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Exposure Assessment of Asthma and Modeling of PM2.5 during the 2007 Southern California Wildfires

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EXPOSURE ASSESSMENT OF ASTHMA AND MODELING OF PM$_{2.5}$ DURING
THE 2007 SOUTHERN CALIFORNIA WILDFIRES

A Thesis

Presented to

The Faculty of the Department of Meteorology and Climate Science

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In Partial Fulfillment

of the Requirements of the Degree

Master of Science

by

Areana Flores

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The Designated Thesis Committee Approves the Thesis Titled

EXPOSURE ASSESSMENT OF ASTHMA AND MODELING OF PM$_{2.5}$ DURING THE 2007 SOUTHERN CALIFORNIA WILDFIRES

By

Areana Flores

APPROVED FOR THE DEPARTMENT OF METEOROLOGY AND CLIMATE SCIENCE

SAN JOSÉ STATE UNIVERSITY

December 2016

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ABSTRACT

EXPOSURE ASSESSMENT OF ASTHMA AND MODELING OF PM$_{2.5}$ DURING
THE 2007 SOUTHERN CALIFORNIA WILDFIRES

By Areana Flores

A three-year study (1 Jan 07 to 31 Dec 09) was conducted for Los Angeles and
Riverside counties to validate current findings on impacts of wildfires on respiratory
health. A dataset developed from multiple sources containing daily rates of air pollution
(O_3, NO_2, CO, and PM$_{2.5}$) and meteorological variables (temperature, dew point, wind
speed, and inversion height) was correlated with asthma emergency department (ED)
visits. A second correlation was calculated for a modified dataset that excludes all
episodes of wildfire events within the study period. The difference in correlations
between both datasets was computed. PM$_{2.5}$ was positively associated with asthma ED
visits during Fall 2007 and its correlation differed significantly between the original and
modified datasets. Using CALMET/CALPUFF/WRF from BlueSky's air modeling
framework, the October 2007 wildfires in Southern California were simulated to evaluate
and assess the accuracy of PM$_{2.5}$ concentrations produced by the models. WRF
meteorological fields were used as a first guess for input to the CALMET diagnostic
meteorological model. This study attempts to improve on the Jackson et al. 2006 study by
using a CALMET/WRF hybrid, as WRF is a more physically advanced model than
MM5. A sensitivity analysis was performed for the four terrain adjustment schemes. In
conclusion, results from this model framework proved to be accurate within 10 µg/m³ on
October 24th for all schemes, but varied for other dates. After October 26th, PM$_{2.5}$
underestimations may have resulted from excluding emissions from San Diego wildfires.

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I also want to thank my coworker Dr. Tzu-Sai Soong who not only took his time to reviewed and advised me on my thesis, but gave me wise words of encouragement "You are young, you have many more years ahead of you so take your time and don't stress. There is no rush, just look at me (72-years old)."

Moving to a new city and getting through grad school would not have been easy if it wasn't for the constant support of Diana Centeno, Jack Keovongsa, Laura Hodgens, Kelly McDonnell, Trent Smith and family, and many others from the Meteorology and Climate Science Department.

Lastly, I want to thank my family for being understanding and supportive of my decisions to pursue higher education. My mother Elvira Flores, father Jose Flores, siblings Maura, Jose Jr., and Edgar. You guys are my backbone and continuous motivation.

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1. Introduction

Atmospheric conditions, including air quality and weather, influence the response of the human respiratory system. The frequency and duration of exposure to the detrimental effects of poor air quality depend on factors such as current weather conditions, location, topography, climate, and socioeconomic status. Continuous exposure to poor air quality has been linked to impairment of normal lung growth and development of diseases such as asthma (Peden 2005). Air pollutants and meteorological conditions have been found to be correlated with exacerbation of acute respiratory tract illnesses (Peden 2005), that can sometimes lead to emergency department (ED) visits or hospital admissions.

Asthma is a chronic inflammatory disorder of the airways characterized by repeated incidents of impaired breathing when the airways become congested. Approximately 26 million Americans are diagnosed with asthma, the third leading cause of hospitalization among children (American Lung Association 2014). Asthma episodes tend to occur with certain conditions and vary from one asthmatic to the next as well within the same individual over time. Common conditions, or triggers, of asthma attacks include physical activity, air pollution, infections, house dust, animal allergens, pollen allergens, and psychological factors such as watching an emotional film (Ritz et al. 2006).

During the autumn in Southern California, hot and dry westerly Santa Ana winds following a dry summer creates the optimal conditions for wildland fires. Fire season

varies yearly depending on weather patterns, moisture content, and vegetation present and usually ends with the onset of cooler weather and precipitation (Phuleria et al. 2005).

In the Fall of 2007, California endured wildfires that burned approximately 970,977 acres ("California Fire Siege 2007: An Overview" 2008). The strong, dry Santa Ana winds dispersed smoke plumes towards the Los Angeles basin, where a large urban population was exposed to elevated concentrations of air pollutants from the fires. Past results show that quantitatively the area burned per day is 3.5–4.5 times larger on Santa Ana days than on non-Santa Ana days with relative humidity having the strongest correlation with burned area per day (Billmire et al. 2014).

In general, the Los Angeles basin is a coastal lowland area, surrounded by high mountains. The topography and common temperature inversions lead to the accumulation of airborne pollutants, predominantly in the eastern region of the basin, due to the prevailing westerly sea breeze (Lu et al. 1996).

1.1 Weather Conditions on Air Quality and Health Effects

Meteorological conditions affect the oxidation of air pollutants in the atmosphere. Ozone concentrations peak in the summer months when temperatures are warmest and have been shown to exacerbate asthma (Cody et al. 1992). White et al. (1994), found that the average number of visits for children in Atlanta with asthma or reactive airway disease was 37% higher on the days following a 6-day period in which maximum ozone levels equaled or exceeded 0.11 ppm.

Atmospheric inversions during winter time trap pollutants, increasing the concentrations of particulate matter. The smallest particulates caused by wood burning

during this time penetrate deep in the lung triggering asthmatics. Passage of a cold front tends to be followed by stagnant, rain-free conditions which helps retain airborne particles and has resulted in asthma epidemics (Goldstein 1980). In three separate studies lower air temperature and lower absolute and relative humidity resulted in higher ED visits for asthma (Carey and Cordon 1986; Abe et al. 2009; Nastos et al. 2008). However, in a study by Mireku et al. (2009), significant increases in relative humidity and temperature were associated with additional ED visits for asthma.

After standardizing for temperature, NO_2 concentrations were found to be correlated significantly with hospital attendances for asthma (Rossi et al. 1993). Girsh et al. (1966), found a threefold increase of bronchial asthma in children in Philadelphia during "noteworthy" air pollution days, days during which pollutant concentration scored above the highest tenth percentile of scores observed during the 2-year study period. In addition, a fourfold increase in asthma hospital visitations occurred on days when barometric pressure exceeded 1020 hPa for a 24-hour period. When the conditions coincided, there was approximately a nine-fold increase in attacks for bronchial asthma.

1.2 Health Effects of Wildfires

Wildfires can have mental and physical effects on humans while also affecting the environment. For example, news of an inherently unpredictable force of nature in itself can induce psychosocial stress in the population (Kumagai et al. 2004). Pregnancy during a wildfire event can lead to slightly reduced average birth weight among infants exposed in utero (Holstius et al. 2012). Exposure to wildfire smoke is associated with

increased eye and respiratory symptoms, medication use, and physician visits (Künzli et al. 2006).

However, the most significant health-related pollutant from wildfire events is particulate matter (PM) (Naeher et al. 2007). Air pollutants released during a wildfire such as particulate matter with aerodynamic diameter of less than 10 µm (PM_{10}), fine particulate matter with aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$), carbon monoxide (CO), and sulfur dioxide (SO_2), can directly affect the respiratory system.

US Environmental Protection Agency (USEPA) set National Ambient Air Quality Standards (NAAQS) for PM_{10} in 1989 and more recently adopted new standards for primary and secondary $PM_{2.5}$ seen in Table 1. Most of the $PM_{2.5}$ mass consists of the condensed products of either atmospheric chemical reactions and incomplete combustion. Epidemiologic studies have shown a correlation between PM exposure and asthma exacerbation (Nemmar et al. 2002; Penttinene et al. 2001; Utell and Frampton 2000). Due to their small size, once inhaled they penetrate deep into the lungs whereas larger size PM ends up deposited in the upper airways. Inhaled ultrafine particles diffuse rapidly into the systematic circulation, inducing oxidative stress and mitochondrial damage, relevant for the cardiovascular morbidity and mortality related to ambient particle pollution (Li et al. 2003; Nemmar et al. 2002).

Concentrations of PM are higher during wildfire episodes and more toxic to the lung than PM collected from normal ambient air in the same region (Wegesser et al. 2009). One study found that during the 2003 Southern California wildfires (21-30 October), 2-day average $PM_{2.5}$ was associated with respiratory admissions that were

greater during than before or after the fires. Average increases of 70 μgm^{-3} $PM_{2.5}$ during

heavy smoke conditions compared with $PM_{2.5}$ in the pre-wildfire period were associated

with 34% increases in asthma admissions (Delfino et al. 2009). While the primary cause

for exacerbated asthma during a wildfire event is due to the air pollution effects,

comparing the possibilities mentioned earlier is scientifically complex when determining

quantitatively how wildfire pollution correlates to increased asthma exacerbations.

Table 1. NAAQS $PM_{2.5}$

Pollutant	Primary/Secondary	Averaging Time	Level	Form
$PM_{2.5}$	Primary	1 year	12.0 ug/m3	Annual mean, averaged over 3 years
	Secondary	1 year	15.0 ug/m3	Annual mean, averaged over 3 years
	Primary and secondary	24 hours	35 ug/m3	98th percentile, averaged over 3 years

1.3 Wildfire Modeling

In a separate 2003 Southern California wildfire study, Phuleria et al. (2005),

looked at averages of criteria pollutants in the Los Angeles basin before, during, and after

the wildfire outbreak and found that coarse-particle mass concentrations measured at

sampling sites downwind of the fires were 3-4 times higher than typical background

concentrations. This is one example of a method used to assess air quality impacts from

wildfires using ground observations. However, in order to evaluate pollutant

concentrations from fires separate from background levels, further analysis and modeling

is essential. Choi et al. (2007), presented a methodology that calculated PM by simulating

smoke plumes from agriculture burns using the CALPUFF/CALMET/MM5 modeling

system. Wiedinmyer et al. (2006), developed a modeling framework to estimate the

emissions from fires in North and parts of Central America by combining complementary satellite and ground-based data.

The BlueSky modeling framework offers numerous pathways for running third-party models for the production and simulation of emissions, transport, and chemistry of smoke from fires (Larkin et al. 2009). Weather model output and fire information is run through a sequence of modeling steps in order to generate smoke trajectory and concentrations. Strand et al. (2012), used the BlueSky Gateway modeling system to evaluate predictions of $PM_{2.5}$ surface concentrations during the 2007 Southern and 2008 Northern California fires. BlueSky has been coupled with SMARTFIRE (Raffuse et al. 2009), and SMOKE (Houyoux et al. 2000), in ongoing research for the US Forest Service, US EPA, and NOAA to improve the wildland fire emissions inventory (Pouliot et al. 2005; Sullivan et al. 2008).

1.4 Objectives and Study Design

A three-year study using data from 2007 to 2009 was conducted for the California counties of Los Angeles and Riverside. Given that air pollution is a trigger in respiratory sensitivity, this study focused on periods when air pollution concentrations were elevated to validate current findings between asthma exacerbation and $PM_{2.5}$. We first look for trends in county level population who required medical attention for asthma. A dataset that includes daily rates of air pollution and meteorological variables was correlated with asthma emergency department visits. A second correlation was calculated for a new dataset that excludes all episodes of wildfire events within the study period. All statistically significant differences in both datasets were noted.

Using the CALMET/CALPUFF/WRF pathway from BlueSky's air modeling framework, the October 2007 wildfires in Southern California were simulated to evaluate and assess the accuracy of $PM_{2.5}$ concentrations produced by the pathway. WRF meteorological fields were used as a first guess into the CALMET meteorological model, adjusting the meteorological fields to more realistically reflect land use and higher terrain. To further enhance the simulation, CALMET incorporates ground observations.

A previous study by Jackson et al. 2006 found that simulating ozone concentrations using the CALMET/MM5 hybrid resulted in better agreement with observed concentrations than those simulated using only MM5 generated inputs. This study attempts to improve on the Jackson et al. (2006), study by using a CALMET/WRF hybrid, as WRF is a more physically advanced model than MM5.

2. Methods: Statistics and Data

2.1 Exposure Assessment

Meteorological variables and criteria pollutants that have potential respiratory impact were considered to analyze emergency department (ED) visits due to asthma. The data used for the analysis included daily ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter with diameter less than 2.5 microns ($PM_{2.5}$), temperature, dew point, wind speed, inversion height, and asthma count per county.

