet periods annually (Fig. 3b). The North American monsoon season (approximately July through September) is evident in the pattern of precipitation, while the secondary wet season of December through March is also evident, albeit less marked than the monsoon season. However, due to lower temperatures during the winter season, the amount of P relative to the amount of PE (P – PE) is higher in winter than during the monsoon season (Fig. 3c). This translates to a considerably moister soil at Nogales in winter than during the summer months, in-

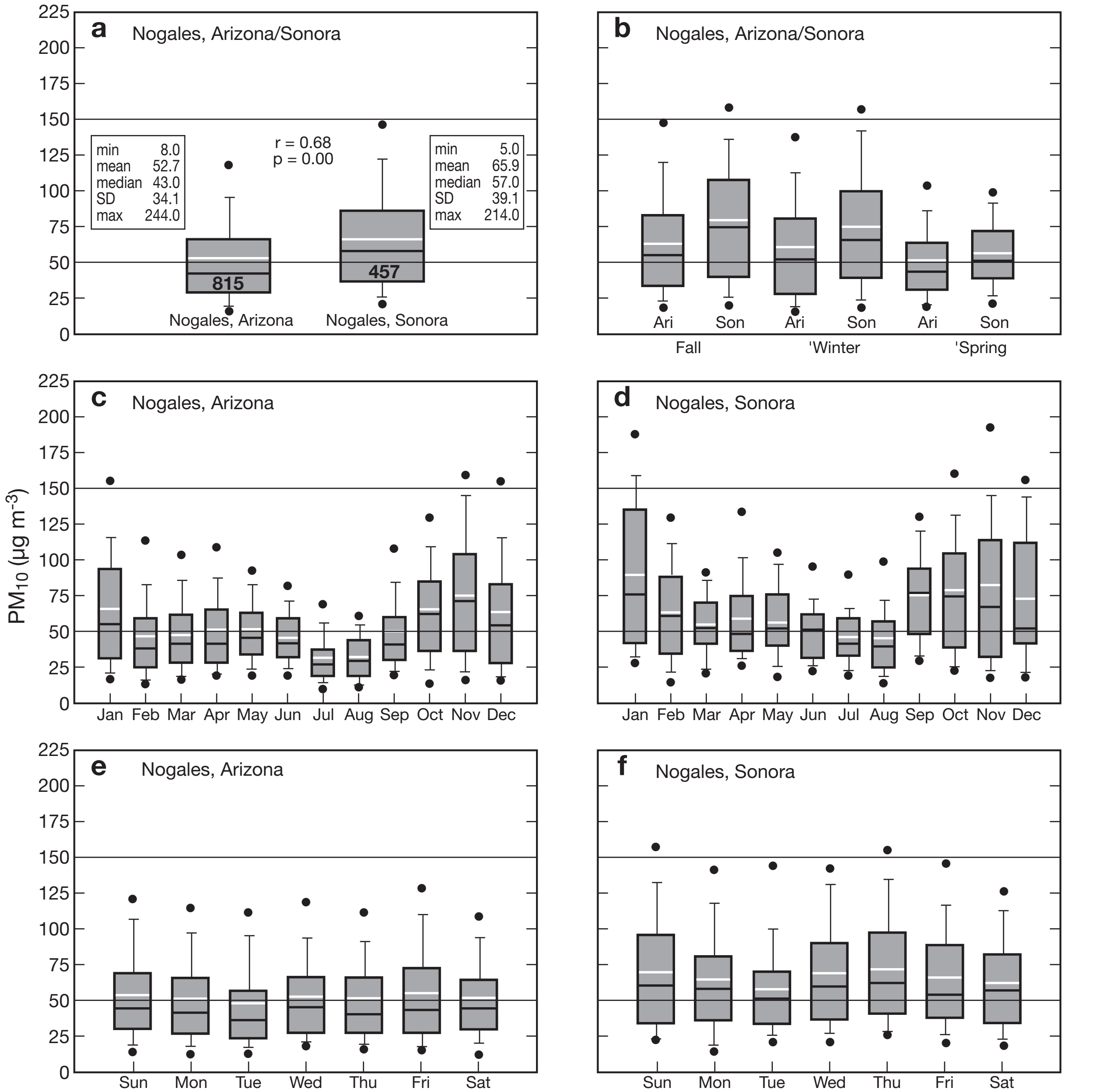

Fig. 2. PM_{10} concentrations for (a) for the period of record; (b) by season; (c) and (d) by month; and (e) and (f) by day of the week. Horizontal black lines within each box: median; white horizontal lines: mean; top and bottom of each box: 75th and 25th percentiles; whiskers: 90th and 10th percentiles; (•): 95th and 5th percentiles. Solid horizontal lines across panels: 24 h (150 mg m^{-3}) and annual (50 mg m^{-3}) U.S federal standards. Period of record — Nogales, Arizona: 1985–2001; Nogales, Sonora: 1993–2001. Ari: Arizona; Son: Sonora

cluding during the monsoon season (Fig. 3d). Nevertheless, with a soil moisture capacity (field capacity) of nearly 178 mm, the most moist portion of the year at Nogales (February and March, Fig. 3d) is still rather dry.

Intuitively, the greatest PM_{10} concentrations at Nogales would coincide annually with the driest soil conditions. However, this is not the case, as concentrations on both sides of Nogales are lowest during June, July, and August when the soil is driest (Fig. 2b–d), and highest during November and January, when soil moisture is highest. Historically, the weak relationship between the hydroclimatological conditions and PM_{10} concentration is even more apparent when examining PM_{10} concentrations for the seasons associated with the higher concentrations: fall, winter, and spring. Values in fall and winter are similar (Fig. 2b) despite the very different soil moisture conditions of those 2 seasons (Fig. 3d). PM_{10} concentrations in spring are lower than in fall and winter despite the soil being very dry at the end of spring.

