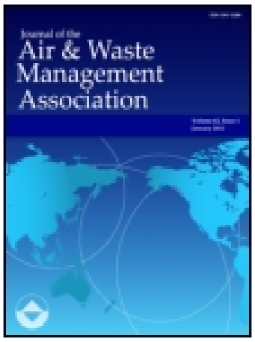

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An Analysis of Effects of San Diego Wildfire on Ambient Air Quality

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ABSTRACT

The impact of major gaseous and particulate pollutants emitted by the wildfire of October 2003 on ambient air quality and health of San Diego residents before, during, and after the fire are analyzed using data available from the San Diego County Air Pollution Control District and California Air Resources Board. It was found that fine particulate matter (PM) levels exceeded the federal daily 24-hr average standard during the fire. There was a slight increase in some of the gaseous pollutants, such as carbon monoxide, which exceeded federal standards. Ozone (O_3) precursors, such as total hydrocarbons and methane gases, experienced elevated concentration during the fire. Fortunately, the absence of sunlight because of the cloud of thick smoke that covered most of the county during the fire appears to have prevented the photochemical conversion of the precursor gases to harmful concentrations of O_3. Statistical analysis of the compiled medical surveillance data has been used to establish correlations between pollutant levels in the region and the resultant health problems experienced by the county citizens. The study shows that the increased PM concentration above the federal standard resulted in a significant increase in hospital emergency room visits for asthma, respiratory problems, eye irritation, and smoke inhalation. On the basis of the findings, it is recommended that hospitals and emergency medical facilities engage in pre-event planning that would ensure a rapid response to an impact on the healthcare system as a result of a large wildfire and appropriate agencies engage in the use of all available meteorological forecasting resources, including real-time satellite imaging assets, to accurately forecast air quality and assist firefighting efforts.

IMPLICATIONS

The purpose of this research project is to document the amounts and effects of major gaseous pollutants and particulate matter emitted into the ambience of San Diego County by the wildfire of October 2003. In addition, establish correlations between pollutant levels in the region and resultant health problems experienced by the county citizenry using the medical surveillance report compiled in collaboration with area hospitals. Establishing a nexus between the major pollutants emitted and air quality related health problems would be useful in preparing for similar events and developing preventive strategies for the future.

INTRODUCTION

San Diego, the sixth largest county in the United States, is home to 2.8 million residents, and is the third most populous city in California. The county encompasses 4300 square miles and includes a mixture of urban and rural communities that live in the coast, the mountains, and the desert. It borders Orange and Riverside counties to the North, Mexico to the south, Imperial County to the East, and the Pacific Ocean to the West. San Diego enjoys desirable weather receiving only approximately 20–30 days of rain per year. Around October, this region experiences persistent dry weather and low moisture that create conditions conducive for fire that are reinforced by Santa Ana winds. It was precisely that these conditions that were partially responsible for the 2003 wildfires that besieged Southern California. These turned out to be the most disastrous in the history of the state, as they was characterized by 14 fires in the counties of San Diego, Los Angeles, San Bernardino, and Ventura.

The fires that occurred in San Diego mainly took place in three different locations. The Cedar Fire was the most intense and largest of the fires. The other two were the Paradise and Otay Fires. The Cedar Fire spread ~20 miles to the east of Interstate Route 805, then moved on toward Pine Valley and Julian to the North, and soon spread over the entire area that demarcates the communities of Ramona, Poway, Miramar, Tierrasanta, and Grossmont. The Paradise Fire covered the area of Valley Center, and the Otay Fire burnt the mountainous area close to the U.S.–Mexico border and East Chula Vista. The Santa Ana winds took the fires toward the west, directly into wild vegetations and the residential areas. The task of fighting the fires was made difficult as local wind patterns sporadically changed the direction of the fire. The whole region was blanketed with clouds of smoke, and ashes were carried over hundreds of miles. The San Diego Air Pollution Control District issued a health advisory recommending that all of the schools in the county be closed and all outdoor activities be limited for over a week. Mass attention was focused, by the increased number of hospital admissions, on what was emitted into the regional atmosphere from the fires.

The wildfire of October 2003 brought residents of San Diego and neighboring cities unprecedented devastating effects far beyond the short-term and long-term harmful suffering done to the environment, flora, and fauna. The San Diego fire consumed an area of >390,000 acres; burned 5597 homes, commercial, and accessory buildings; destroyed 3773 automobiles, trucks, and boats;[1] and caused 16 deaths.[2] The incident became a catalyst for instituting legislations that would ensure that different private and public agencies would be ready to respond to similar catastrophes in the future.

The Cedar Fire released ~300,150 t of PM and other pollutants into the atmosphere.[3] These pollutants are known to cause serious adverse health effects in the human respiratory system. If the government air quality standards are met, a healthy person can expect minimal adverse epidemiological consequences. However, when natural disasters, such as wildfires, occur, they produce such unpredictable, uncontrollable pollutant masses in the atmosphere that no living, breathing creature can escape from its poisonous effects. The purpose of this research project was to document the amounts and effects of major gaseous pollutants and PM emitted into the ambience of San Diego County by the wildfire of October 2003. Another objective was to establish correlations between pollutant levels in the region and resultant health problems experienced by the county residents, by using the medical surveillance report that was compiled in collaboration with area hospitals. It is assumed that establishing a nexus between the major pollutants emitted and air quality-related health problems would help both private and public agencies develop preventive strategies and, thus, be better prepared for similar events in the future.

Literature Review

Biomass burning and wildfires emit a substantial amount of gaseous pollutants and PM into the environment and cause people to suffer from respiratory illnesses. The seriousness of illness that they may suffer from depends not only on the concentration levels but also on individual sensitivity, physiological characteristics, and susceptibility. Other consequences include nuisance, visibility impairment, ozone (O_3) generation, and greenhouse effects. In recent years, air pollution has been considered to be an important cause or risk factor for reproductive health. There have been growing concerns about the adverse effects of air pollution on birth outcomes, such as low birth weight (LBW), intrauterine growth retardation, preterm births, and birth defects.[4–7] Coarse PM (PM_{10}) exposure in the second and fourth months has been associated with LBW.[8] Particulate air pollution has been associated with both acute and chronic exacerbation of childhood asthma. More chronic symptoms of bronchitis have been observed in previous cross-sectional studies of children with asthma exposed to PM[9–14].

Wildfire smoke is comprised of a complex mixture of particles, liquids, and gaseous compounds. These include PM_{10}, carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2), oxidants that may include small amounts of O_3, polycyclic organic material,[15] and toxic pollutants. These emissions may significantly impact air quality on local, regional, and global scales. Some events are extreme, and the contributions of fires to air pollutant concentrations are readily observable.[16] For instance, the 1997 Indonesia forest fire caused massive transboundary air pollution, producing large amounts of haze in the region and causing visibility and health problems within Southeast Asia. Furthermore, fires of such magnitude have the potential to contribute to global warming and climate change as they emit large amounts of greenhouse gases and other pyrogenic products.[17,18]

PM is the pollutant that has most consistently been associated with short-term effects on mortality.[19] Recent findings tend to relate particulate pollution to an increased plasma viscosity,[20] increased risks of heart rate,[21] electrocardiographic changes in humans,[22–24] and the triggering of myocardial infraction.[25] A high degree of human exposure to concentrated air particles has also been associated with plasma fibrinogen.[26] Several studies have indicated that the smaller particles, which are <2.5 μm in diameter, are mainly responsible for the above effects.[19]

Long-term exposure to combustion-related fine particulate and sulfur oxide (SO_x)-related air pollution has been identified as an important environmental risk factor for cardiopulmonary and lung cancer mortality. Each 10 $\mu g/m^3$ increase in fine particulate air pollution is associated with an ~4, 6, and 8% increased risk of all cause, cardiopulmonary, and lung cancer mortality, respectively. However, measures of coarse particle fraction and total suspended particles are not consistently associated with mortality.[27]

Time-series and panel studies have shown acute increases in ambient PM to be associated with increases in emergency room visits,[28] hospital admissions for asthma,[29,30] acute symptoms,[31–35] medication use,[31,33] and a decline in peak exploratory flow rates.[31,32,34] There was a 91% increase in asthma and chronic bronchitis incidences during a fire in central Florida in 1998. On average, there was a 1–1.5 day lag between the fire event and the increased emergency room visits and in-patient admissions for asthma.[36]