Daily time series plots for each of the variables were evaluated for trends. Correlations between asthma and all variables were conducted for the entire period from 2007 through 2009, for each individual year, and for annual season where winter is December, January, February, spring is March, April, May, summer is June, July,

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August, and fall is September, October, November. The highest seasonal correlations were reviewed further. Los Angeles and Riverside counties were chosen for comparison based on the correlations and population density.

Wildfire events have the greatest short-term impact on air quality. Wildfires were strategically excluded from the dataset, which will now be known as the modified dataset, using set rules for open burn programs by the air district. Open burn programs in California are designed to ensure that open burning is conducted in a manner that minimizes emissions and impacts, and that smoke is managed consistent with state and federal law in order to protect public health and safety. Rule 444-Open Burning from South Coast Air Quality Management District (SCAQMD) states that the Executive Officer may allow the maximum daily burn acreage of 175 for prescribed wildland and range burning for all areas within the district jurisdiction. Using Rule 444 as a guide, all fires greater than 175 acres were eliminated from the dataset. This was conducted by excluding the rows whose date fell within that specific wildfire event, with some events overlapping. Correlations were once again re-calculated.

Wildfires that occurred between 2007 and 2009 and exposed significant threat to communities surrounding Los Angeles and Riverside counties transpired during the fall seasons (CAL FIRE). One such wildfire event occurred between 20 and 31 October 2007 burning more than 100,000 acres (Fig. 1). This time period was used in the modeling of wildfires and exposure assessment.

Fig. 1. NASA/MODIS Terra Satellite passing over Southern California 23 October 2007 1925 UTC.

2.2 Synoptic Weather Data

Daily weather maps from the National Centers for Environmental Predictions (NCEP) Weather Prediction Center were used for synoptic analysis of the observed meteorological conditions.

2.3 Data Sources

2.3.1 EPA-AQS

Criteria pollutant data acquired from the Air Quality System (AQS) database through the Environmental Protection Agency (EPA) included: daily max 1-hour nitrogen dioxide measured in parts per billion (NO_2) (ppb); daily max 8-hour ozone measured in parts per million (O_3) (ppm); and daily max 8-hour carbon monoxide measured in parts per million (CO) (ppm).

All measuring sites fall under the state or local air monitoring stations (SLAMS) network. The SLAMS network comprises of ambient air quality monitoring sites that are operated by state or local agencies for comparison to the NAAQS.

2.3.2 ARB-AQMIS

Maximum dew point temperature (°F) was acquired from the California Air Resources Board (ARB) Air Quality and Meteorological Information System (AQMIS) database. Meteorological data provided through ARB was collected from various outside sources and staff conducted preliminary quality assurance. Stations chosen for data retrieval were University of Southern California (USC), CA and Riverside Municipal Airport (RMA), CA. These sites best represented our area of study due to their central location in each county respectively.

2.3.3 NOAA-NCEI

Fastest 2-minute sustained wind speed (ms^{-1}) was retrieved from NOAA's National Centers for Environmental Information (NCEI) for the USC and RMA sites.

NCEI is responsible for hosting and providing access to comprehensive oceanic, atmospheric, and geophysical data. NCEI's Center for Weather and Climate acquires, preserves, monitors, and assesses historical weather data and information (NCEI, 2016).

2.3.4 NLDAS-CDC WONDER

Data obtained through The North America Land Data Assimilation System (NLDAS) from the Centers for Disease Control Wide-ranging Online Data for Epidemiologic Research (CDC WONDER) database included county-level maximum air temperature (°F) and outdoor daily average fine particulate matter (μgm^{-3}).

The modified regional surfacing algorithm of Al-Hamdan et al. (2009), used EPA AQS $PM_{2.5}$ measured in micrograms per cubic meter (μgm^{-3}) in-situ data and NASA MODIS aerosol optical depth remotely sensed data. Using a geographic information system (GIS) they identified the associated geographic locations of the centroids of the gridded $PM_{2.5}$ datasets, by county and state, to enable aggregation to different geographic levels in CDC WONDER. County-level data aggregated from 10-kilometer square spatial resolution grids were used. The data used in CDC WONDER were acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

2.3.5 UW-Department of Atmospheric Science

Raw radiosonde data from the University of Wyoming Department of Atmospheric Science was used to calculate the *inversion height*. The maximum mixing depth is calculated using the following equation:

$$IH = \frac{\Delta \theta}{\Delta Z} \tag{1}$$

where θ is potential temperature in degrees Kelvin and Z is geopotential height in meters. Radiosonde data produces a vertical profile of temperature, moisture and wind shear between 200 and 850 hPa. To understand the dispersion of pollutants in the lower atmosphere it is essential to determine the depth of the mixing layer where $\frac{\Delta \theta}{\Delta Z} > 0$, the height at which the atmospheric temperature reverses its profile. The greater the height, also known as the maximum mixing depth, the larger the volume of atmosphere that is available to dilute the pollutant concentration.

2.3.6 OSHPD

Data on emergency department (ED) visits for *asthma* by county, day, and type

for the years 2007 to 2009 for all ages was obtained from the Office of Statewide Health

Planning and Development (OSHPD) database. The ED data set includes information

from hospitals licensed to provide emergency medical services. The ED visits included

those patients who had face-to-face contact with the provider. Per legislation, hospitals

are required to report patient data to OSHPD using the Medical Information Reporting

for California manual to ensure quality of data. In healthcare, diagnoses codes are used to

classify diseases, illnesses and injuries known as the International Statistical

Classification of Diseases and Related Health Problems (ICD). For this study the type of

diagnoses for *asthma* with their respective ICD code were extrinsic (493.00, 493.01,

493.02), intrinsic (493.10, 493.11, 493.12), chronic (493.20, 493.21, 493.22), other

(493.81, 493.82), and unspecified (493.90, 493.91, 493.92). The daily sum for all types of

asthma was calculated and imported to the dataset.

2.4 Population Data Collection

Data on population estimates by county were obtained and produced by the State

of California Department of Finance Demographic Research Unit. The data file provides

population estimates by single years of age, gender, race for California and its counties.

These estimates were for the time period of July 1, 2000 through 2010. A baseline

cohort-component method was used to estimate population by age, gender, and race

(Department of Finance, 2012). The sum of population estimates was calculated per

county per year for the years 2007, 2008, and 2009.

2.5 Statistical Software

MATLAB version R2014a and the RHO=CORR (X, Y) function was used to perform a pairwise linear correlation coefficient between each pair of columns in the dataset.

In addition, the CORREL function under the EXCEL Data Analysis Tool was used. The correlation analysis tool examines each pair of measurement variables to determine whether the two measurement variables tend to move together — that is, whether large values of one variable tend to be associated with large values of the other (positive correlation), whether small values of one variable tend to be associated with large values of the other (negative correlation), or whether values of both variables tend to be unrelated (correlation near 0 (zero)). The value of any correlation coefficient must be between -1 and +1 inclusive.

A two-tail Pearson correlation significance test was performed to calculate *P*-values.

3. Methods: Modeling

3.1 Modeling Template

The BlueSky smoke modeling framework (Table 2), was utilized to model both the meteorology and pollutant dispersion and transport of the wildfires. BlueSky is a modular framework that integrates existing datasets and models into a uniform structure. It enables a user to compare models. If ran as a complete system, it needs meteorological data, fire location, and size to produce smoke concentrations and trajectories (Larkin et al. 2009). BlueSky has been adopted by various government agencies to predict smoke

from wildfires and has been used as a decision-making tool for prescribed burns. The framework has also been used for air quality forecasting.

BlueSky requires four-dimensional (x, y, z, t) meteorological information, daily fire growth, and fire location (longitude, latitude). Additional information can be manually inserted, overriding default model settings. Once fire information is loaded into the framework, fuel loadings and moisture conditions are determined, consumption is calculated, and the emissions from the consumption are speciated and allocated diurnally (Larkin et al. 2009). The results are then used to run the dispersion or trajectory models. The following sections describe the models used for the October 2007 wildfires as seen in Table 2.

Table 2. BlueSky Smoke Modeling Framework pathway

PATH NAME	MODEL
METEOROLOGY	Advanced Weather Research and Forecasting Model (WRF-ARW) v3.4 [Shamarock et al. 2008] CALMET [Scire et al. 2000b]
FIRE INFORMATION	US Incident Command System (ICS)-209 Incident Status Summary
FUEL LOADING	US National Fire Danger Rating Systems (NFDRS) [Cohen and Deeming 1985]
FUEL CONSUMED	Fire Emissions Production Simulator v1 (FEPS) [Anderson et al., 2004]
TIME PROFILE	FEPS
EMISSIONS	FEPS
SMOKE CONC. & TRAJECTORY	CALMET-CALPUFF v.8.2 [Scire et al. 2000b]

3.2 Model Domain

The area of interest over Southern California is depicted in Fig. 2. The horizontal CALPUFF modeling domain in UTM coordinates was centered at 11N 419.981 km E, 3764.959 km N with size 183 x 157 km².
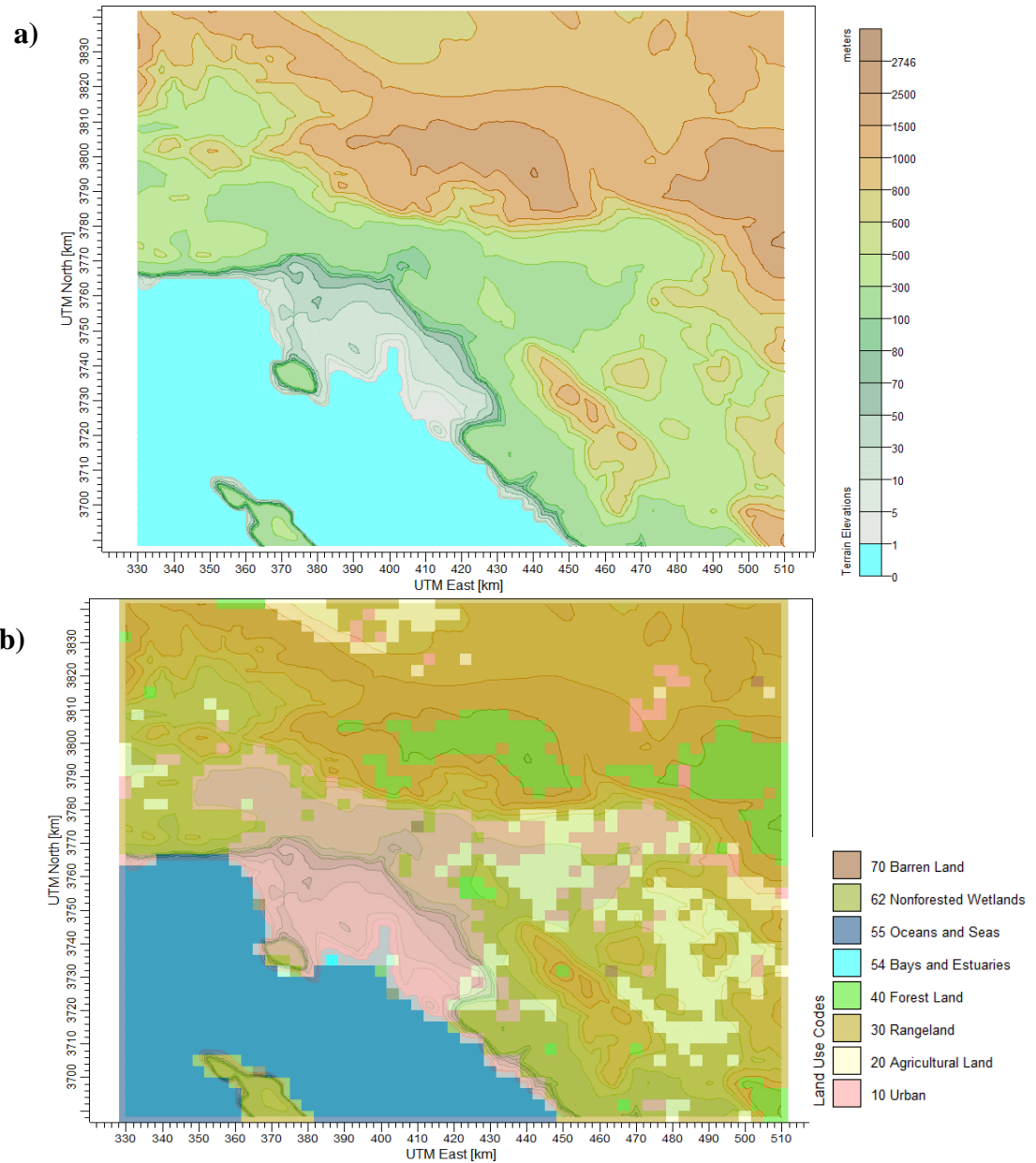

Fig. 2. (a) Terrain Elevations and (b) Land Use with terrain elevation over CALPUFF domain

3.3 Fire Emissions

The Fire Emissions Production Simulator, version 1 (FEPS) [Anderson et al. 2004], was used to estimate emissions of trace gases and particulate matter from wildland fires that occurred during the October 2007 fire outbreak. The model manages data concerning consumption, emissions, and heat release characteristics of prescribed burns and wildland fires (Anderson et al. 2004). Total fuels consumption values are distributed over the life of the fire to generate hourly emission and release information.