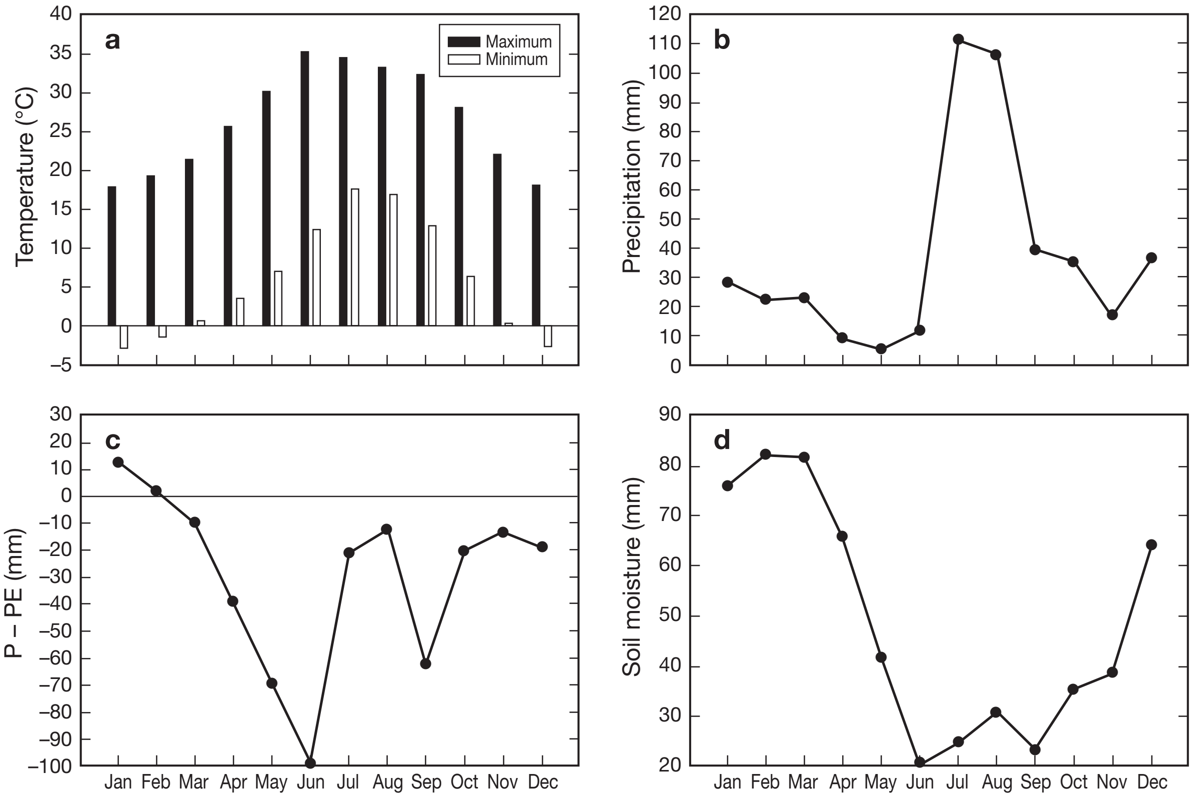

Fig. 3. Mean monthly (a) air temperature, (b) precipitation, (c) difference between precipitation and potential evapotranspiration (P – PE), and (d) soil moisture for Nogales, Arizona, USA, 1971–2000

In what appears to be an anthropogenic signal in the concentration of PM_{10} in Nogales, the highest concentrations occur on the shoulders of weekends (Fig. 2e,f). Peaks occur on Sunday on both the Arizona and Sonora sides of Nogales, and on Friday on the Arizona side and Thursday on the Sonora side. This may correlate with ground traffic activity in Nogales, possibly in the form of border crossing traffic. However, this is indeterminable due to the lack of ground traffic data in general and the lack of available daily border traffic data. This non-natural pattern should be remembered when interpreting subsequent results.

3.2. Composite synoptic weather pattern

A synoptic-scale weather pattern conducive to lower-atmospheric stagnation is important for high PM_{10} concentrations in Nogales (Fig. 4). Days of high concentrations in fall and winter (which have the highest frequency of such days) are marked by higher 500 hPa heights relative to the climatological average for those seasons over the southwestern USA/northwestern Mexico region (Fig. 4a,b). This is indicative of higher pressure in the middle portion of the atmosphere (approximately 5200 to 5800 geopotential height [m a.s.l.] above sea level), which is typically associated with relatively clear, calm surface atmospheric conditions. The height increases are in the vicinity of a ridge in the typical pattern of 500 hPa over western USA, and they are accompanied by large height decreases in the eastern Pacific Ocean in the vicinity of the eastern portion of the typical trough in the height pattern.

Further evidence of a regionally stagnant atmosphere is the pattern of weak winds at 850 hPa (approximately 1400 to 1500 gpm above sea level on average). However, winds during episodes of high PM_{10} concentration are not very different from the climatological mean across the study region during fall (Fig. 4c) or winter (Fig. 4d). Little difference exists for wind speed or direction, indicating little importance in regional wind patterns. This may well not be the case for local winds specifically within the airshed of Nogales, but the lack of a long-term and complete surface wind data base for Nogales makes this hard to determine.

3.3. PM_{10} concentration vs. independent variables

Testing the individual atmospheric and surface variables for the significance of the difference between days of high (top quartile) and low (bottom quartile)