The most abundant air pollutant from wild land fires is CO. This, coupled with carbon dioxide and methane (CH_4), has been found to be a significant source of greenhouse gases. Besides CO, NO_x can also form at lower temperatures, although the amount primarily depends on the nitrogen content of the fires burnt. However, the SO_x produced are in negligible quantities, because forest fires normally contain low sulfur content. Fires also emit a large amount of semivolatile organic compounds (VOCs), which are partitioned between the gaseous and liquid or solid phase at ambient temperatures. Some VOCs are carcinogenic and can condense or absorbed into the surface

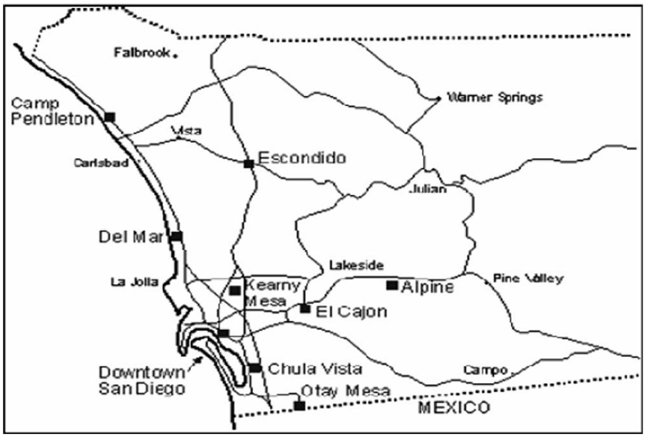

Figure 1. San Diego APCD-chosen monitoring stations.

Table 1. Pollutants monitored by the nine monitoring stations in the San Diego APCD.

Station	Pollutant Measured
Alpine	O_3, NO_2, NO, NO_x, PM_{10}
Camp Pendleton	O_3, NO_2, NO, NO_x
Chula Vista	O_3, NO_2, NO, NO_x, PM_{10}, $PM_{2.5}$
Del Mar	O_3
El Cajon	O_3, NO_2, NO, NO_x, PM_{10}, $PM_{2.5}$, CH_4, non-CH_4 hydrocarbon, THC
Escondido	O_3, NO_2, NO, NO_x, CO, $PM_{2.5}$
Otay Mesa	O_3, NO_2, NO, NO_x, CO, SO_2, PM_{10}
San Diego–Downtown	O_3, NO_2, NO, NO_x, CO, SO_2, PM_{10}, $PM_{2.5}$
Kearny Mesa	O_3, NO_2, NO, NO_x, CH_4, THC, PM_{10}, $PM_{2.5}$

of the particulate. Incomplete combustion produces hydrocarbons, including ethylene, alkynes, aldehydes, furans, and carboxylic acids.[15]

The main health impact is from the exposure to PM. It is a major component of smoke and is comprised of a complex mixture of soot, tars, and volatile substances and, thus, is harmful to human health.[15] In many cases, pollutant gases, such as SO_x, NO_x, and VOCs, interact with other compounds in the air to form fine particles. Their chemical and physical compositions vary depending on location, time of the year, and weather.[37] Fine PM ($PM_{2.5}$) is becoming more commonly measured during fire-related incidents, because the fine fraction predominates in the smoke and haze, and it is thought to be more responsible than larger particles for the observed health effects.[38,39]

Methodology

San Diego Air Pollution Control District (APCD) has established nine air monitoring stations that are strategically located to evaluate pollution levels that affect the county residents (Figure 1). Each station monitors specific pollution levels borne by sources pertaining to the area, such as stationary and mobile sources (Table 1).

To assess the impact of the pollutants emitted by the San Diego Wildfire, a 4-week baseline surveillance period before the start of fire (October 25, 2003), a 10-day period during the fire, and a 4-week post-fire surveillance period immediately after the fire were established. For the purpose of analysis, data were primarily obtained from two urban and one remote monitoring locations: Downtown San Diego, Escondido, and Alpine. Downtown San Diego and Escondido are heavily urbanized with a high density of vehicular population. Alpine is a rural town ~25 miles east-northeast of the city of San Diego. It is in the foothill zone, and its western sloping terrain traps air pollutants. For the purpose of this study, average daily, 1-hr maximum and 8-hr maximum readings were referenced to analyze the resultant effects of gaseous pollutants. Standard and local conditions for PM were also noted. Contributions by O_3 precursors, such as total hydrocarbons (THC), CH_4, and non-CH_4 hydrocarbons, were analyzed to determine the behavior of the major pollutants. The conditions for each criteria pollutant of concern in 2002 were recorded by San Diego County as described below.[40]

O_3. O_3 levels were measured in all nine of the locations. The county did not exceed the federal 1-hr concentration of 0.125 ppm. However, the federal 8-hr concentration of 0.085 ppm was exceeded for a total of 13 days. The Alpine station measured the greatest number of days exceeding the 8-hr standard[12] days for O_3. This was because emissions from motor vehicles, industry, and anthropogenic activities were blown inland through dense urban areas by the onshore breeze and tended to stay along the west-facing mountain slopes ~2000 ft above sea level. There were also enough pollutant generators in San Diego County to contribute to higher pollution concentrations. The region has adequate conducive atmosphere to produce higher O_3 levels, such as persistent light winds, hot temperature, and plenty of sunlight.

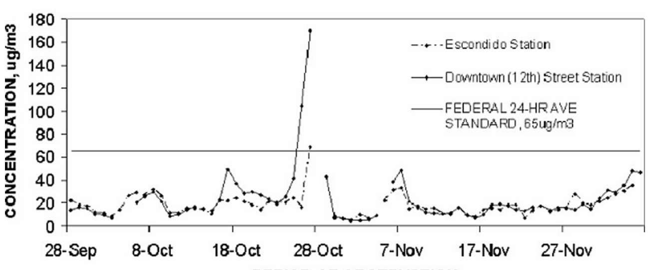

Figure 2. $PM_{2.5}$ daily 24-hr average measurements during the surveillance period.

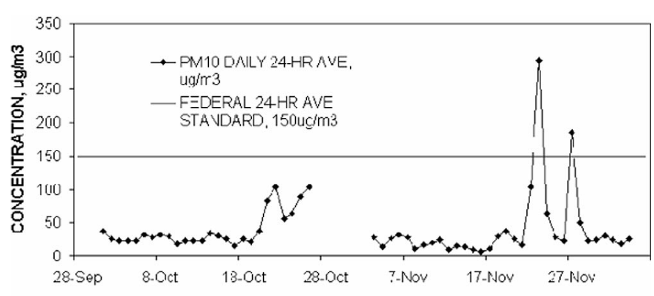

Figure 3. PM_{10} measurement in Alpine station during the surveillance period.

PM_{10}. San Diego APCD measured PM_{10} standards as mandated by both federal and state governments in six locations as shown in Table 1. The stations collected 24-hr samples on specific filters and compared data to air quality standards (annual arithmetic mean: federal –50 $\mu g/m^3$ and state –20 $\mu g/m^3$; and maximum 24-hr, federal –150 $\mu g/m^3$ and state –50 $\mu g/m^3$). The results indicate that the county did not exceed the federal standards except for one location, Otay Mesa, where a high volume of border crossings occurred, and this contributed to a high generation of PM_{10}. However, most locations failed to meet state standards, which are more stringent than federal standards.

$PM_{2.5}$. $PM_{2.5}$ samples were collected daily in three sites, El Cajon, Escondido, and downtown San Diego. Samples from Kearny Mesa and Chula Vista were taken for measurements every third day. All of the locations met the federal 24-hr standard of 65 $\mu g/m^3$ for $PM_{2.5}$. Three sites exceeded the annual standard, arithmetic mean 15 $\mu g/m^3$, and the more stringent state standard of 12 $\mu g/m^3$.

CO. The county attained all of the federal and state standards for CO (maximum 1-hr concentration of 35 ppm for federal and 20 ppm for state, and maximum 8-hr concentrations of 9 ppm for federal and state). The emissions of CO came primarily from automotive vehicles. Strict motor vehicle emission requirements controlled CO emissions formed during combustion.