FEPS can be used for most forest, shrub and grassland types in North America and the world. A list of fuel loading profiles based on the National Fire Danger Rating System (NFDRS) [Cohen and Deeming, 1985], is provided. The NFDRS is a model that allows for predictions of potential fire danger. It combines the effects of existing and expected states of selected fire danger factors into one or more qualitative or numeric indices that reflect an area's fire protection needs (USDA Forest Service, 2016). Fuels, weather, topography, and risks are main inputs into the NFDRS model. For our purposes, Fuel Model B best represented the setting of our domain. This model is described as mature, dense fields of brush 6 feet or more in height. One-fourth or more of the aerial fuel in such stands is dead and foliage burns instantly. Model B fuels are potentially very dangerous, fostering intense fast-spreading fires. This model is for California mixed chaparral, generally 30 years or older.

To estimate plume rise, FEPS requires cumulative area burned in acres and daily extreme temperature and relative humidity values as input. Wildfire incident information for the state of California was made available through The California Department of

Forestry and Fire Protection (CALFIRE). Incidents involving any fire under a full suppression management strategy that exceeds 100 acres in timber (fuel models H-N), 300 acres in grass and brush (fuel models A-G), or has a Type 1 or 2 incident management team assigned, require an Incident Status Summary (ICS-209) report. This is provided by the Federal Emergency Management Agency (FEMA) and submitted to the Geographic Area Coordination Center (GACC) that serves the Federal and State wildland fire agencies through logistical coordination and mobilization of resources. Frequency of reporting varies with strategies employed.

Temperature and relative humidity extremes were retrieved from the weather observation data archive through University of Utah's MesoWest network made available by governmental agencies, commercial firms, and educational institutions participating in MesoWest (Horel et al. 2002). Individual station data was provided and only those close to the proximity of the wildfire were selected and used for input to the Fire Emission Production Simulator (FEPS).

FEPS is complementary to CALPUFF for the simulation of fire area source buoyancy. The FEPS buoyancy and emission results file are converted to a Buoyant AREA Source Variable Emissions File (BAEMARB.DAT) for input into CALPUFF.

3.4 Meteorology

The Advanced Weather and Research Forecasting Model, Version 3.4 (WRF-ARW) [Skamarock et al. 2008], was used to generate meteorological fields on a 30km Lambert Conformal horizontal grid with 3 nested domains at dimensions of 43 by 43 for the parent grid, 61 by 61 for the 2nd domain, and 85 by 85 for the 3rd domain.

The WRF Pre-Processing System (WPS) version 3.4 was used to prepare data for input into the real case program. For the initial and time-dependent lateral boundary conditions, the National Centers for Environmental Prediction (NCEP) North American Mesoscale Forecast System (NAM) 3-hourly reanalysis data at 34.5 km horizontal resolution was used. The YSU planetary boundary layer scheme was used along with RRTM's longwave radiation scheme and Dudhia (1985), shortwave radiation scheme.

The meteorological fields developed by WRF were integrated into CALMET (Scire et al. 2000b). CALMET is a diagnostic meteorological model that interpolates surface observations retrieved from NCEI (Fig. 3), and upper air prognostic data to produce an enhanced wind field. It develops hourly wind and temperature fields on a three-dimensional gridded modeling domain and mixing height, surface characteristics, and dispersion properties on a two-dimensional gridded domain. The data interpolation takes into account terrain effects and ensures the preservation of air-mass continuity (Scire et al., 2000). CALMET is coupled with CALPUFF to develop hourly concentration amounts. The horizontal CALMET modeling domain mirrors the CALPUFF domain with a 3.33-km resolution grid space. Vertically, the domain consisted of 10 fixed-height layers to 4000m.
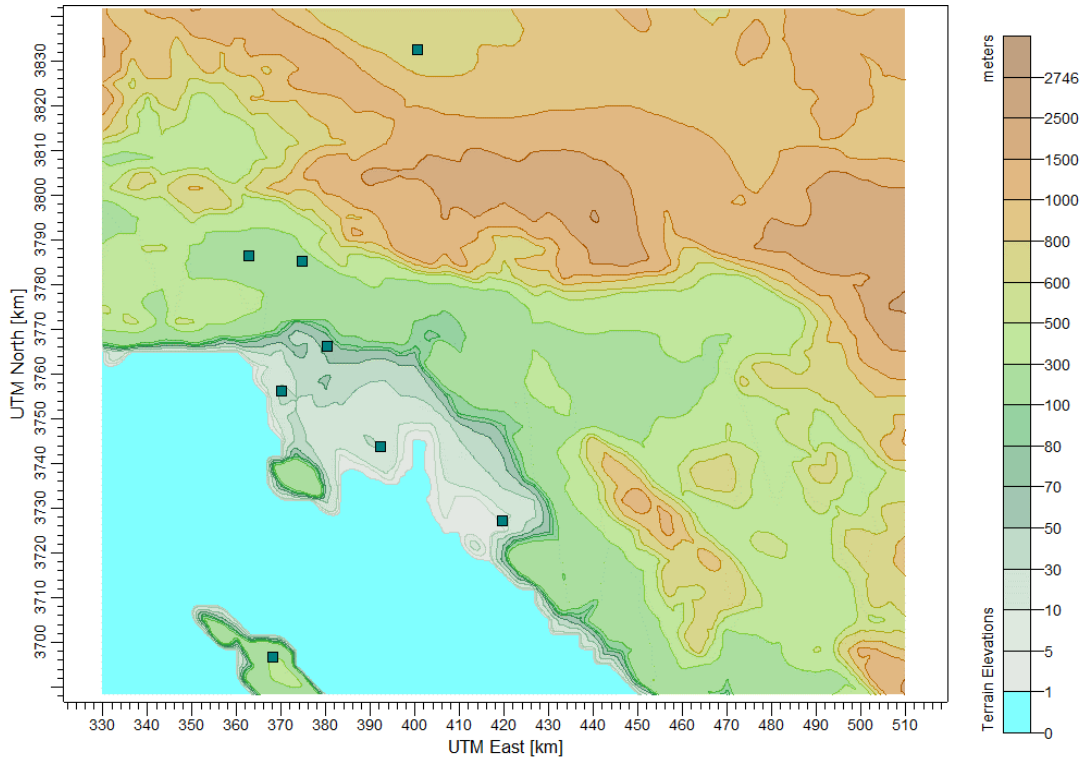
Fig. 3. Location of Land-Based Weather Stations (NCEI) and terrain elevation.

3.5 Smoke Concentration and Trajectory Model

California Mesoscale Puff Model (CALPUFF), a multi-layer, multi-species non-steady-state Lagrangian Gaussian puff dispersion model, adopted and approved by U.S. EPA as a regulatory model of choice, simulates the effects of time and space-varying meteorological conditions on pollution transport, transformation, and removal (Scire et al., 2000). For this study CALPUFF model version 8.2, the latest version, is set to simulate fire as a buoyant area source. This version accounts for effects of vertical wind shear, large initial plume size, and density differences between the plume and ambient air. Continuous puffs of pollutants are released from an area source into the ambient wind flow and as the wind flow changes temporally and spatially, the puff diffuses. As the puff

travels over a surface receptor point, the receptor simulates the total concentration value from the contribution of multiple puffs.

3.6 Development of PM$_{2.5}$ Concentration Scenarios

The Southern California 2007 wildfire outbreak started the night of 20 October 2007 and lasted through the end of the month ("California Fire Siege: An Overview", 2008). The peak fire-smoke action within the CALPUFF domain occurred between 20 and 27 October 2007. The CALPUFF run was initiated on 20 October 2007 00:00 Local Time (LT) and terminated 28 October 2007 23:00 LT. Species modeled included PM$_{2.5}$, CO, and CH$_4$. No chemical transformation was modeled due to the strict purpose of obtaining PM$_{2.5}$ concentration values from the wildfires.

The Partial Plume Penetration-Buoyant Area (MPARTLBA) option was selected under the Plume Rise option. For dispersion options (MDISP), the Puff Plume Element Modeling Method was used along with the dispersion coefficient option that uses turbulence computed from micrometeorology. This option internally calculates σ-v and σ-w using input meteorological data from CALMET. No puff splitting or turbulence advection was selected.

A sensitivity analysis was conducted for the four Terrain Adjustment Method options. The terrain adjustment is applied to gridded and discrete receptors and adds variation to the model and consequently its results. The four adjustment schemes and descriptions are as follows:

1. *No Adjustment*: Holds the puffs at a constant height above the surface, using only 'flat-terrain' calculations.

2. *ISC Terrain Adjustment:* Puff remains at 'stack-height'. The distance between the ground and the puff reduces when the terrain rises and all elevations above 'stack-height' are eliminated.

3. *CALPUFF Terrain Adjustment:* The vertical size of the puff is modified rather than its height above the ground.

4. *Partial Plume Path Adjustment:* Adjusts puff height based on stability class and local terrain elevation above 'stack-height'. Adjustment coefficient 0.5 is used on the original puff height in non-stable conditions and reduces with increasing stability.

An evaluation of the performance of all four adjustments was made by comparing receptor results, including background values, with measurements from EPA's local monitoring stations. The receptor locations (Fig. 4), were configured using EPA's active site coordinates.
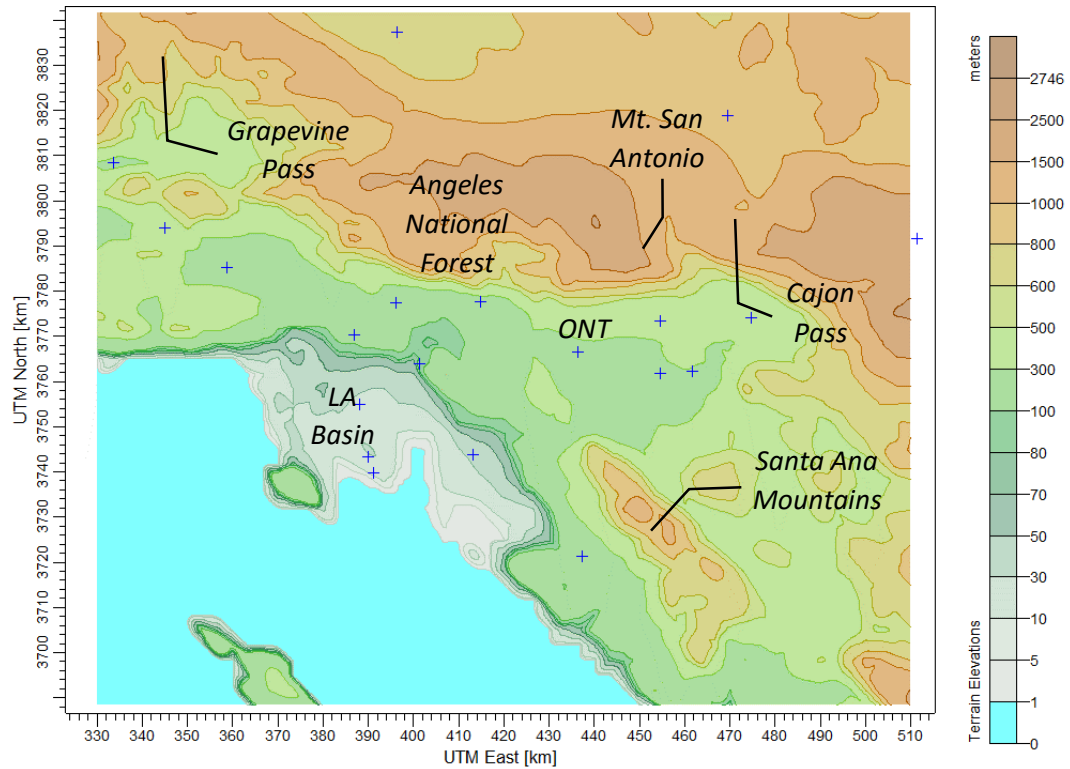
Fig. 4. Location of discrete receptors (+) and terrain elevation.