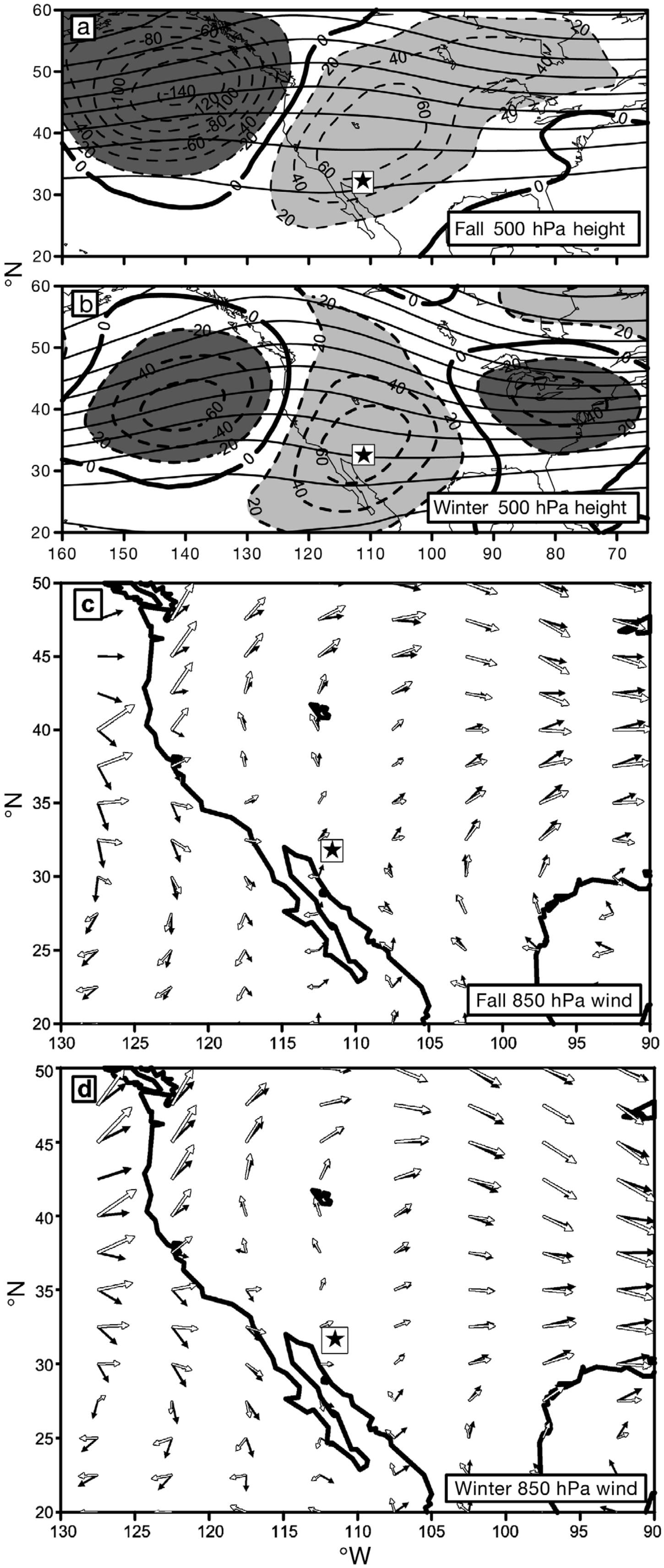

Fig. 4. Climatological means and anomalies (1971–2000) for days of high PM_{10} concentration in Nogales for 500 hPa height (m a.s.l.) in (a) fall and (b) winter, and 850 hPa wind (vectors) in (c) fall and (d) winter. (★) Nogales; solid bold lines: mean 500 hPa; dashed lines in shaded areas: height anomalies (high PM_{10} days minus climatology; light shade: positive, dark shade: negative). Black vectors: mean wind; white vectors: wind for days of high PM_{10} concentration

concentration helped to illustrate the physical differences in the 2 types of days (Table 1). Correlation coefficients representing the significance of the linear relationship between PM_{10} concentrations and the individual variables indicate the strength of the relationships across the full range of the data (Table 2).

Significant differences in synoptic scale wind between high and low PM_{10} concentration days are scarce in fall and winter on both sides of the border (Table 1), and no significant correlations between the wind variables and PM_{10} concentration exist at either location in fall and winter (Table 2). The few relationships that exist suggest that higher wind speeds are associated with lower concentrations, and in some cases a change in wind direction is evident between high concentration (easterly) and low concentration (westerly) days. The only consistently significant wind–concentration relationship exists in spring. On the Arizona side of the border, winds are stronger from the southwest on low concentration days than the weaker northwest (morning) and northeast (evening) winds on high concentration days (Table 1). A positive relationship indicating stronger and/or more easterly evening winds associated with higher PM_{10} concentrations exists in spring on the Sonora side of the border (Table 2). In general, stronger and more westerly synoptic scale winds are loosely associated with higher PM_{10} concentrations. This is also suggested in the fall and winter synoptic composites (Fig. 4c,d).