NO_2. The annual average federal allowable standard is 0.053 ppm, and the California maximum 1-hr standard is 0.25 ppm. The county has not exceeded either of these limits in more than a decade.

SO_2. There has never been a violation of SO_2 exceeding the standards in San Diego County, although three federal standards and two state standards are in place to limit SO_2 pollution. The three federal standards include an annual average of 0.030 ppm, a maximum 24-hr concentration of 0.14 ppm, and a maximum 3-hr concentration of 0.5 ppm. More stringent state standards are a maximum 24-hr concentration of 0.05 ppm and a maximum 1-hr concentration of 0.25 ppm.

The San Diego APCD archives the data on the pollutants, which were measured from the nine monitoring stations. In addition to this source of raw data, similar data are available from the California Air Resources Board (CARB). The meteorological impact on the behavior of pollutant dispersion and movement during the fire was based on the daily forecast generated by San Diego APCD meteorologists. Real-time observations of the meteorologists were also taken into consideration in the analysis of the overall impact to ambient air quality from the fires.

Before October 1, 2003, San Diego County APCD was using the Federal Reference Method (FRM) samplers to collect $PM_{2.5}$ data for data analysis and archiving. The FRM is based on statistical analyses of filter samples collected at the five monitoring stations located throughout the county. These five stations are located in downtown San Diego (Twelfth Avenue), Chula Vista, El Cajon, Kearny Mesa (Overland Avenue), and Escondido. When San Diego APCD became part of the national forecasting program on October 1, 2003, district meteorologists began relying on data collected from the two $PM_{2.5}$ Beta Attenuation Monitor (BAM) samplers for real-time data reporting and forecast verification. Statistical analysis of the FRM data did not show sharp gradients across the county or radical departures from mean conditions. As a result, the two BAM samplers were thought to be adequate for ambient conditions expected in the county. These two BAM samplers are located at downtown San Diego and Escondido monitoring stations. The only real-time PM_{10} Tapered Element Oscillating Microbalance (TEOM) sampler is located at the Alpine monitoring station. Meteorological data were provided by the District Radar Wind Profilers (RWPs) and the Radio-Acoustic Sounding Systems (RASS) located in Miramar and Point Loma.

Medical Surveillance Methods

Health effects to county residents were assessed through the efforts of San Diego County Health and Human Services Agency, Public Health Services. On Tuesday, October 28, 2003, in response to the fires, smoke, and circulating ashes, a fire-related surveillance process was developed, and by Thursday, October 30, 2003, 15 of the 19 civilian hospital emergency departments in the county (two Navy hospitals were excluded from this surveillance) were asked to participate in this fire-related surveillance. A 3-week surveillance period was established, including 1 week of baseline (pre-event) and 2 weeks following the fires. Because this surveillance was conducted during the fires, the intent was to capture critical information from a limited time period to quickly assess the impact of the fires.

A number of potential fire-related indicators were identified as categories to be monitored. These surveillance categories included the following: asthma, bronchitis, or emphysema; other respiratory conditions with no fever; eye irritation; smoke inhalation; burns; chest pain or cardiac arrests; and diarrhea. The total number of visits made by patients to the hospital was also considered. Each hospital was asked to provide the necessary data to support these surveillance activities.

A standard univariate approach to analysis of the surveillance data using a variety of statistical quality control charts was used in this project. Atypical increases in the number of emergency department (ED) visits, in terms of raw numbers and as a proportion of total ED visits, were monitored with U-charts and P-charts, respectively. Additionally, exponentially weighted moving average (EWMA) charts were generated to detect small shifts in the mean of a variable over time. Time series graphs were generated to evaluate the behavior of the variable over time, and detailed descriptive statistics were inspected to gain insight into the long-term behavior and distributional properties of the variable, including measures of central tendency, dispersion, and degree of normality.

Estimated Amount of Emissions Computation Method

In a study conducted by the University of California, Berkeley,[3] for the CARB, researchers used the U.S. Department of Agriculture Forest Service First-Order Fire Effects Model

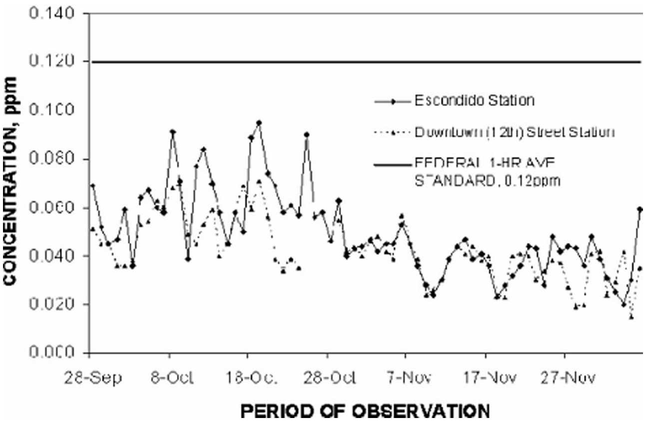

Figure 4. O_3 daily max. 1-hr average measurements during the surveillance period.

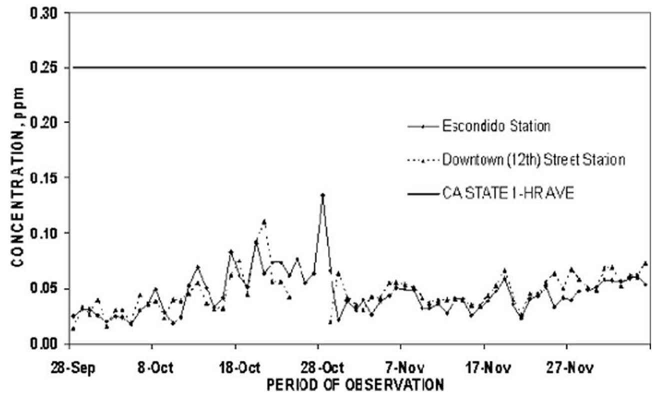

Figure 6. NO_2 California State 1-hr average standard measurements during the surveillance period.

(FOFEM), adapted to run in a Geographic Information System, to assess the fuels that contributed to the fires and the emission amounts and components that resulted from the combustion. The model requires the following inputs: (1) a spatial fuel, vegetation, or land cover map, which should contain vegetation types that can be linked to the FOFEM fuel model library to determine preburn fuel loadings in terms of tons per acre; (2) a fuel model look-up table, which is a relational database table that contains characteristic loadings in several fuel categories and a link to the vegetation-type map that establishes the loadings to be used for each vegetation type; (3) a fire perimeter map, which establishes the spatial extent of the burn area and can be decomposed temporally (into daily perimeters, for example) if those data exist; and (4) user-defined parameters of fuel moisture, seasonality, and fuel loadings.

RESULTS AND DISCUSSION

Data on pollutants between the period of September 28 and December 6, 2003, from Escondido, downtown (12th Avenue), Kearny Mesa (Overland Avenue), and Alpine monitoring stations were analyzed. The Escondido and downtown stations provided gaseous pollutants and $PM_{2.5}$ data. The PM_{10} data from Alpine station and gaseous pollutant data from Kearny Mesa station, along with meteorological data recorded by San Diego APCD RWPs and RASS located in Miramar and Point Loma were analyzed. Statistical analysis of medical surveillance data compiled by San Diego County Health and Human Services Agency in collaboration with area hospitals was used to establish correlations between pollutant levels in the region and resultant health problems experienced by the county citizens.

PM

$PM_{2.5}$. The $PM_{2.5}$ trend during the observation period is shown in Figure 2. On October 27, 2003, during the fire, the $PM_{2.5}$ U.S. Environmental Protection Agency (EPA) limit of 65 $\mu g/m^3$ was exceeded in the Escondido station. This measurement was recorded by the FRM monitor. The recorded readings during the period before and after the fire episode did not exceed the EPA limit. The data plot before and after the fire episode reveals a consistent trend.

The $PM_{2.5}$ trend during the observation period in the downtown station is shown in Figure 2. During the fire episode on October 26, 2003, the first full day of the fire, $PM_{2.5}$ daily 24-hr average measurement rose sharply to 104.6 $\mu g/m^3$. On October 27, 2003, $PM_{2.5}$ daily 24-hr average measurement recorded was >2.5 times the EPA limit at 170 $\mu g/m^3$. However, similar to the Escondido station, the EPA limit was not exceeded during the surveillance period, the period before and after the fire episode. The data plot revealed a consistent trend before and after the fire episode.