4. Results and Discussion

4.1 2007-2009 Asthma Emergency Department Data analysis

Fig. 5 depicts daily time series plots for asthma ED visits per ten million people for Los Angeles and Riverside counties. As shown in the graph, asthma follows an evident seasonal pattern in which asthma rates are higher in the fall and winter and lower during the spring and summer with Riverside having greater variability. For Los Angeles, asthma counts ranged between 34 and 245 while for Riverside they ranged between 19 and 227. A maximum of 215 occurred on 24 October 2007 in Los Angeles and 202 on 27 October 2007 for Riverside. The average for each year is shown in Table 3. It is clear that between 2007-2009, the averages for asthma ED visits increased over time.
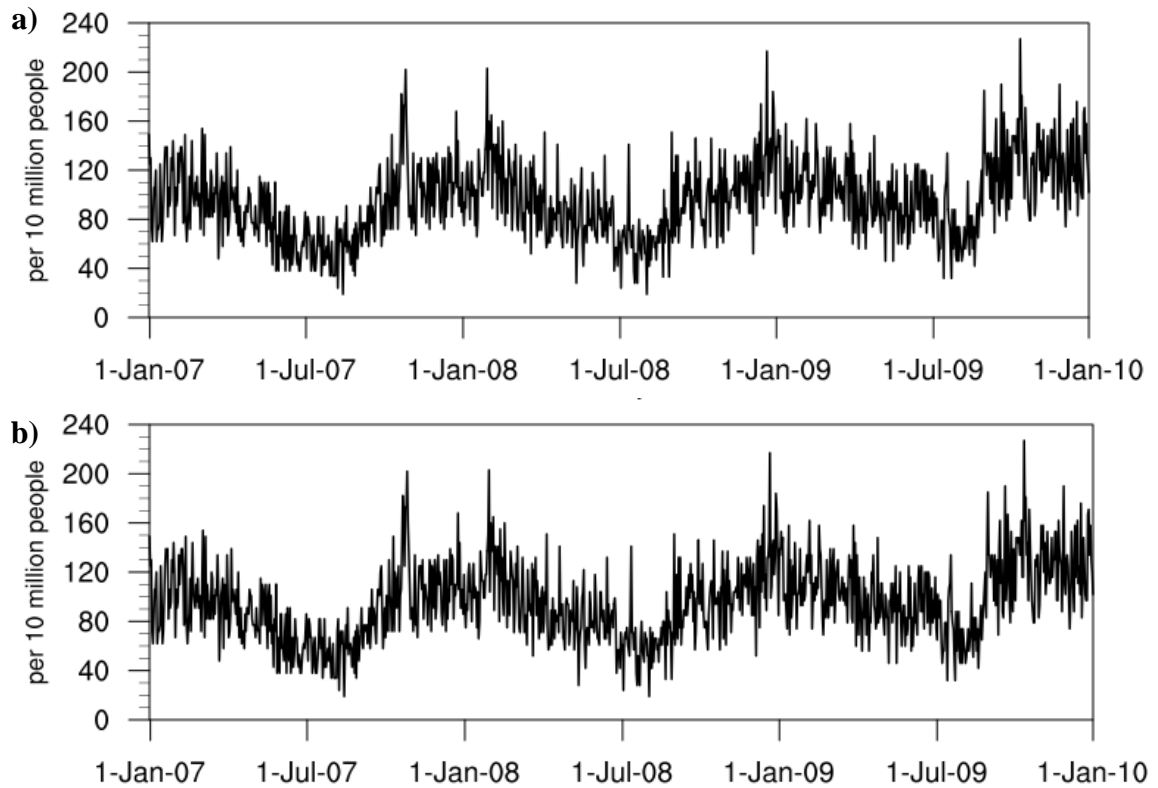
Fig. 5. Time Series of Asthma ED counts per ten million people for all hospitals in (a) Los Angeles County and (b) Riverside County during the years 2007-2009

Table 3. Average Asthma ED visits per ten million people by year

	2007	2008	2009
LOS ANGELES	102	105	119
RIVERSIDE	85	91	105

Fig. 6 illustrates daily time series plots of county-level average surface $PM_{2.5}$. There is no clear seasonal trend for minimums. Short-term peaks are seen for maximums as opposed to minimums in both counties. Maximums occurred during the fall and winter seasons. Los Angeles and Riverside both had a maximum value on 23 October 2007 at 65 μgm^{-3} and 61.29 μgm^{-3} respectively. Peak values decreased between 2007-2009 for both

counties. Values for Los Angeles ranged between 0.11 µgm⁻³ to 65 µgm⁻³ with an average

of 11.95 µgm⁻³ for all three years. Values for Riverside ranged between 2.06 µgm⁻³ to

61.29 µgm⁻³ with an average of 12.57 µgm⁻³ for all three years.
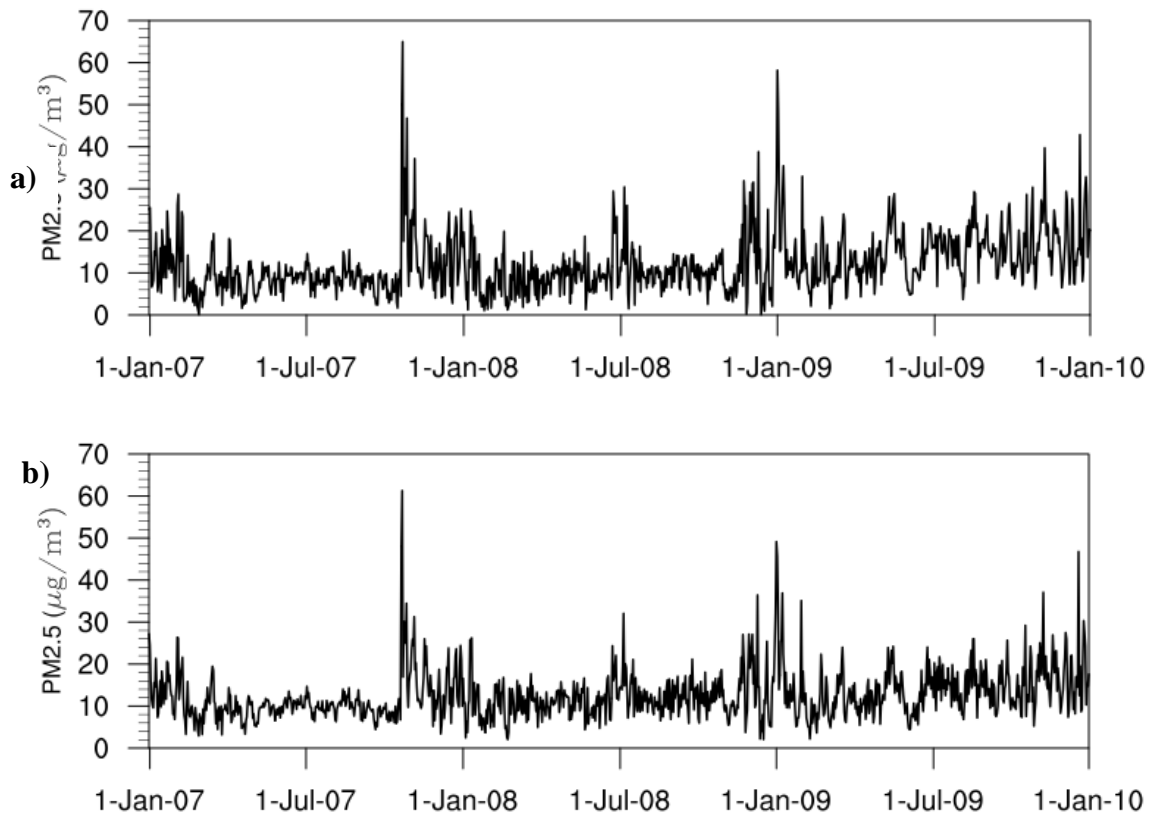
Fig. 6. Daily fine particulate matter (PM$_{2.5}$) (µg/m³) for years 2007-2009 on CDC
WONDER Online Database, released 2012, for (a) Los Angeles County and (b) Riverside
County.

4.2 Data correlations

NO$_2$, CO, PM$_{2.5}$, and inversion height were positively correlated with asthma for

the entire 2007-2009 period and per individual year while O$_3$, dew point, temperature,

and wind speed were negatively correlated with asthma (Table 4).

Table 4. Correlations for original dataset and modified dataset with difference between both datasets for (a) Los Angeles and (b) Riverside Counties 1-Jan-07 to 31-Dec-09.

Los Angeles 2007-2009	O3	NO2	CO	PM2.5	Dew Pt	Temp	WSF2	Inv. H
Asthma (n=1096)	-0.449**	0.196**	0.326**	0.180**	-0.481**	-0.544**	-0.136**	0.289**
Asthma+ (n=966)	-0.502**	0.199**	0.339**	0.143**	-0.530**	-0.611**	-0.107**	0.299**
Difference	0.053	0.003	0.013	0.037	0.048	0.067	0.029	0.010

Riverside 2007-2009	O3	NO2	CO	PM2.5	Dew Pt	Temp	WSF2	Inv. H
Asthma (n=1096)	-0.441**	0.128**	0.192**	0.188**	-0.366**	-0.441**	-0.150**	0.256**
Asthma+ (n=1045)	-0.464**	0.124**	0.185**	0.142**	-0.375**	-0.480**	-0.151**	0.269**
Difference	0.023	0.004	0.007	0.047	0.010	0.039	0.001	0.012

* P-value < 0.05   ** P-value < 0.01

Analyzing the differences between both datasets (Table 4), we found that all correlations increased from the original to modified version with the exception of $PM_{2.5}$ and wind speed in Los Angeles. Riverside saw increases in correlations for O_3, dew point, temperature, wind speed, and inversion height and decreases in NO_2, CO, and $PM_{2.5}$. Differences ranged between 0.001 and 0.067.

Datasets were broken down by year as shown in Table 5. Differences ranged between 0.001 and 0.144 with $PM_{2.5}$ having the highest difference, approximately 2.5 times more than the second highest value in both Los Angeles and Riverside. All variables followed the same positive or negative correlation pattern as per Table 4.

Table 5. Correlations for original dataset and modified dataset with difference between both datasets for (a) Los Angeles and (b) Riverside Counties 1-Jan-07 to 31-Dec-07.

Los Angeles-2007	O3	NO2	CO	PM2.5	Dew Pt	Temp	WSF2	Inv. H
Asthma (n=365)	-0.547**	0.268**	0.398**	0.290**	-0.541**	-0.610**	-0.175**	0.369**
Asthma+ (n=327)	-0.575**	0.231**	0.374**	0.147**	-0.543**	-0.668**	-0.136*	0.368**
Difference	0.028	0.037	0.024	0.143	0.001	0.058	0.039	0.001

Riverside-2007	O3	NO2	CO	PM2.5	Dew Pt	Temp	WSF2	Inv. H
Asthma (n=365)	-0.490**	0.174**	0.310**	0.376**	-0.480**	-0.504**	-0.111*	0.315**
Asthma+ (n=350)	-0.501**	0.168**	0.316**	0.232**	-0.481**	-0.562**	-0.102	0.332**
Difference	0.011	0.005	0.006	0.144	0.001	0.058	0.009	0.017