For all seasons on both the Arizona and Sonora sides of Nogales, episodes of high PM_{10} concentrations are marked by positive anomalies in Tmax, and low concentrations are associated with negative anomalies (Tables 1 & 2). Evidence of negative (positive) anomalies in Tmin in association with episodes of high (low) concentrations exists during all seasons on the Arizona side of Nogales (Tables 1 & 2), but only during winter on the Sonora side (Table 2). A large temperature range is an indication of a dry and calm atmosphere, whereby significant surface heating

Table 1. Mean values for variables with statistically significant ($p \leq 0.05$) differences between days of high (upper quartile) and low (lower quartile) PM_{10} concentrations for Nogales. u: W–E component (positive: easterly; negative: westerly); v: N–S component (positive: northerly; negative: southerly)

Variable	Fall		Winter		Spring	
	High	Low	High	Low	High	Low
Arizona						
n	80	37	60	46	43	39
Wind (m s^{-1})						
0500 u wind			−0.6	−7.2	−5.6	−10.0
0500 v wind					+2.9	−2.3
1700 u wind	+1.9	−2.1			+0.9	−4.3
1700 v wind					+1.2	−4.0
Temperature (°C)						
Tmax anomaly	+1.7	−0.8	+2.9	−2.5	+2.1	−2.5
Tmin anomaly	−1.0	+1.4	−0.9	+0.7	−0.7	+1.6
Stagnation						
500 hPa height (m)			5749.4	5641.4	5779.3	5696.6
Inversion height (m)	286.0	129.0	293.0	144.0	240.0	99.0
Inversion strength (°C km^{-1})			22.5	11.2	21.6	13.3
Surface						
PDSI (dimensionless)						
Soil moisture (mm)	19.3	41.4	62.3	85.3		
P – PE (mm)						
Last precipitation (d)	13.7	6.3	21.3	11.2	22.2	9.9
Sonora						
n	25	48	29	45	22	13
Wind (m s^{-1})						
0500 u wind						
0500 v wind			+1.9	−2.3		
1700 u wind			−0.2	−6.1		
1700 v wind						
Temperature (°C)						
Tmax anomaly	+2.2	−1.6	+3.5	−2.8	+2.8	−2.6
Tmin anomaly						
Stagnation						
500 hPa height (m)	5828.2	5742.0	5757.9	5639.0	5785.3	5688.0
Inversion height (m)	230.0	110.0	310.0	144.0	261.0	95.8
Inversion strength (°C km^{-1})	26.8	7.6	26.5	12.9		
Surface						
PDSI (dimensionless)	−1.3	−0.2			−2.5	+0.7
Soil moisture (mm)	18.8	50.8			22.1	77.1
P – PE (mm)	−39.9	−10.6	−7.8	+10.3		
Last precipitation (d)	13.6	7.0				

through a clear, calm atmosphere during daytime hours is counteracted by efficient radiational cooling at night under the same conditions. This supports the idea of anomalously high 500 hPa levels associated with high concentrations (see Section 3.2 and Fig. 4a,b).

The notion of a stagnant synoptic weather pattern during episodes of high PM_{10} concentrations is further supported by 500 hPa height and morning inversion height/strength data at Tucson. Days of high PM_{10} concentration were marked by significantly higher 500 hPa heights than during days of low concentrations during all seasons on the Sonora side of Nogales, and during winter and spring on the Arizona side (Table 1). However, no correlation between PM_{10} concentration and 500 hPa height exists when using the full record of data (Table 2). The height of the morning (05:00 h LST) inversion layer at Tucson is significantly related to the daily PM_{10} concentration on both sides of the border and for all seasons when comparing high and low concentration days (Table 1) and when using the full record (Table 2). The relationship suggests that the deeper the inversion layer is, the higher the PM_{10} concentration will be. Similarly, a stronger inversion is related significantly to higher concentrations by at least one of the statistical measures during all seasons on the Arizona side of the border and during fall and winter on the Sonora side (Tables 1 & 2). Both a deeper inversion layer and a stronger inversion are indicative of stagnant atmospheric conditions that promote high PM_{10} concentrations.