PM_{10}. The Alpine station monitors real-time PM_{10} using the TEOM monitor. The PM_{10} trend measurement for the

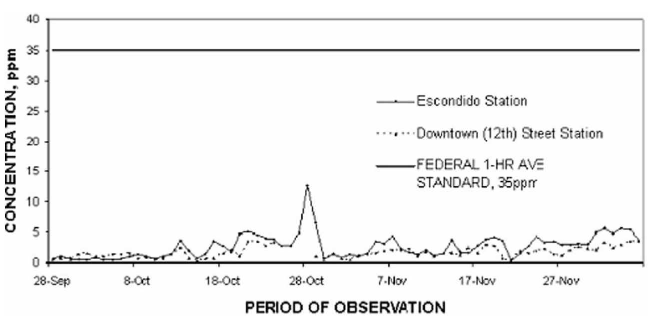

Figure 5. CO federal 1-hr average standard measurements during the surveillance period.

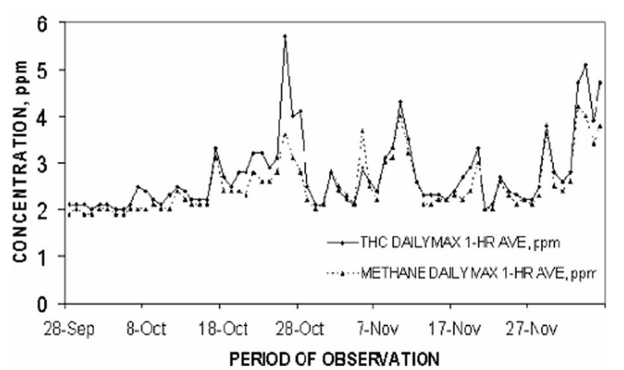

Figure 7. CH_4 and total THC measurement at the Overland station (Kearny Mesa) during the surveillance period.

Figure 8. Photograph of the localized turbulence near the fire.

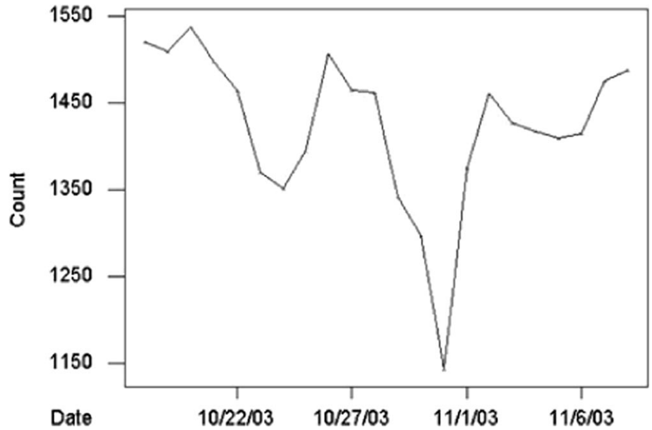

Figure 10. Time-series plot for total visits (interval: October 18–November 8, 2003).

Alpine station is shown in Figure 3. There was no real-time measurement recorded between October 27 and November 2, 2003, because power supply to the Alpine monitoring station was interrupted by the fire. Just before data recording was lost, the trend showed a steady increase, although it did not reach the maximum 24-hr average federal standard of 150 $\mu g/m^3$. However, the FRM PM_{10} measurement from the Escondido station recorded 179 $\mu g/m^3$ on October 29, 2003. This level exceeded the federal maximum 24-hr average limit. Therefore, it could be inferred that if the Alpine real time monitor was functional at that time, it would have recorded a much higher concentration because of its close proximity to the fire. Real-time measurement indicated an unusually high concentration of PM_{10} on November 23 and 27, 2003, at 294 $\mu g/m^3$ and 184 $\mu g/m^3$, respectively. This was because of the Santa Ana wind condition during that time frame. The strong offshore wind direction stirred and carried the ashes deposited in the burned areas.

Gaseous Pollutants

Three gaseous pollutants of concern namely O_3, CO, and NO_2 were analyzed at the Escondido and downtown (Twelfth Avenue) stations based on data recorded by the station monitoring equipment. No data were available between October 25 and October 28, 2003, the period when the fires were burning. The station equipment monitoring these parameters was powered down to support construction efforts of the ballpark nearby.

O_3. The O_3 trend during the observation period is shown in Figure 4. Throughout the surveillance period, the federal 1-hr O_3 concentration of 0.12 ppm was not exceeded on either the Escondido or downtown station. The trend showed a relative decrease in concentration after the start of the fire and continued until the end of the surveillance period.

CO. The CO trend during the surveillance period at the Escondido and downtown stations is shown in Figure 5. Recorded data showed that CO concentrations before, during, and after the fire were well below and did not exceed the federal 1-hr standard of 35 ppm. However, on October 28, 2003, the state and federal 8-hr standard was exceeded by 1.6 ppm over the 9-ppm maximum.

NO_2. The NO_2 trend during the surveillance period in Escondido station is shown in Figure 6. There is no federal 1-hr maximum concentration for NO_2. However, the state of California mandates a 1-hr maximum concentration

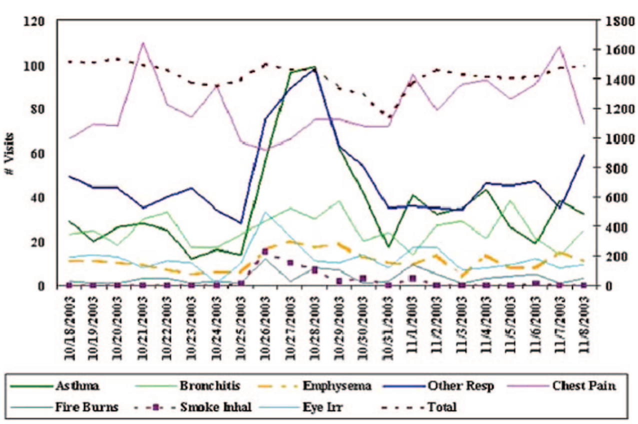

Figure 9. Frequency of selected types of visits to San Diego hospital EDs.

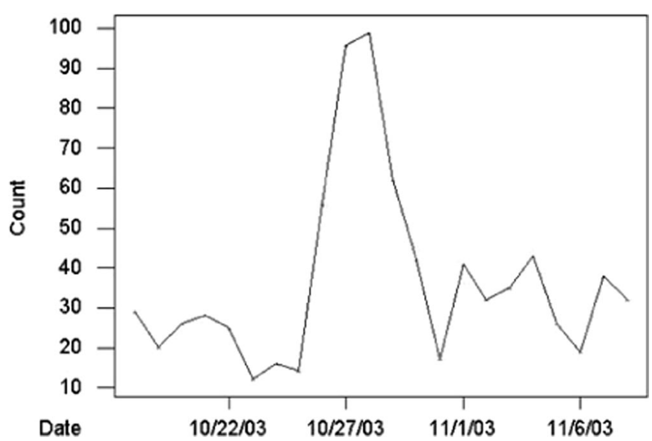

Figure 11. Time-series plot for asthma. (interval: October 18–November 8, 2005)

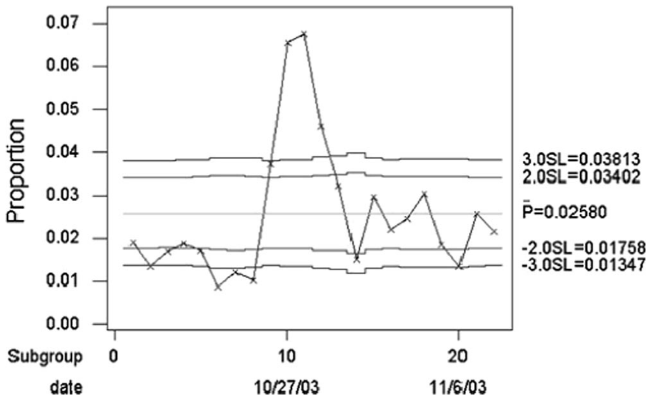

Figure 12. P-chart plot for asthma (interval: October 18–November 8, 2003).