* P-value < 0.05   ** P-value < 0.01

Fall of 2007 (Table 6), had the highest positive correlation for $PM_{2.5}$ in the original dataset for both Los Angeles and Riverside counties compared to all other variables. $PM_{2.5}$ also had the greatest differentiation between the original and modified version. Delta values ranged between 0.021 and 0.471 with $PM_{2.5}$ being 3.5 times more than the second highest difference in Riverside and 1.5 times more in Los Angeles. A two-tail Pearson correlation significance test was applied for Fall of 2007 values. $PM_{2.5}$, dew point, temperature, wind speed, and inversion height were statistically significant with a *P-value* less than 0.01 in the original set for Los Angeles while only significant for temperature in the modified dataset. For Riverside's original dataset, at the same *P-value*, O_3, $PM_{2.5}$, dew point, and temperature were statistically significant while for the modified dataset ozone and temperature were.
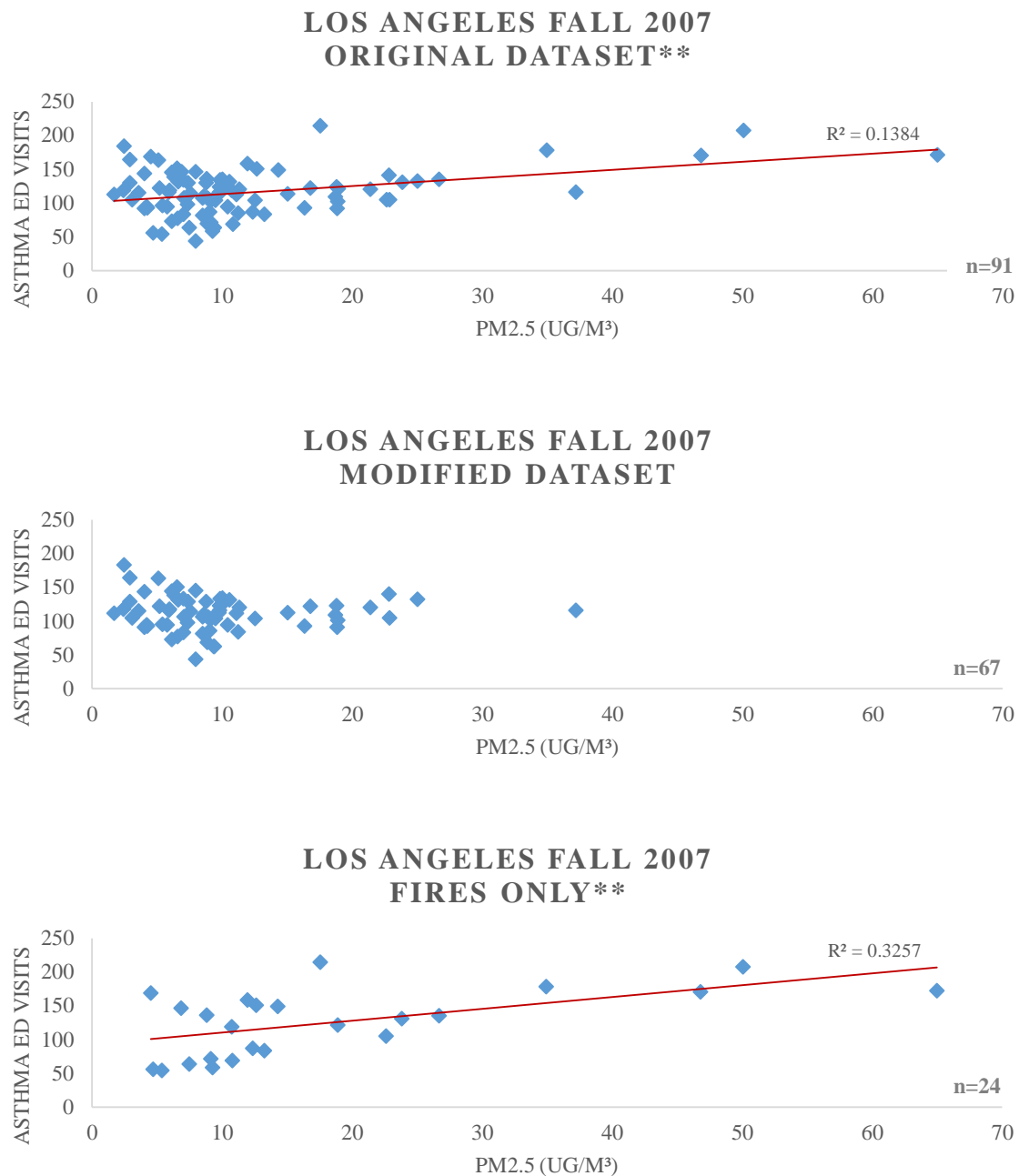
Table 6. Correlations for original dataset and modified dataset with difference between both datasets for (a) Los Angeles and (b) Riverside Counties 1-Sep-07 to 30-Nov-07.

Los Angeles-Fall 07	O3	NO2	CO	PM2.5	Dew Pt	Temp	WSF2	Inv. H
Asthma (n=91)	-0.200	0.124	0.206	0.372**	-0.490**	-0.354**	-0.263**	0.306**
Asthma+ (n=67)	-0.088	-0.026	0.019	-0.045	-0.211	-0.415**	-0.123	0.171
Difference	0.112	0.150	0.187	0.417	0.279	0.061	0.140	0.135
Riverside-Fall 07	O3	NO2	CO	PM2.5	Dew Pt	Temp	WSF2	Inv. H
Asthma (n=91)	-0.271**	0.024	0.176	0.481**	-0.357**	-0.285**	-0.166	0.212*
Asthma+ (n=76)	-0.307**	0.004	0.144	0.010	-0.211	-0.414**	-0.238*	0.128
Difference	0.036	0.021	0.033	0.471	0.146	0.129	0.072	0.084

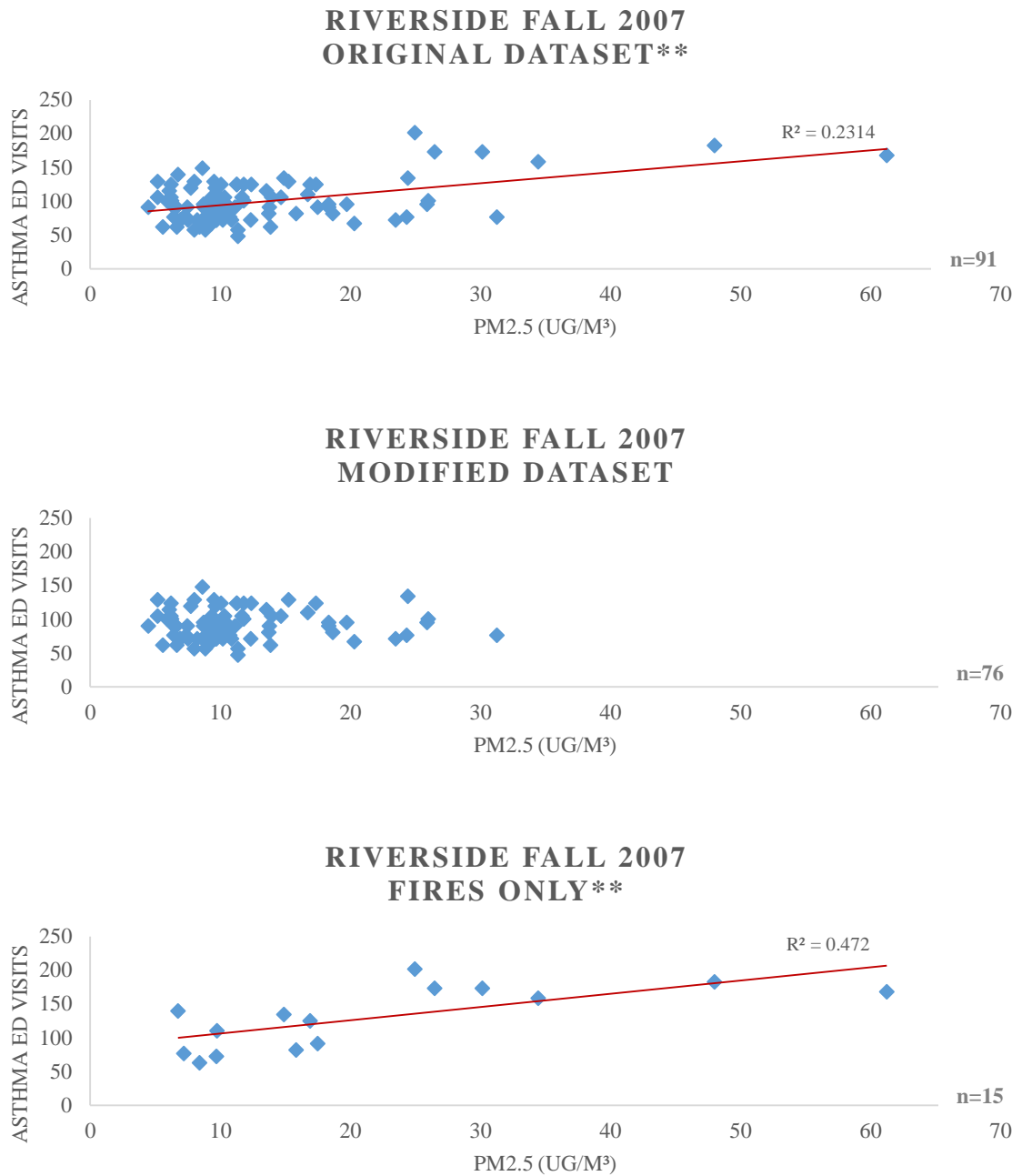** P-value < 0.05   ** P-value < 0.01*

It is important to note that the modified dataset that excludes fire events do not take into account fires whose plume might have dispersed into the county. Wind direction was considered but excluded from the study.

Fig. 7 and Fig. 8 are graphical representations of the correlations between $PM_{2.5}$ and asthma for Los Angeles and Riverside during fall of 2007. Set (a) original dataset and set (c) fires-only dataset had a *P-value <0.01* making them statistically significant while set (b) modified dataset was not. Set (c) had a significant positive correlation at 0.571 for Los Angeles and 0.687 for Riverside.

LOS ANGELES FALL 2007 ORIGINAL DATASET with $R^2 = 0.1384$, $n=91$

LOS ANGELES FALL 2007 MODIFIED DATASET with $n=67$

LOS ANGELES FALL 2007 FIRES ONLY with $R^2 = 0.3257$, $n=24$

** P-value < 0.01

Fig. 7. Scatter diagrams for daily average $PM_{2.5}$ and Asthma ED Visits from 1-Sep-07 to 31-Nov-07 in Los Angeles County for (a) original dataset (b) modified dataset and (c) dataset during fire events. The regression line is included when correlation data is statistically significant.

Fig. 8. Scatter diagrams for daily average $PM_{2.5}$ and Asthma ED Visits from 1-Sep-07 to 31-Nov-2007 in Riverside County for (a) original dataset (b) modified dataset and (c) dataset during fire events. The regression line is included when correlation data is statistically significant.

*** P-value < 0.01*

4.3 Ground Observations for PM$_{2.5}$

A time series of PM$_{2.5}$ was produced to analyze particulates during October 2007.

Ground observations (Fig. 9), show higher than average values of PM$_{2.5}$ between October

22 and October 28. The average PM$_{2.5}$ was 13.96 µgm^{-3} for Los Angeles and 14.79 µgm^{-3}

for Riverside. The highest amount of PM$_{2.5}$ occurred on October 23rd at a value of 64

µgm^{-3} for Los Angeles and 61.29 µgm^{-3} for Riverside, both approximately 1.8 times

higher than the National Ambient Air Quality Standard (NAAQS) of 35 µgm^{-3} per 24-

hour period. Most significant increase was noticed on October 22nd, approximately 4

times higher than average levels.

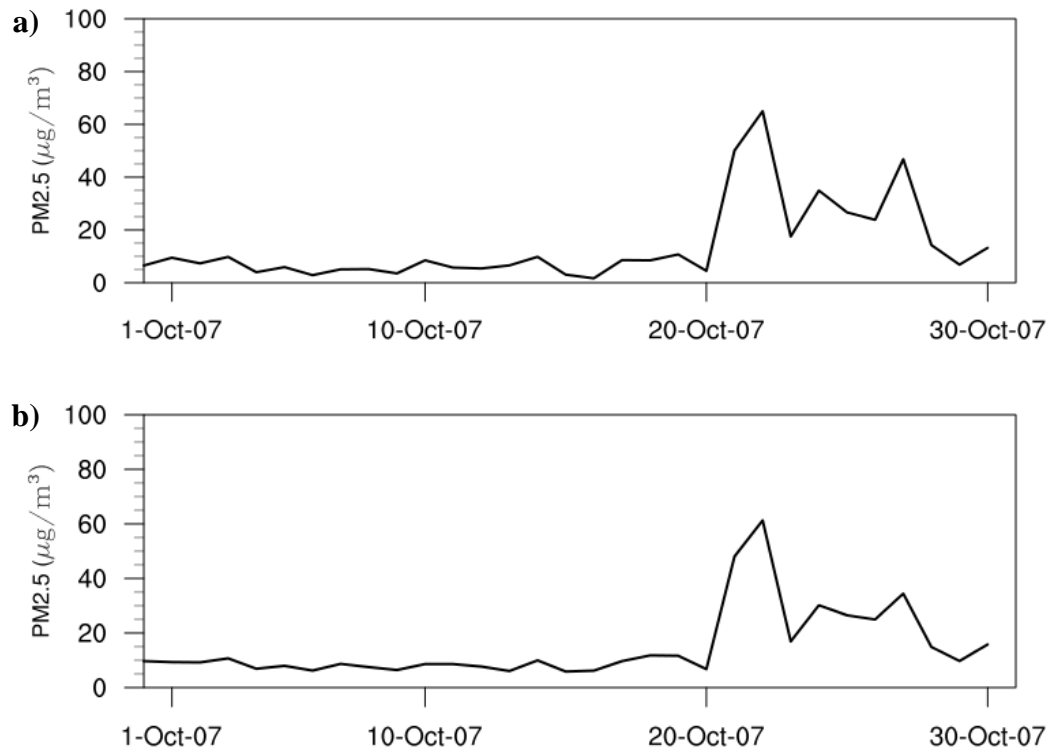**Fig. 9.** Daily average fine particulate matter (PM$_{2.5}$) (µgm^{-3}) from 1-Oct-07 to 31-Oct-07 on CDC WONDER Online Database, released 2012, for (a) Los Angeles County and (b) Riverside County.