In the case of surface variables, the PDSI has a significant relationship with PM_{10} concentrations during fall and spring only on the Sonora side of the border. Historically, the PDSI is more negative (drier) during episodes of high PM_{10} concentrations than during episodes of low concentrations (Table 1), although only significantly so from a linear correlation standpoint during spring (Table 2). Soil moisture is significantly lower in association with high PM_{10} concentrations during fall and winter on the Arizona side of Nogales and during fall and spring on the Sonora side (Tables 1 & 2). The balance of P – PE is significantly inversely correlated with PM_{10} concentration during winter on both sides of Nogales (Table 2). However, significant differences in P – PE between the populations of high and low PM_{10} concentrations exist only on the Sonora side of the border during fall and winter (Table 1). In each case, the difference between input and potential loss (P – PE) is more negative during episodes of high concentrations of PM_{10}. Finally, during all seasons on the Arizona side of the border and during fall on the Sonora side, episodes of high PM_{10} concentration typically followed extended dry spells (Tables 1 & 2).

Relationships between the independent variables and PM_{10} concentrations suggest that days of high concentrations at Nogales are associated with (1) weak

Table 2. Linear correlation coefficients for relationships between PM_{10} concentrations and characteristics of atmosphere and surface. *u*: W–E component (positive: easterly; negative: westerly); *v*: N–S component (positive: northerly; negative: southerly). Bold: significant relationships ($p \leq 0.05$)

Variable	Arizona Fall	Arizona Winter	Arizona Spring	Sonora Fall	Sonora Winter	Sonora Spring
n	210	180	205	117	131	110
Wind ($m\ s^{-1}$)						
0500 *u* wind	−0.01	0.04	0.08	−0.03	0.00	0.10
0500 *v* wind	0.06	−0.02	0.10	0.10	0.01	0.11
1700 *u* wind	0.08	0.00	0.06	0.06	0.03	**0.38**
1700 *v* wind	0.07	−0.03	0.09	0.11	0.02	0.17
Temperature (°C)						
Tmax anomaly	**0.36**	**0.45**	**0.27**	**0.44**	**0.44**	**0.39**
Tmin anomaly	**−0.25**	−0.14	**−0.15**	−0.15	**−0.21**	0.13
Stagnation						
500 hPa height (m)	0.09	0.01	0.13	0.00	0.04	−0.02
Inversion height (m)	**0.39**	**0.33**	**0.22**	**0.29**	**0.42**	**0.42**
Inversion strength (°C km^{-1})	**0.19**	**0.23**	0.05	**0.53**	**0.26**	0.09
Surface						
PDSI (dimensionless)	0.07	−0.10	0.12	−0.13	−0.10	**−0.24**
Soil moisture (mm)	**−0.15**	**−0.15**	−0.02	**−0.20**	−0.05	**−0.20**
P – PE (mm)	−0.03	**−0.16**	−0.02	−0.17	**−0.21**	−0.14
Last precipitation (d)	**0.30**	**0.21**	**0.21**	**0.24**	0.14	0.10

Table 3. Stepwise multiple regression analysis ($p \leq 0.05$) by season, including variables chosen, linear correlation coefficient (R), and the cumulative coefficient of determination (R^2). *u*: W–E component (positive: easterly; negative: westerly); *v*: N–S component (positive: northerly; negative: southerly)