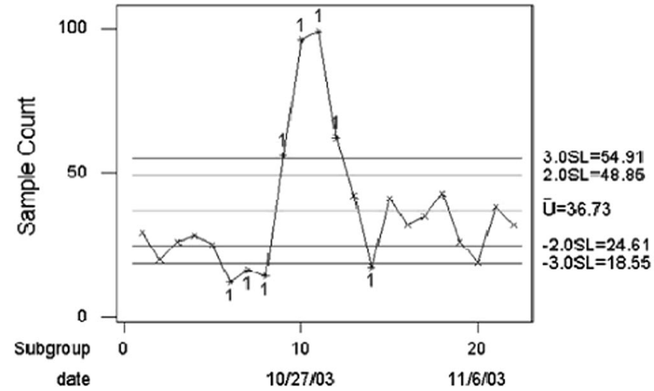

Figure 13. U-chart plot for asthma (interval: October 18–November 8, 2003).

level for NO_2 of 0.25 ppm. Recorded data showed that NO_2 concentrations before, during, and after the fire did not exceed the California state 1-hr standard of 0.25 ppm in both the Escondido and downtown stations.

CH_4 and THC. The CH_4 and THC trend during the surveillance period is shown in Figure 7. The Overland Avenue station is the station closest to the Cedar Fire in which CH_4 and THC were measured.

Meteorological Influence

The San Diego APCD forecasted for a moderate level of $PM_{2.5}$ throughout the county from Saturday, October 25, 2003, through Sunday, October 26, 2003, because of the Santa Ana winds. Santa Ana winds are warm, dry winds that blow from the east (offshore) and have wind speeds >25 knots (12.9 m/sec). The Cedar Fire began at ~5:30 p.m. on Saturday, October 25, 2003. On Saturday evening, at ~7:30 p.m., data recorded by the San Diego APCD RWP indicated a wind direction shift that was consistent with Santa Ana condition.

Although on October 26, 2003, the fire was driven in the southwest direction by the Santa Ana winds, there was no significant surface smoke impact except in the areas immediately around the fire. The wind condition near the coast was not strong. The Point Loma RASS recorded a shallow mixed layer during the morning followed by a weak neutral atmosphere later in the day. These conditions were not conducive to heavy smoke impacts at the surface level from a lofted plume of smoke.

As the first full day of the fire progressed on October 26, 2003, conditions in the close proximity of the fire recorded a different result. Throughout the morning, the fire advanced rapidly in a southwesterly direction and burned the heavily populated communities of Poway, Miramar, and Tierrasanta. Flames and a vortex of heavy smoke prevailed in the vicinity of the fires, particularly downwind and on the leading edge of the fire. Figure 8 shows the localized turbulent condition as the wind fanned the fire. In addition, the intense fire produced its own circulation, an indication of a firestorm.

The Santa Ana wind condition decreased in strength toward the end of the day on October 26, 2003. Consequently, the westward progression of the fire was either stopped or was put under control. At dawn of October 27, 2003, the fire progression was shifted toward the east, away from major population centers and into the mountain communities. Data recorded on October 27, 2003, showed offshore winds aloft during the first half of the day followed by a turning of the winds to weak onshore in the early afternoon and then general stagnation conditions during the evening and nighttime. At the same time, the recorded data showed an isothermal atmosphere during the early morning with surface-based inversion forming later in the day. These meteorological conditions were more conducive to trapping smoke in the surface layer.

On October 28, 2003, the data recorded showed wind conditions becoming stagnant during the day with low-level winds becoming southerly in the evening. The data also showed a surface-based inversion during most of the day. These stable conditions were conducive for trapping the smoke in the surface layer. Even as the fires continued burning eastward into the more rural areas of the county, satellite imaging taken by the National Oceanographic and Atmospheric Administration showed an abrupt stop and slow smoke movement offshore.

Data recorded on Wednesday, October 29, 2003, showed southerly winds in the low levels during the early morning hours, turning to offshore during the day and south-southwest and southerly winds at night. For the same day, the recorded data showed a shallow marine layer capped by an inversion that lifted during the day and dissipated at night. These conditions were consistent with air mass change and improved air quality conditions. Although the fires continued to burn in the inland, mountain areas of the county, similar meteorological conditions continued until the fire was out on November 4, 2003.

Medical Surveillance

During the surveillance period, 15 of the 19 hospitals (79%) participated by providing the following surveillance information from October 18 through November 8, 2003: (1) number of patients admitted to the hospital; (2) date of admission; and (3) type of medical problems encountered (asthma, bronchitis, emphysema, other respiratory problems, and/or chest pain).

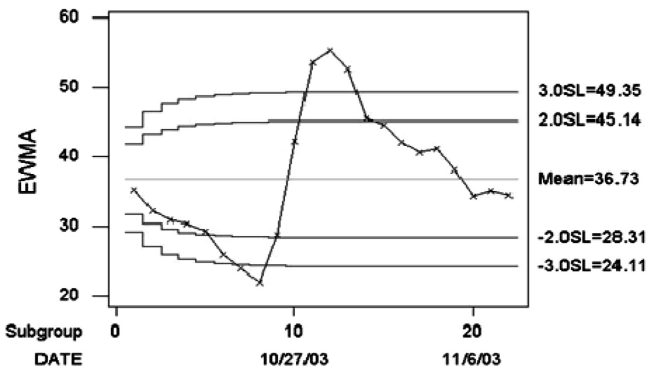

Figure 14. EWMA plot for asthma (interval: October 18–November 8, 2003).

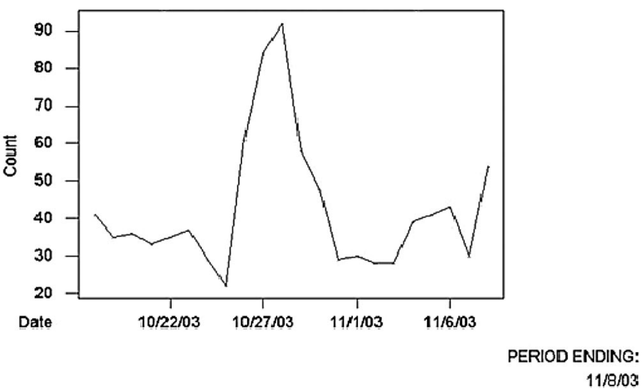

Figure 15. Time-series plot for other respiratory conditions with no fever (interval October 18–November 8, 2003).

The participating hospitals represented geographic diverse locations and included several hospitals near the fire-impacted areas. As seen in Figure 9, several of the surveillance indicators increased significantly during the periods of the fire. The most dramatic increase was asthma and other respiratory complaints with no fever. Each of the surveillance indicators is additionally described below.

Total Visits. The impact of the fires on area ED visits varied across hospitals. In total, information on 31,321 visits was recorded and analyzed. For the surveillance time period, the mean number of cases was 1423 visits per day among 15 hospitals. In general, the total number of ED visits declined (Figure 10) during selected periods of the fire. The day with the minimum number of total visits was October 31, 2003. The period of greatest decrease in total volume of patients corresponds with the days that the schools and employees were asked to remain at home (October 27–31, 2003). When the total visits were analyzed using the EWMA method, the mean number of total visits continued to remain lower for over a week after the fires began. During this period, the moving average decreased substantially.

Asthma. Several respiratory indicators were monitored at EDs throughout the county, and related visits were assessed. In general, each of the respiratory indicators demonstrated significant increases during the fire period with expected postfire levels approaching prefire levels with the decline in the fires and subsequent improvement in air quality.

Asthma-related visits increased significantly, particularly during the days of greatest fire burn and unhealthy air quality. Both the total number of asthma visits and the proportion of asthma visits increased. These increases correspond well with the increases in the air quality index. Figure 11 displays the number of asthma-related visits over time with the days of greatest number of asthma-related visits occurring on Tuesday, October 28. Controlling for the total number of visits, Figure 12 includes the proportion of asthma-related visits during the surveillance period. Additional information about the asthma-related results are detailed in Figures 13 and 14.