4.4 Meteorological Conditions

The outbreak of fires and its containment are directly impacted by existing weather conditions. Fire weather is a term used to describe the meteorological conditions that are routinely observed during wildfire events (Clements 2011). Radiosonde data indicated a weakly stable atmosphere with a shallow inversion from 22 to 27 October. A strong inversion was evident on October 23rd (Fig. 10).
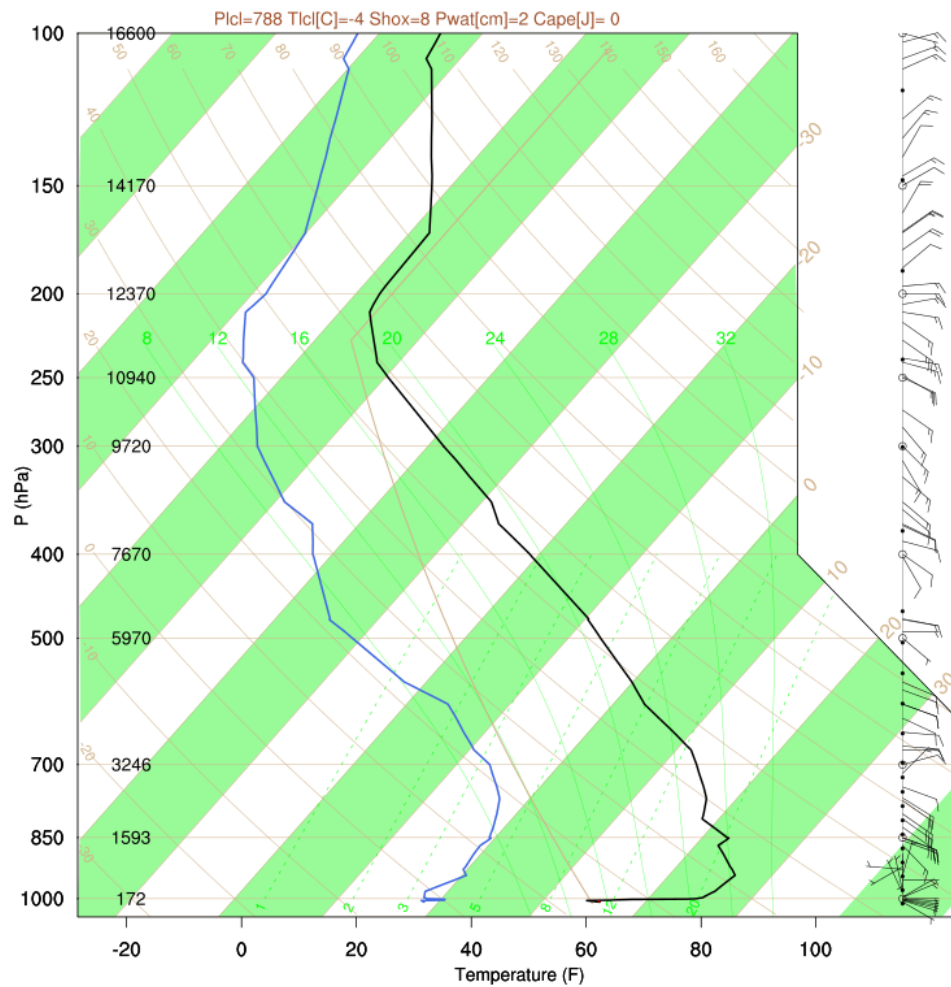

Fig. 10. Vertical temperature profile at Vandenberg Air Force Base 1200 UTC 23 October 2007.

A subsidence inversion creates a stagnant atmosphere and can lead to an accumulation of pollutants at or near the surface, such was the case for our study period. In addition, winds were offshore from the surface to the 100-millibar level with slight veering (Fig. 10), an indication of warm advection in the upper atmosphere. Eventually, a shift in winds and the eastward movement of the high pressure system eroded the inversion.

A dominant ridge at the 500-millibar level (Fig. 11a), indicated a warm air mass over the region. At this same level a high pressure system was centered over the Sierra Nevada and western Nevada. At the surface (Fig. 11b), a high pressure system was centered over the border of Nevada, Utah, Idaho, and Colorado. High pressure at the surface and aloft generates northeasterly sinking air and offshore winds in the southeast quadrant of the high pressure system. By October 25th (Fig. 13a), the high pressure system at the 500-millibar level moved eastward and weakened.

In addition, a strong pressure gradient at the surface was located over Southern California (Fig. 11b), due to a low pressure system off the coast of Baja California. A strong pressure gradient produces high winds. The pressure gradient weakened (i.e. isobars are more widespread) by October 24th (Fig. 12a,b), and further on October 25th (Fig. 13b), reducing the speed of the winds. By October 26th (Fig. 14a,b), the high pressure system passed the region at the surface and aloft. A low pressure system is now visible at the surface with the return of onshore winds.
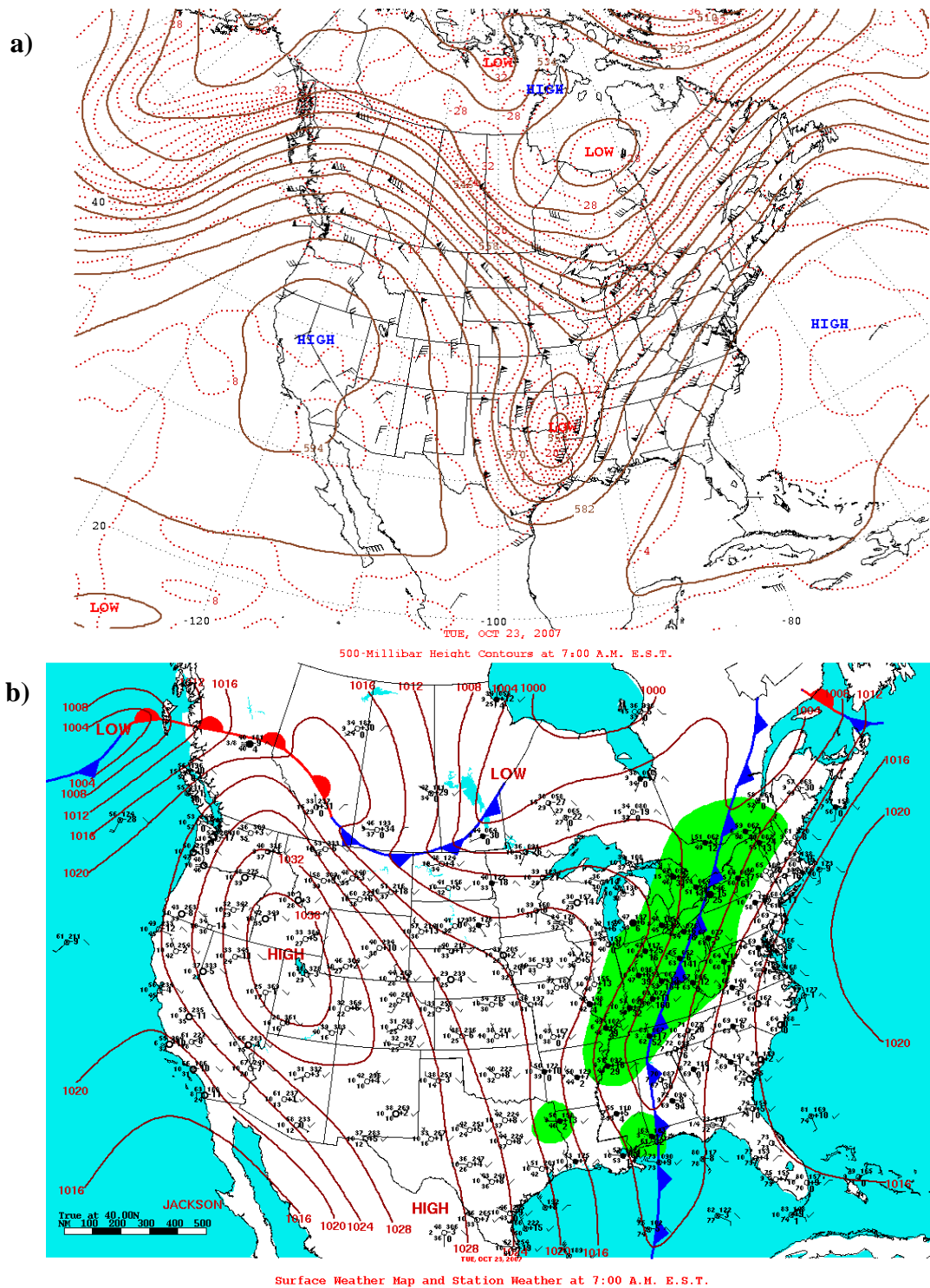
a)

TUE, OCT 23, 2007
500-Millibar Height Contours at 7:00 A.M. E.S.T.

b)

Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Fig. 11. National Centers for Environmental Prediction, Weather Prediction Center daily weather map at 23 October 2007 1200 UTC for (a) 500-millibar height observations and (b) surface analysis
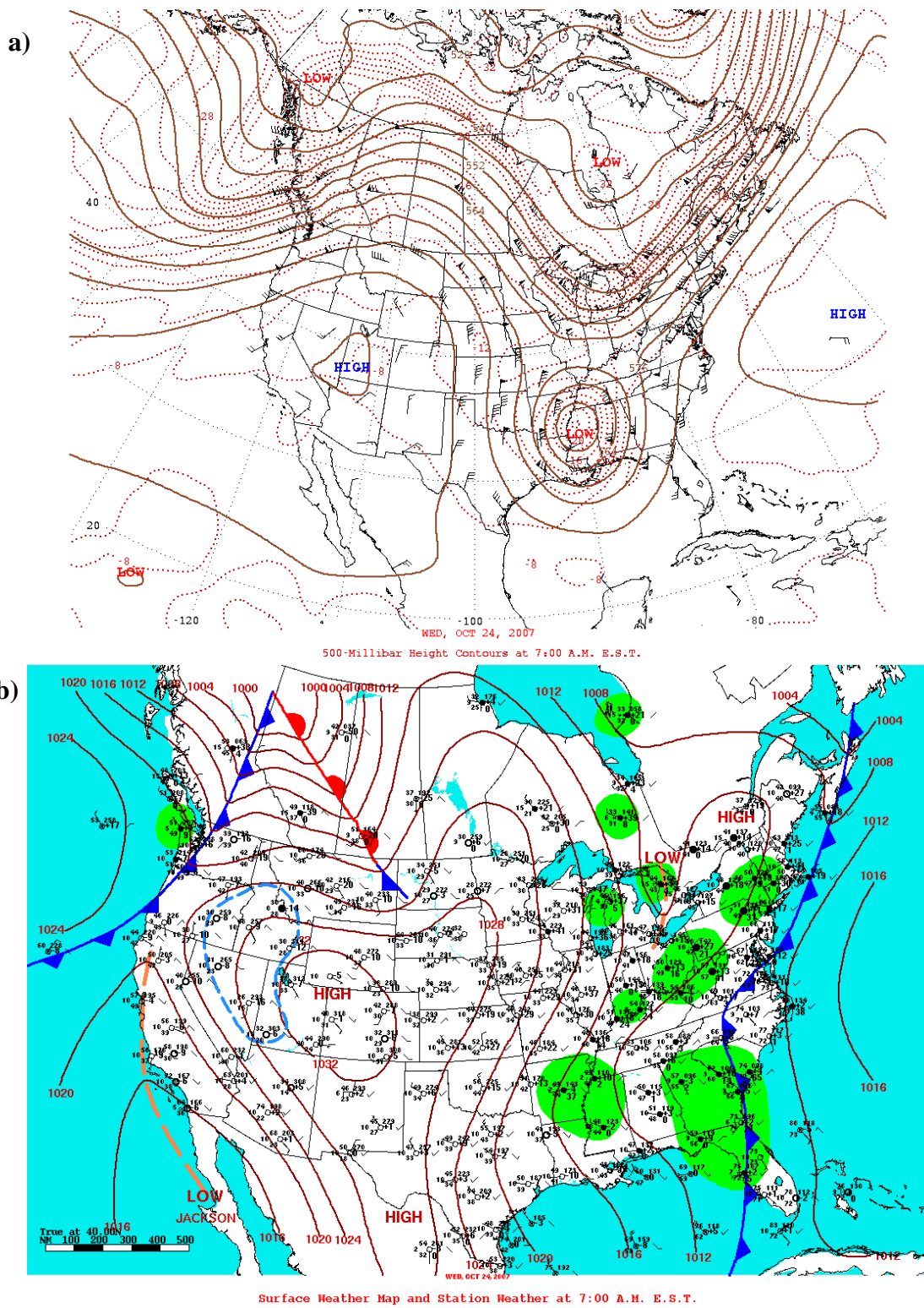
33

a)

WED, OCT 24, 2007
500-Millibar Height Contours at 7:00 A.M. E.S.T.

b)

WED, OCT 24, 2007
Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Fig. 12. Continued 24 October 2007 1200 UTC.

a)

500-Millibar Height Contours at 7:00 A.M. E.S.T.

b)

Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.
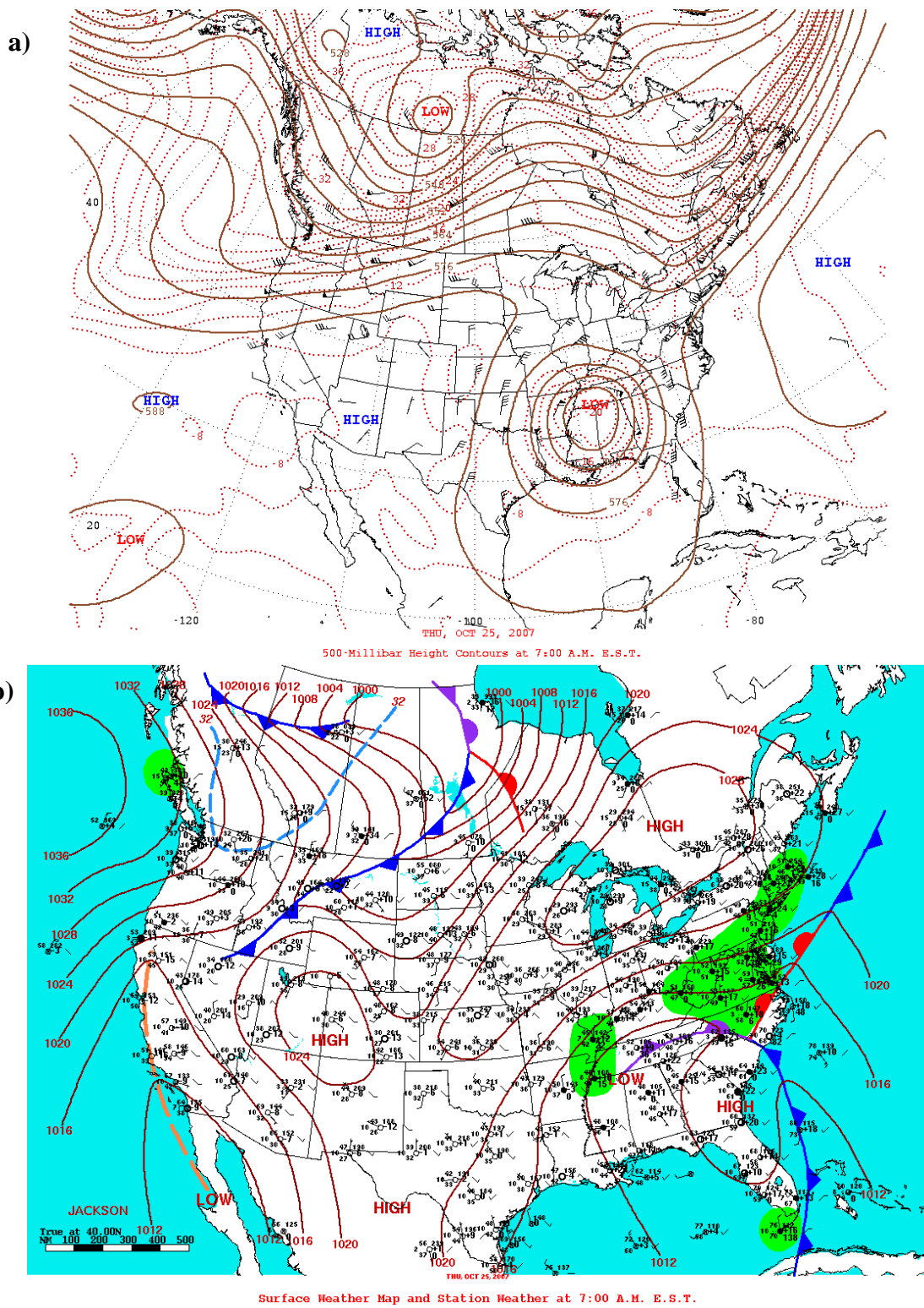
Fig. 13. Continued 25 October 2007 1200 UTC.

a)

FRI, OCT 26, 2007
500-Millibar Height Contours at 7:00 A.M. E.S.T.

b)

Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.
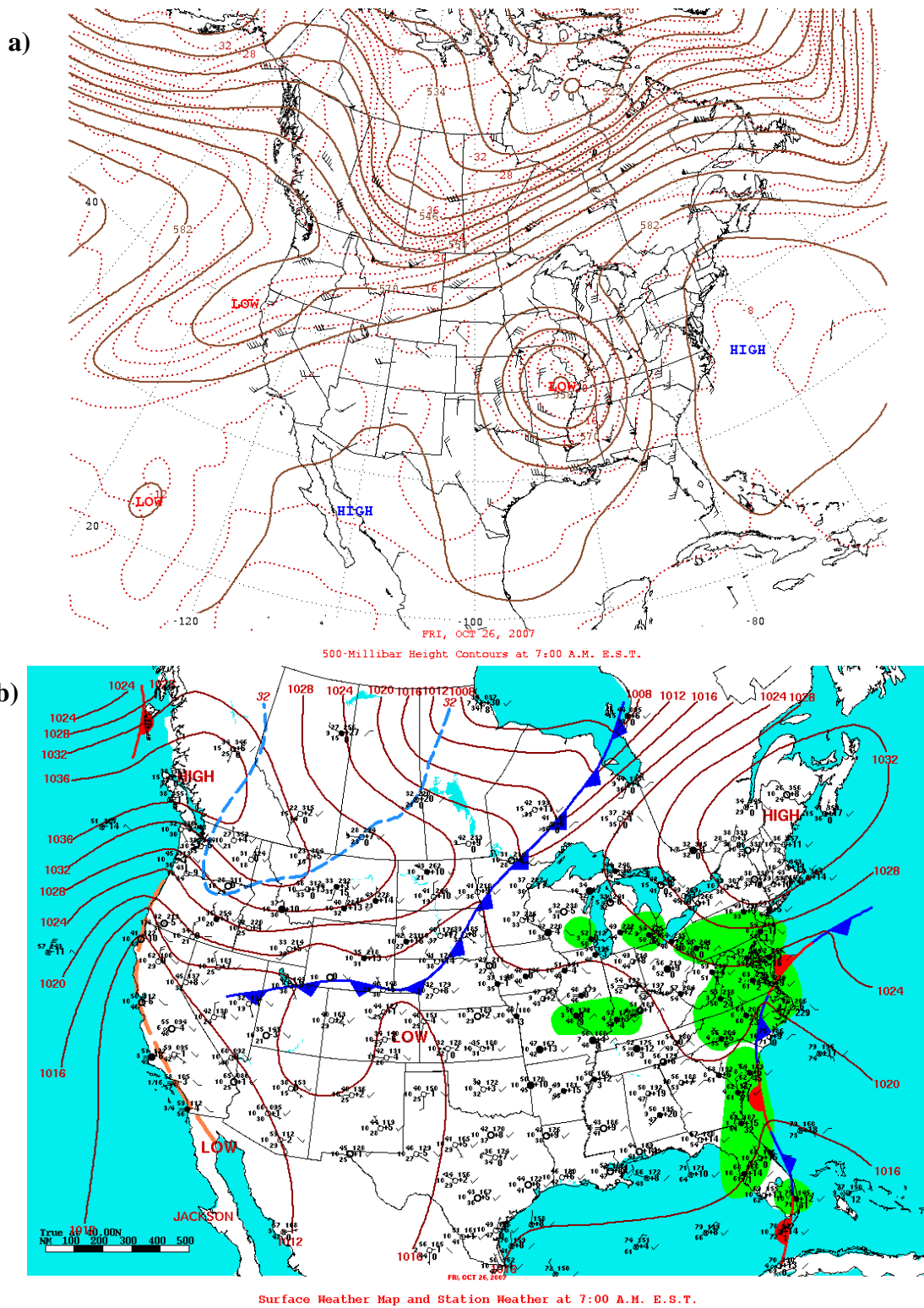
Fig. 14. Continued 26 October 2007 1200 UTC.

A common and important factor affecting fire behavior are winds produced by mountainous terrain known as foehn winds. Foehn winds are warm dry winds that develop on the leeside of a mountain range and are associated with extreme fire behavior because of their near-surface high wind speeds, warm temperatures, and low relative humidity (Durran 1990, Whiteman 2000). The most prominent foehn wind related to extreme fire cases in the Southern California region are the Santa Ana winds. Santa Ana winds develop as a result of a high pressure over the Great Basin and development of a surface low off the Southern California coast, with an upper level trough to the east and a ridge in the eastern North Pacific (Barry 2008). Surface Santa Ana winds are due to two factors according to Hughes and Hall (2009). The first is strong mid-tropospheric winds that touch the mountaintops in a stable environment causing midlevel momentum from gravity waves transferring to the surface and thus strong lee-side surface winds. The second factor is cold air that is trapped in the Great Basin by topography. A pressure gradient forms due to the hydrostatic desert and ocean air interaction. This results in a negatively buoyant gravity current to flow through mountain gaps, accelerating the air as it is channeled through the passes and canyons. During the October 2007 wildfire event, Santa Ana winds were considered a factor in the outbreak ("California Fire Siege 2007: An Overview", 2008).

Between 22 and 25 October Los Angeles had temperatures above 80°F and dew points at its lowest during the same period (Fig. 15a), plunging to 39°F on October 22nd. Riverside (Fig. 15b), had temperatures above 80°F between 23 and 29 October and its minimum dew point on October 22nd at 16°F. Dew point, a measurement of water vapor

in the air, indicates how dry the atmosphere is. Riverside County appears to be warmer and dryer than Los Angeles County.
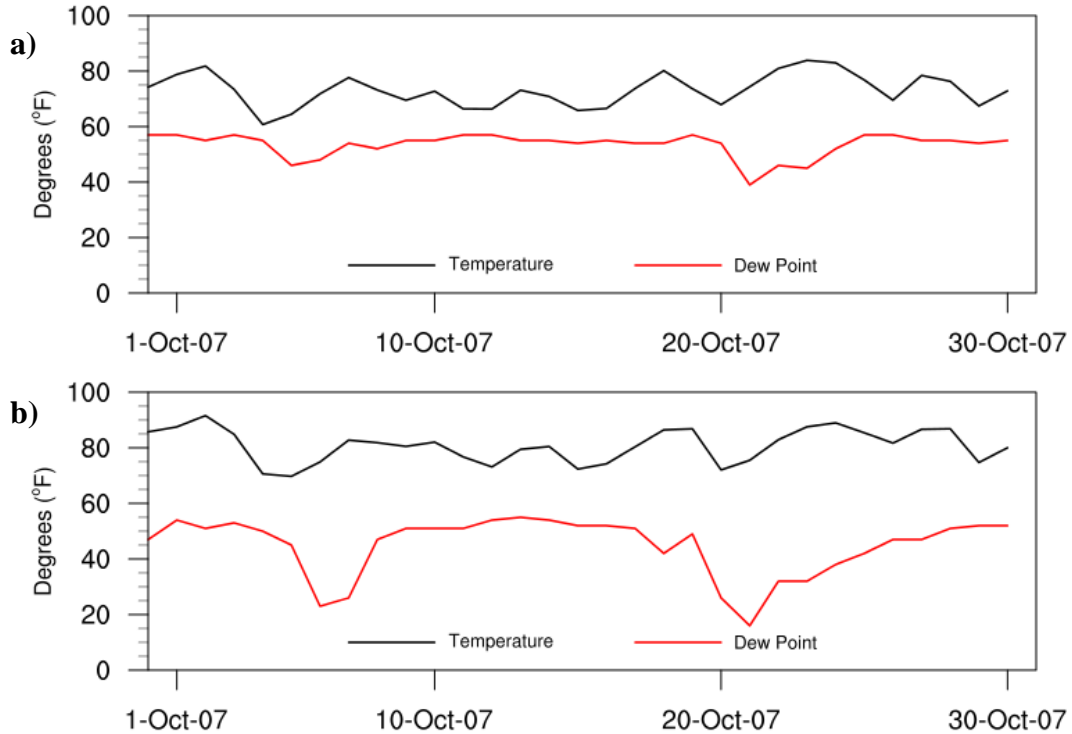

Fig. 15. Surface maximum temperature and dew point for (a) Los Angeles and (b) Riverside from 1-Oct-07 to 31-Oct-07.

The existence of Santa Ana winds dried out the surface further. Hot, dry winds lead to a drop in humidity values and under these conditions fires burn at a higher rate. By October 25th (Fig. 13), onshore winds advected moisture into the area and subsequently increased dew point values.