Variable	R	R^2	Variable	R	R^2
Arizona Fall (n = 210)			**Sonora Fall** (n = 117)		
Inversion height	+0.42	17.8	Inversion strength	+0.46	21.3
Inversion strength	+0.23	23.0	Soil moisture	−0.36	34.4
Soil moisture	−0.21	27.2	500 hPa height	+0.22	39.2
1700 *u* wind	+0.16	29.9	Inversion height	+0.18	42.6
Arizona Winter (n = 180)			**Sonora Winter** (n = 131)		
500 hPa height	+0.56	31.0	500 hPa height	+0.55	29.9
0500 *v* wind	+0.14	32.9	0500 *v* wind	+0.38	44.0
			P – PE	−0.16	46.6
Arizona Spring (n = 205)			**Sonora Spring** (n = 110)		
Tmax anomaly	+0.34	11.5	Tmax anomaly	+0.45	20.5
PDSI	−0.17	14.5	Inversion height	+0.26	27.1

easterly/variable winds, (2) a large diurnal temperature range, (3) a stagnant lower atmosphere (high 500 hPa height, deeper and stronger morning temperature inversion), and (4) dry soil conditions. However, combinations of variables representing these relationships do not explain a large amount of the variance in daily PM_{10} concentrations on either side of Nogales (Table 3). Stepwise multiple regression analysis was used to indicate the combination of variables that best explain PM_{10} concentrations for each season on both the Arizona and Sonora sides of the border. Daily prediction of PM_{10} concentrations seems to be elusive, at least without daily ground traffic and local surface wind data. The best prospect for such a prediction is in the winter season, as 2 and 3 variables explain 32.9 and 46.6% of the variance in concentrations on the Arizona and Sonora sides, respectively (Table 3). The fall models consist primarily of inversion height/strength and soil moisture, while the winter models are dominated by 500 hPa height and morning wind (Table 3). The significantly weaker models of spring consist primarily of the Tmax anomaly (Table 3). The poor prospect for prediction of daily PM_{10} concentration is likely a product of 2 elements: (1) absence of a proxy for anthropogenic activity, which is likely to influence PM_{10} regardless of atmospheric and surface conditions, (2) low daily variability in environmental conditions that are naturally conducive to high PM_{10} concentrations.

3.4. Surface vs. atmosphere

The set of variables representing the level of stagnation in the synoptic weather pattern outperform the sets of variables representing temperature, wind, and surface conditions when discriminating days of high and low PM_{10} concentrations on both sides of the border during fall, winter, and spring (Table 4). The percentage of days correctly classified using the measures of stagnation within a linear discriminant analysis ranges between 77.9 and 78.9% on the Arizona side and between 80.0 and 87.1% on the Sonora side. These values are superior to those associated with surface conditions, which range from 56.2 to 72.6% on the Arizona side and between 65.7 and 68.5% on the Sonora side (Table 4). The results indicate that atmospheric stagnation is the most important variable separating days of high and low PM_{10} concentration. Surface conditions are the third-best discriminator (after temperature) in fall on the Arizona side of Nogales and in winter on the Sonora side (Table 4). Otherwise, the surface condition is least discriminatory or the percentage of correct classifications using the surface condition is rather low (near 50%).

When discriminating between days of moderately high (50th – 75th percentile) and high (>75th per-

Table 4. Discriminant analysis using surface and atmospheric variables to discriminate between populations of days with PM_{10} concentrations in the historical 1st and 4th quartiles (low vs. high) and the 3rd and 4th quartiles (moderately high vs. high). Values: percentage of days categorized correctly. **Bold**: set of variables that discriminates best for each season

	Arizona		Sonora	
	1st↔4th	3rd↔4th	1st↔4th	1st↔4th
Fall				
n	37 80	48 80	25 48	29 48
Surface	72.6	**72.7**	68.5	58.4
Temperature	73.2	58.9	79.5	66.2
Wind	66.7	53.1	76.1	58.3
Stagnation	**77.9**	62.0	**83.1**	**68.8**
Winter				
n	46 60	45 60	29 44	34 44
Surface	56.2	**63.1**	67.6	63.3
Temperature	72.4	62.0	78.4	67.2
Wind	65.1	58.1	76.6	51.5
Stagnation	**78.8**	58.5	**87.1**	**68.2**
Spring				
n	39 43	68 43	22 13	36 13
Surface	69.1	55.5	65.7	55.1
Temperature	78.8	**66.1**	74.3	51.0
Wind	74.4	63.1	74.3	**69.4**
Stagnation	**78.9**	61.4	**80.0**	45.9

centile) PM_{10} concentration, the surface condition is the best discriminator in fall and winter on the Arizona side of Nogales, but atmospheric stagnation remains as the lead discriminator on the Sonora side during those seasons (Table 4). This suggests that dry soil increases PM_{10} concentrations on the Arizona side of Nogales in fall and winter, but if the atmosphere is stagnant, a dry soil is not as necessary on the Sonora side. These relationships do not exist in spring, when temperature and wind become more important for increasing PM_{10} concentrations on the Arizona and Sonora sides of Nogales, respectively. Spring is marked by weaker discriminations on both sides.