Bronchitis. Bronchitis-related visits were monitored, and they showed a slight increase during the surveillance period when they were measured using the same methodology as the one used for asthma-related cases. The mean number of cases across all of the participating hospitals was 25 per day. Although a slight increase in bronchitis-related visits was noted in each of the analyses, the increase was neither significant nor sustained.

Other Respiratory with No Fever. The surveillance category for other respiratory illness/problems with no fever-related visits were analyzed. The intention of this indicator was to track people with a multitude of respiratory-related symptoms not previously identified as asthma, bronchitis, or respiratory illness that occur along with fever, such as influenza and pneumonia. A dramatic increase in visits with complaints primarily associated with the other respiratory illnesses without fever observed after the beginning of fires on October 25 is likely a direct result of the increasingly poor air quality. Analysis of this indicator reveals that both the total number of visits and the proportion of visits increased significantly, particularly during the days of greatest fire burn and ash fallout (Figures 15 and 16, respectively).

Smoke Inhalation. Because of the large area of fire burn in both densely and rural populated areas, it was expected

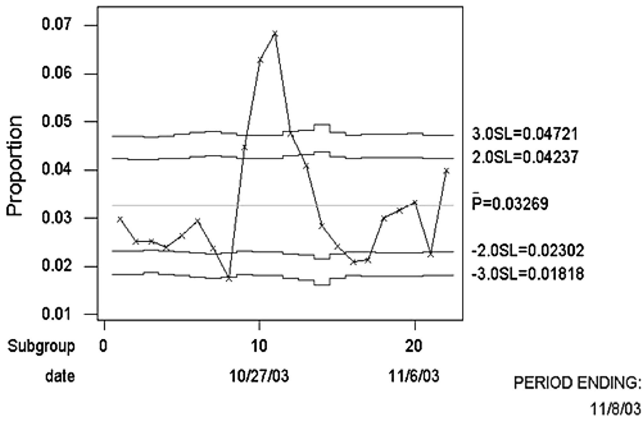

Figure 16. P-chart plot for other respiratory conditions with no fever.

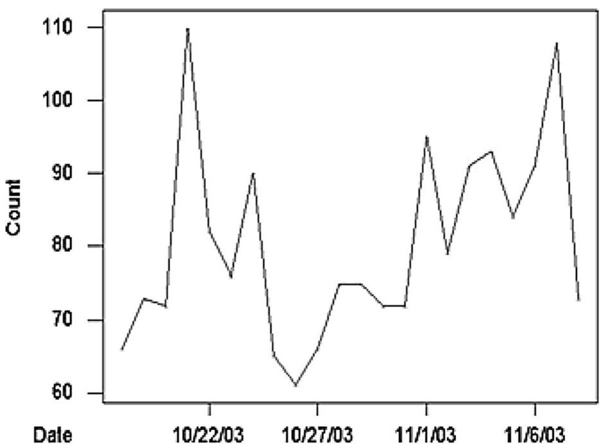

Figure 17. Time series plot for chest pain or cardiac arrest (interval October 18–November 8, 2003).

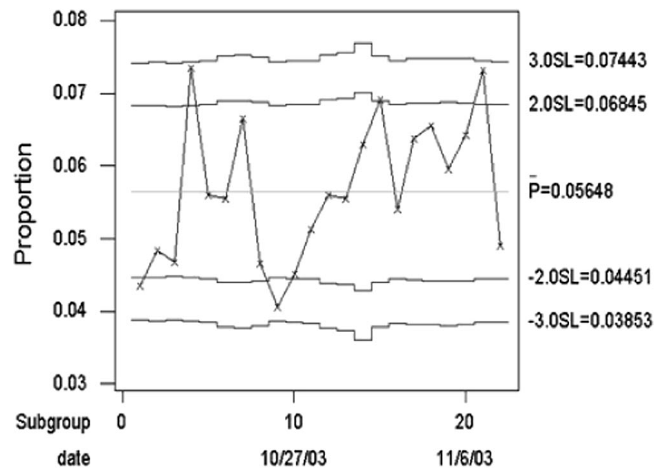

Figure 18. P-chart plot for chest pain or cardiac arrest (interval October 18–November 8, 2003).

that hospitals would experience a number of patients with smoke inhalation. Although the overall number of smoke inhalation-related visits across participating hospitals was small each day during the surveillance period, smoke inhalation-related visits increased markedly. Both the total number of smoke inhalation visits and the proportion of visits increased for a brief period during the periods of greatest fire burn.

Eye Irritation. Because of several days of large ash fall throughout San Diego County, it was expected that a number of patients would seek treatment for eye irritation at EDs. The indicator for eye irritation was analyzed. Although very few patients experiencing eye irritation problems were reported during the prefire period, a brief increase in those with eye irritation occurred during the days of greatest fire burn and ash fallout.

Chest Pain/Cardiac Arrest. Because of the uncertainty of determining how the fire and air quality would impact patients suffering from chest pain or cardiac arrest, an indicator was selected to assess the same during the surveillance period. The indicator for chest pain was analyzed. As seen in Figures 17 and 18, the number of chest pain and cardiac arrest visits does not appear to have noticeably increased as a result of the fire. Figure 19 describes the U-chart and Figure 20 describes the EWMA during this time. Although the time period is limited to ~3 weeks, it is difficult to determine whether this pattern is typical during nonfire periods.

Diarrhea/Gastroenteritis. During the fires, selected parts of the county were without power for several days. Because of the increased chance of people consuming spoiled food or contaminated water, an indicator for diarrhea/gastroenteritis was monitored. This indicator was analyzed using the same criteria explained before. In general, diarrhea-related visits during this surveillance period did not increase or decrease from the usual trend.

Sources and Estimated Amount of Emissions

The estimated prefire fuel loading for the Cedar and Paradise fires, the predominant fires that occurred about the same time, is shown in Table 2. Table 3 shows the estimated emission amounts of selected pollutants. The data

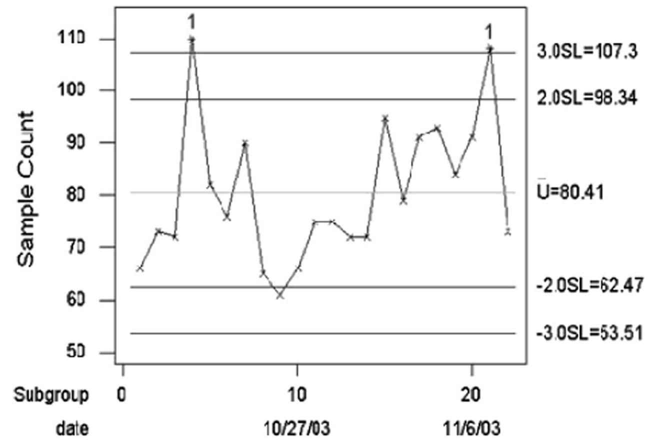

Figure 19. U-chart plot for chest pain or cardiac arrest (interval October 18–November 8, 2003).

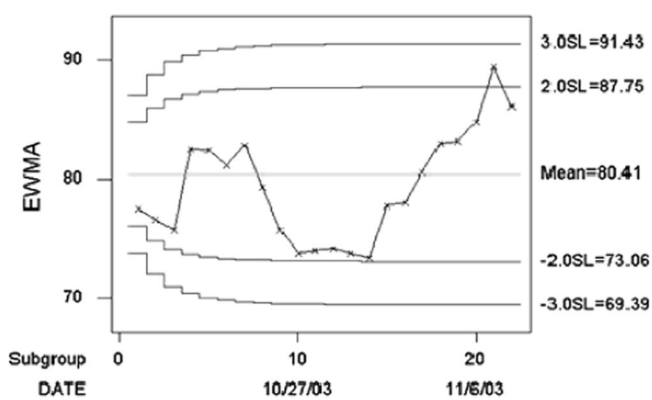

Figure 20. EWMA plot for chest pain or cardiac arrest (interval October 18–November 8, 2003).

Table 2. Estimated prefire fuel loading in tons.