3.5. Arizona vs. Sonora

In each season the surface condition is the best discriminator between days where PM_{10} concentrations are anomalously higher on one side of the border relative to the corresponding anomaly on the other side, and vice versa (Table 5). In fall and especially in winter, the difference between the surface condition and the representations of the atmosphere are large. When examining the individual surface variables (i.e. PDSI, soil moisture, P – PE, days since last precipitation) for the 2 populations using a 2-sample *t*-test, drier soil conditions were linked to higher anomalies on the Arizona side of Nogales than on the Sonora side. Conversely, more moist soil conditions were linked to higher anomalies on the Sonora side. This was most significantly represented by the number of days since the last precipitation event.

Table 5. Discriminant analysis using surface and atmospheric variables to discriminate between populations of days where the standardized PM_{10} concentration on one side of the border was higher than on the other side. Values: percentage of days categorized correctly (Arizona > Sonora or Sonora > Arizona). **Bold**: set of variables that discriminates best for each season. n: Arizona/Sonora

	Fall	Winter	Spring
n	39/52	39/55	37/44
Surface	**63.8**	**71.4**	**58.0**
Temperature	59.6	53.8	56.8
Wind	57.0	59.5	57.9
Stagnation	59.7	50.7	52.3

4. CONCLUSIONS

PM_{10} concentrations on the Sonora side of Nogales tend to be considerably higher than on the Arizona side, and at both locations concentrations tend to be highest in fall and winter despite the fact that soil moisture is typically high during those seasons. PM_{10} concentrations are highest around weekends: Friday and Sunday on the Arizona side, and Thursday and Sunday on the Sonora side.

During the time of year marked by episodes of high PM_{10}, high (low) concentrations on both sides of the border are associated with relatively lighter (stronger) morning winds that are more easterly (westerly) in direction, a greater (lesser) diurnal temperature range, higher (lower) middle-atmospheric pressure across the region, a deeper (more shallow) and stronger (weaker) morning surface air temperature inversion, and a drier (moister) soil. However, multiple regression analysis reveals that only a small amount of the historical variance in PM_{10} concentrations is explained by a small subset of atmospheric and surface variables. This is likely due to the lack of a proxy for anthropogenic activity, which can influence PM_{10} regardless of atmospheric and surface conditions, and low daily variability in an environment that is naturally conducive to high PM_{10} concentrations.

The character of the atmosphere best discriminates days of high PM_{10} concentrations from days of low concentrations, suggesting that atmospheric stagnation is a necessary factor for high PM_{10} levels. However, when PM_{10} concentrations are high, soil moisture is most important in discriminating the days of very high concentrations on the Arizona side of the border during the most problematic seasons of fall and winter.

On the Sonora side, atmospheric stagnation is still the leading discriminator of very high from moderately high PM_{10} concentrations. Furthermore, in fall, winter, and spring the surface condition was the best discriminator between days where the PM_{10} concentration anomaly is higher on one side of the border than on the other side. Drier soil conditions were linked to higher anomalies on the Arizona side of Nogales relative to the Sonora side.

Overall, our results suggest a greater degree of dust production through anthropogenic activity for Sonora. Without detailed data capable of representing different facets of human activity, it is difficult to conclude what the sources may be, assuming that they are anthropogenic in nature. As for cross-border transport of PM, a detailed analysis of winds within the airshed or a modeling effort is necessary to determine the contribution of one side of the border to the other. This was beyond the goal of this study, but it forms a logical next step.

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