Fuel Component	Paradise Fire	Cedar Fire	Total Both Fires
Canopy branch wood	0	12,104	12,104
Canopy foliage	0	85,399	85,399
Duff	86,059	509,287	595,346
Herbs	6562	43,983	50,545
Litter	27,458	151,329	178,814
Regen	286	3447	3733
Shrubs	321,020	1,585,703	1,906,723
Wood 0–1 inch	2861	23,483	26,344
Wood 1–3 inch	0	12,115	12,115
Wood >3 inches	0	87,059	87,059
Total all fuel types	444,246	2,513,909	2,958,155

output for preburn conditions and emissions tabulated in Tables 2 and 3 was based on the Cedar and Paradise fire perimeter input and processed by the FOFEM. The model determined the emissions based on the moisture content of the fuel and the moisture in the burning environment and the preburn fuel loading from the fuel models.[3]

CONCLUSIONS

On the first full day of the San Diego Wildfire on October 26, 2003, the Overland Avenue station recorded the highest THC concentration level, about twice the average concentration of the period before the fire. THC is a precursor to the formation of ground-level O_3. However, the meteorological condition during this phase of the fire progression was such that the heavy smoke produced by the fire was allowed to rise and blanket the entire county. Photochemical reaction provided by sunlight did not happen. Therefore, O_3 levels on this day and subsequent days during the fire remained below the allowable levels set by EPA at 0.12 ppm.

The CO concentration level rose by 250% on October 28, 2003, at the Escondido station, the highest recorded level during the fire and during the surveillance period, which slightly exceeded the state and federal 8-hr average. There was a 100% increase in the NO_2 level recorded on October 28, 2003, at the Escondido station. However, this level is within the allowable limit of 0.25 ppm according to the California state daily maximum 1-hr average standard. Although there were no data available on O_3, CO, and NO_2 at the downtown station on October 25–28, 2003, other stations that monitor these pollutants of concern did not record concentrations that exceeded the allowable limits during the entire period that the downtown station was offline.

Table 3. Emissions mass estimate totals, in tons.

Pollutant	Paradise Fire	Cedar Fire	Total Both Fires
PM_{10}	3951	22,610	26,561
$PM_{2.5}$	3,354	19,188	22,542
CO	38,963	222,190	261,153
CH_4	1558	8886	10,444
TNMHC	2727	15,549	18,276
NH_3	388	2221	2609
N_2O	69	399	468
NO_x	1198	6958	8156
SO_2	371	2147	2518

TNMHC = total non-CH_4 hydrocarbon.

The meteorological condition that allowed the heavy smoke to lift and create a thick blanket that turned day almost into night let the PMs settle over most of the county. Consequently, the downtown and Escondido stations recorded the highest level of $PM_{2.5}$ concentration. The downtown station recorded a $PM_{2.5}$ concentration of 104.6 $\mu g/m^3$ on the first full day of the fire on October 26, 2003, and 170.1 $\mu g/m^3$ on October 27, 2003. The Escondido station recorded a 69.2 $\mu g/m^3$ $PM_{2.5}$ concentration on October 27, 2003. All of these readings exceeded the federal daily maximum 24-hr average.

The ability of the fire to create a localized weather condition, such as a different wind pattern from the general prevailing condition, suggests that actual levels of pollutants in random points within the surveillance area may vary from measured levels recorded by the monitoring stations. During the fire, actual air quality depended on where one was located in the affected areas of the county. This also accounted for the variance in the concentration levels above the allowable range for those pollutants that exceeded established standards as recorded in different monitoring stations.

Meteorological conditions that allowed for massive air mass change, such as that which began to prevail on October 29, 2003, during the fire, helped mitigate the effects of pollutants to affected areas. This was indicated by the decrease in concentration of pollutants to allowable levels and the decrease in ED admissions during the surveillance period.

The total number of ED visits declined during the period of the fire, and these correspond with the days that the school children and employees were asked to remain at home. In addition, many roads and freeways were closed because of the fires. Each of these is likely to have influenced the behavior of people seeking treatment or refuge at local EDs. These results presented in the medical surveillance demonstrated that selected increases in certain types of ED visits did occur during this period. Particularly, selected respiratory-related conditions increased significantly. Communication with various medical providers during the fires indicated that the ash, smoke, and unhealthy air quality resulted in an increase in asthma-related medical visits and inquiries.

There are a number of limitations associated with an assessment related to the disaster. The medical surveillance was primarily based on the chief complaint of the patient on arrival at the ED. Because this is not the final diagnosis of the patient's reason for visit, it is possible, although unlikely, that the final results may have been slightly different from that presented by this study. Additional studies are needed to additionally assess the impact of the fire on ED utilization trends, long-term impact of the fire on health outcomes, and the effect of a local disaster on health service options.

The results indicated that there was a direct correlation between the increase in PM, specifically $PM_{2.5}$, concentration level and the significant increase in ED visits for asthma, other respiratory with no fever, eye irritation, and smoke inhalation. The pattern for increase in emergency visits for asthma was consistent with documented studies from previous wildfires[36] in which there was a 1–1.5-day lag between the periods of exposure to high concentrations of PM from wildfires to the actual time of admission.

The FOFEM results indicated that shrubs and duff were the predominant sources of combustion, totaling ~2.5 million t or ~85% of the fuel components of the San Diego wildfire. Clearly, these were catastrophic fire events that burned, for the most part, in chaparral and other shrub-dominated ecosystems.[3]

RECOMMENDATIONS

The following recommendations are made in the event a similar catastrophe occurs in the future: (1) improve the capability of accurate real-time monitoring of PMs, because it is the pollutant of concern that has an immediate impact on the health of county residents; mobile monitoring capability is an added resource, because it can better assess the actual condition independent of prevailing meteorological condition; (2) encourage hospitals and emergency medical facilities to engage in preevent planning that would ensure a rapid response to an impact on the healthcare system as a result of a large wildfire; and (3) use all available meteorological forecasting resources, including real-time satellite imaging assets to accurately forecast air quality, assist firefighting efforts, and mobilize emergency service providers.

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REFERENCES

1. County of San Diego Assessment Team. October Wildfires Damage Assessment Update 2003; available on County of San Diego Web site, http://www.co.san-diego.ca.us/enterprise_portal/announcements/damageupdate.pdf (accessed December 16, 2005).
2. Downey, D. Firestorm 2003: The Story of a Catastrophe. Available at http://www.nctimes.com (accessed 2004).
3. Clinton, N., Scott, K., Gong, P. *Southern California Fires-GIS Estimation of Fuels and Air Quality Impacts*; University of California-Berkeley: Berkeley, CA, 2003.
4. Bobak, M.; Leon, D.A. Air Pollution and Infant Mortality in the Czech Republic, 1986–88; *Lancet* **1992**, *340,* 1010-1014.
5. Dejmek, J.; Selevan, S.G.; Ivan Benes, I.; Sram, R.J. Fetal Growth and Maternal Exposure to Particulate Matter During Pregnancy; *Environ. Health Perspect.* **1999**, *107*, 475-480.
6. Bobak, M. Outdoor Air Pollution, Low Birth Weight, and Prematurity; *Environ. Health Perspect.* **2000**, *108,* 173-176.
7. Ritz, B.; Yu, F.; Fruin, S.; Chapa, G.; Shaw, G.M.; Harris, J.A. Ambient Air Pollution and Risk of Birth Defects in Southern California; *Am. J. Epidemiol.* **2002**, *155*, 17-25.
8. Ha, E.H.; Lee, B.E.; Park, H.S.; Kim, Y.J.; Hong, Y.C.; Kim, H.; Lee, J.T. Exposure to Air Pollution during Different Gestational Phases Contributes to Risks of the Low Birth Weight; *Hum. Reprod.* **2003**, *18*, 638-643.
9. Heinrich, J.; Hoelscher, B.; Wichmann, H.E. Decline of Ambient Pollution and Respiratory Symptoms in Children; *Am. J. Respir. Crit. Care Med.* **2000**, *161*, 1930-1936.
10. Dockery, D.W.; Cunningham, J.; Damokosh, A.I.; Neas, L.M.; Spengler, J.D.; Koutrakis, P.; Ware, J.S.; Raizenne, M.; Speizer, F.E. Health Effects of Acid Aerosols on North American Children: Respiratory Symptoms; *Environ. Health Perspect.* **1996**, *104*, 500-505.
11. Braun-Fahrlander, C.; Vuille, J.C.; Sennhauser, F.H.; Neu, U.; Kunzle, T.; Grize, L.; Gassner, M.; Minder, C.; Schindler, C.; Varonier, H.S.; Wuthrich, B. Respiratory Health and Long-Term Exposure to air Pollutants in Swiss Schoolchildren: SCARPOL Team: Swiss Study on Childhood Allergy and Respiratory Symptoms with Respect to Air Pollution, Climate and Pollen; *Am. J. Respir. Crit. Care Med.* **1997**, *155*, 1042-1049.
12. Dockery, D.W.; Speizer, F.E.; Stram, D.O.; Ware, J.H.; Spengler, J.D.; Ferris, B.G. Jr. Effects of Inhalable Particles on Respiratory Health of Children; *Am. Rev. Respir. Dis.* **1989**, *139*, 587-594.
13. McConnell, R.; Berhane, K.; Gilliland, F.; London, S.J.; Vora, H.; Avol, E.; Gauderman, W.J.; Margolis, H.G.; Lurmann, F.; Thomas, D.C.; Peters, J.M. Air Pollution and Bronchitic Symptoms in Southern California Children with Asthma; *Environ. Health Perspect.* **1999**, *107*, 757-760.
14. Jedrychowski, W.; Flak, E. Effects of Air Quality on Chronic Respiratory Symptoms Adjusted for Allergy Among Preadolescent Children; *Eur. Respir. J.* **1998**, *11*, 1312-1318.
15. Ward, T.J.; Smith, G.C. Air Sampling Study of the 2000 Montana Wildfire Season; University of Montana: Missoula, MT, 2000; Paper #1131.
16. Dennis, A.; Allen, D.; Fraser, M.; Anderson, S. Air Pollutant Emissions Associated with Forest, Grassland, and Agricultural Burning in Texas; *Atmos. Environ.* **2002**, *36*, 3779-3792.
17. Koe, L.C.C., Arellano, A.F.; McGregor, J.L. Investigating the Haze Transport from 1997 Biomass Burning in Southeast Asia: Its Impact upon Singapore; *Atmos. Environ.* **2000**, *35*, 2723-2734.
18. Mukherjee, P.; Viswanathan, S. Contributions to CO Concentrations from Biomass Burning and Traffic during Haze Episodes in Singapore; *Atmos. Environ.* **2001**, *35*, 715-725.
19. Le Tertre, A.; Medina, S.; Samoli, E.; Forsberg, B.; Michelozzi, P.; Baumghar, A.; Vonk, J.M.; Bellini, A.; Atkinson, R.; Ayres, J.G.; Sunyer, J.; Schwartz, J.; Katsouyanni, K. Sort-Term Effects of Particulate Air Pollution on Cardiovascular Diseases in Eight European Cities; *J. Epidemiol. Comm. Health* **2002**, *56*, 773-779.
20. Peters, A.; Doring, A.; Wichman, H.E.; Koenig, W. Increased Plasma Viscosity during an Air Pollution Episode: A Link to Mortality? *Lancet* **1997**, *349*, 1582-1587.
21. Pope, C.A.; Dockery, D.W.; Kanner, R.E.; Villegas, M.G.; Schwartz, J;. Oxygen Saturation, Pulse Rate, and Particulate Air Pollution; *Am. J. Crit. Care Med.* **1999**, *159*, 365-372.
22. Pope, C.A. III, Verrier, R.L.; Lovett, R.G.; Larson, A.C.; Raizenne, M.E.; Schwartz, J.; Villegas, G.M.; Gold, D.R.; Dockery, D.W. Heart Rate Variability Associated with Particulate Air Pollution; *Am. Heart J.* **1998**, *138*, 890-899.
23. Liao, D.; Creason, J.; Shy, C.; Williams, Ron, Watts, R.; Zweidinger, R. Daily Variation of Particulate Air Pollution and Poor Cardiac Autonomic Control in the Elderly; *Environ. Health Perspect.* **1999** *107*, 521-525.
24. Gold, D.R.; Litonjua, A.; Schwartz, J.; Lovett, E.; Larson, A.; Nearing, B.; Allen, G.; Verrier, M.; Cherry, R.; Verrier, R. Ambient Pollution and Heart Rate Variability; *Circulation* **1999**, *101*, 1267-1273.
25. Peters, A.; Dockery, D.W.; Muller, J.E.; Mittleman, M.A. Increased Particulate Air Pollution and the Triggering of Myocardial Infarction; *Circulation* **2001**, *103*, 2810-2815.
26. Ghio, A.J.; Kim, C.; Devlin, R.B. Concentrated Ambient Air Particles Induce Mild Pulmonary Inflammation in Health Human Volunteers; *Am. J. Crit. Care Med.* **2000**, *162*, 981-988.
27. Pope, C.A. III, Burnett, R.T.; Thun, M.J.; Calle, E.E.; Krewski, D.; Ito, K.; Thurston, G.D. Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Air Pollution; *J. Am. Med. Assoc.* **2002**, *287*, 1132-1141.
28. Norris, G.; YoungPong, S.N.; Koenig, J.Q.; Larson, T.V.; Sheppard, L.; Stout, J.W. An Association Between Fine Particles and Asthma Emergency Department Visits for Children in Seattle; *Environ. Health Perspect.* **1999**, *107*, 489-493.
29. Pope, C.A. III. Respiratory Hospital Admissions Associated with PM_{10} Pollution in Utah, Salt Lake, and Cache Valleys. *Arch. Environ. Health* **1991**, *46*, 90-97.
30. Atkinson, R.W.; Anderson, H.R.; Sunyer, J.; Ayres, J.; Baccini, M.; Vonk, J.M. Boumghar, A.; Forastiere, F.; Forsberg, B.; Touloumi, G. Acute Effects of Particulate Air Pollution on Respiratory Admissions: Results from APHEA 2 Project: Air Pollution and Health: A European Approach; *Am. J. Respir. Crit. Care Med.* **2001**, *164,* 1860-1866.
31. Pope, C.A. III, Dockery, D.W.; Spengler, J.D.; Raizenne, M.E. Respiratory Health and PM_{10} Pollution: A Daily Time Series Analysis; *Am. Rev. Respir. Dis.* **1991**, *144*, 668-674.
32. Romieu, I.; Meneses, F.; Ruiz, S.; Sienra, J.J.; Huerta, J.; White, M.C.; Etzel, R.A. Effects of Air Pollution on the Respiratory Health of Asthmatic Children Living in Mexico City; *Am. J. Respir. Crit. Care Med.* **1996**, *154*, 300-307.
33. Delfino, R.J.; Zeiger, R.S.; Seltzer, J.M.; Street, D.H. Symptoms in Pediatric Asthmatics and Air Pollution: Differences in Effects by Symptom Severity, Anti-Inflammatory Medication Use and Particulate Averaging Time; *Environ. Health Perspect.* **1998**, *106*, 751-761.
34. Vedal, S.; Petkau, J.; White, R.; Blair, J. Acute Effects of Ambient Inhalable Particles in Asthmatic and Nonasthmatic Children; *Am. J. Respir. Crit. Care Med.* **1998**, *157*, 1034-1043.
35. Yu, O.; Sheppard, L.; Lumley, T.; Koenig, J.Q.; Shapiro, G.G. Effects of Ambient Air Pollution on Symptoms of Asthma in Seattle-Area Children Enrolled in the CAMP Study; *Environ. Health Perspect.* **2000**, *108*, 1209-1214.

36. Zweiman, B. *Wildfires and Asthma Flares*; American Academy of Allergy, Asthma and Immunology: Milwaukee, WI, 2001.
37. Particulate Matter. Available on U.S. Environmental Protection Agency Web site, http://www.epa.gov/oar/aqtrnd97/brochure/pm10.html (accessed December 13, 2005).
38. Zhang, J.; Morawska, L. Combustion Sources of Particles: 2. Emission Factors and Measurement Methods; *Chemosphere* **2001**, *49*, 1059-1074.
39. Chow, J.C.; Watson, J.G.; Englebrecht, J.; Fujita, E.M.; Wilson, W.E. Receptor Modeling Application Framework for Particle Source Apportionment; *Chemosphere* **2002**, *49*, 1093-1136.
40. Air Quality in 2002 Report; San Diego Air Pollution Control District, San Diego, CA, 2003.

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