Fig. 16 through 18 show surface wind vectors along with terrain elevations. On October 20th (Fig. 16), winds were northwesterly through the Grapevine Pass (Fig. 4), at speeds between 12 and 16 ms^{-1}. A diversion of winds around the Angeles National Forest and Mt. San Antonio was evident (Fig. 4), spilling into the Los Angeles basin. There is

mild channeling of southerly winds through the Cajon Pass (Fig. 4) at speeds between 2 and 4 ms^{-1}. An onshore flow in the Los Angeles basin diverted around the Santa Ana Mountains at wind speeds between 2 and 6 ms^{-1}. Further inland at Ontario International Airport (ONT) (Fig. 4), mild westerly winds can be found between 2 and 4 ms^{-1}.
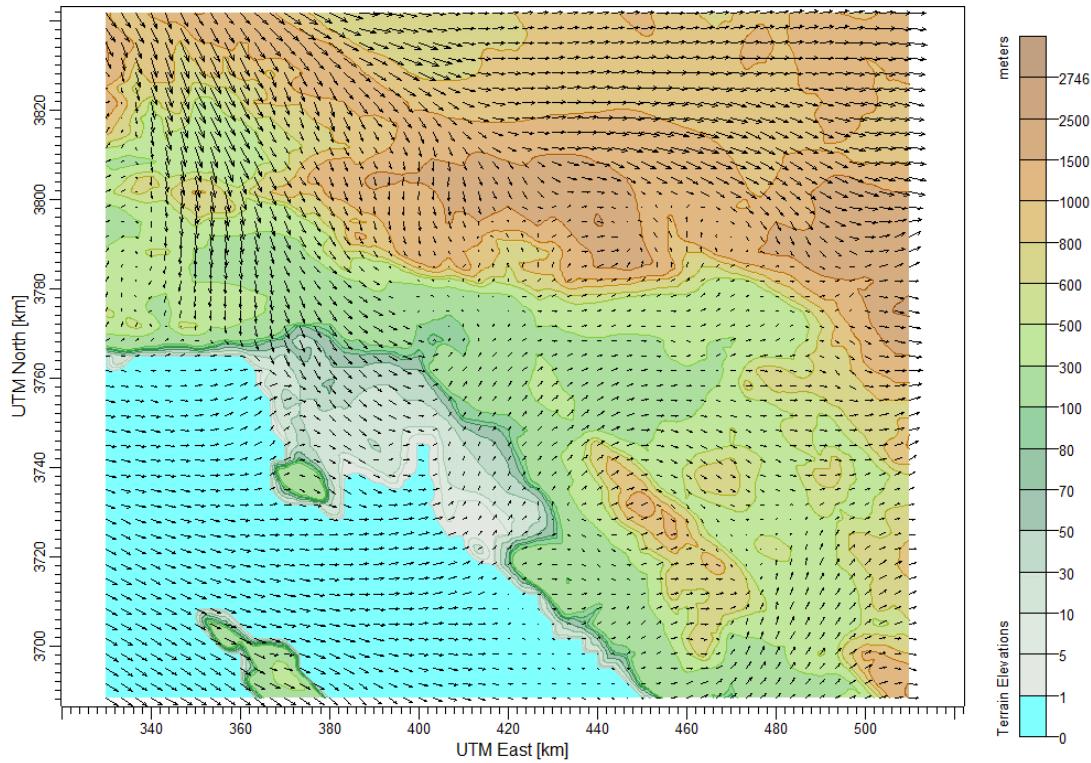

Fig. 16. CALMET 10-meter wind vectors extracted from WRF simulation on 20 October 2007 1900 UTC.
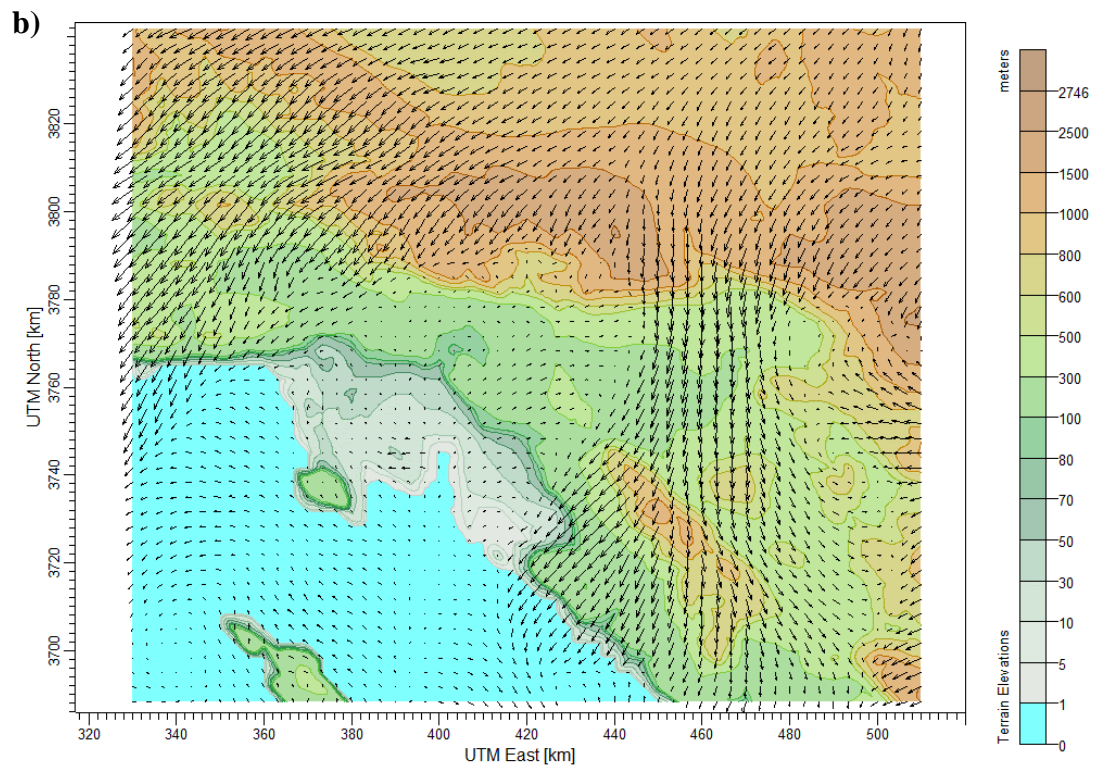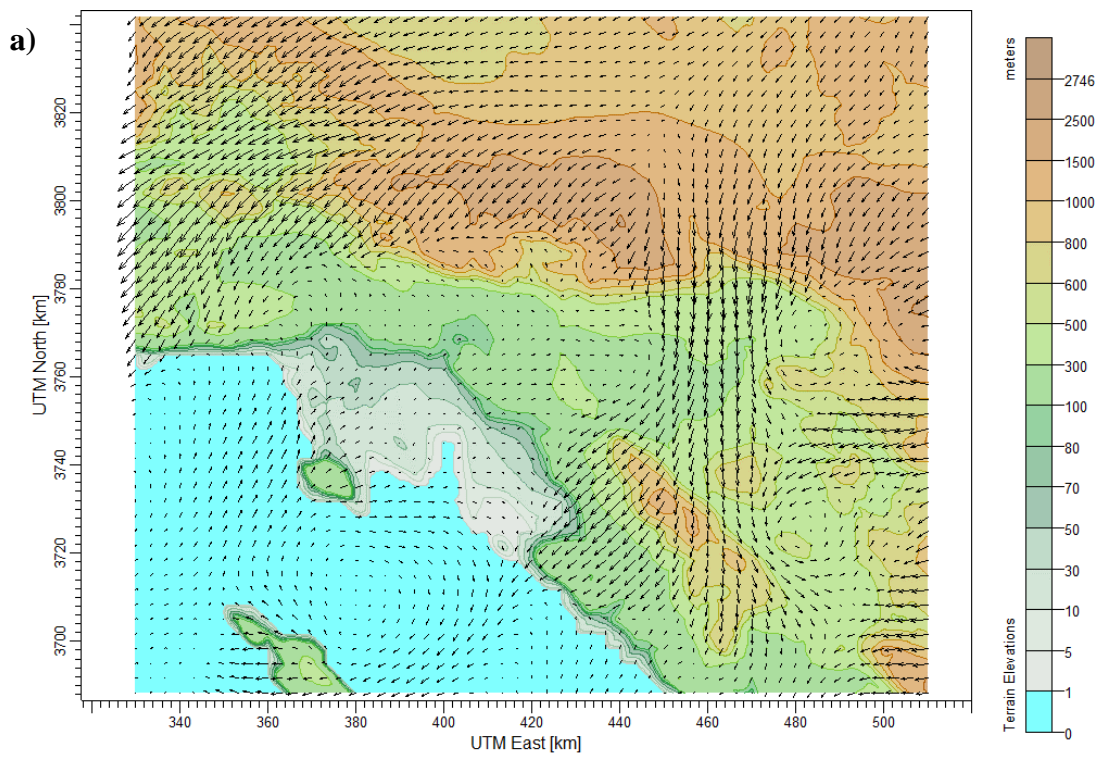
Fig. 17. Continued for (a) 21 October 2007 and (b) 23 October 2007 1900 UTC.

On October 21st (Fig. 17a), there was a noticeable shift in wind direction and speed with winds coming from the northeast diverted around the Angeles National Forest and Mt. San Antonio and channeling through the Grapevine and Cajon Pass. Winds were northeasterly at the Grapevine Pass between 12 and 18 ms^{-1} and northerly at the Cajon Pass at speeds between 10 and 14 ms^{-1} Winds passing through the Cajon Pass continued offshore, reaching the Orange County coastline at speeds between 10 and 16 ms^{-1} along the way. Winds at ONT were northeasterly between 6 and 8 ms^{-1}.

On October 23rd (Fig. 17b), winds continued its pattern channeling through the Grapevine and Cajon Pass, diverting around Angeles National Forest and Mt. San Antonio and continued offshore.

By October 25th (Fig. 18a), a change in wind speed and direction throughout Southern California was visible. Most winds north of Angeles National Forest and Mt. San Antonio shifted northwesterly. An onshore flow was apparent, spreading inland to the Cajon Pass where it experienced both southerly winds at the south end and northwesterly winds at the north end. Wind speeds were between 0 and 4 ms^{-1} throughout the region. ONT experienced another shift in wind direction with winds coming from the northwest.

On October 27th (Fig. 18b), an onshore flow from the south made its way into the Los Angeles Basin at speeds between 0 and 4 ms^{-1}. Southerly winds were apparent at the Grapevine and Cajon Pass while ONT had a new shift in wind direction, from the southwest.
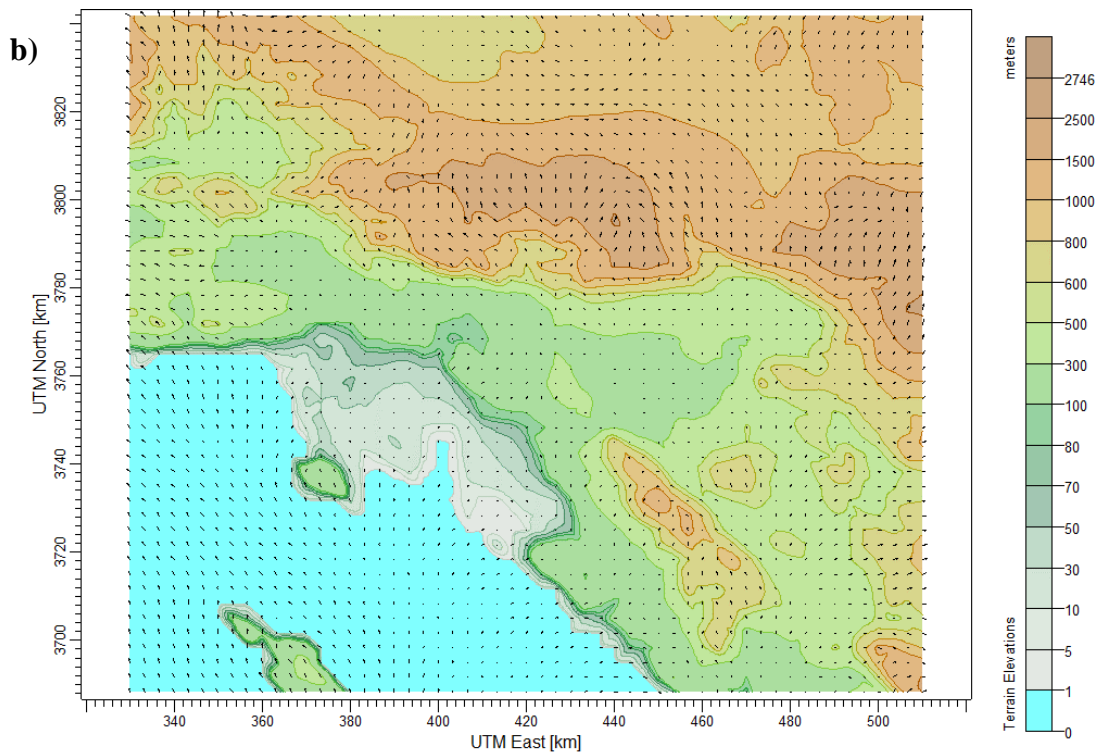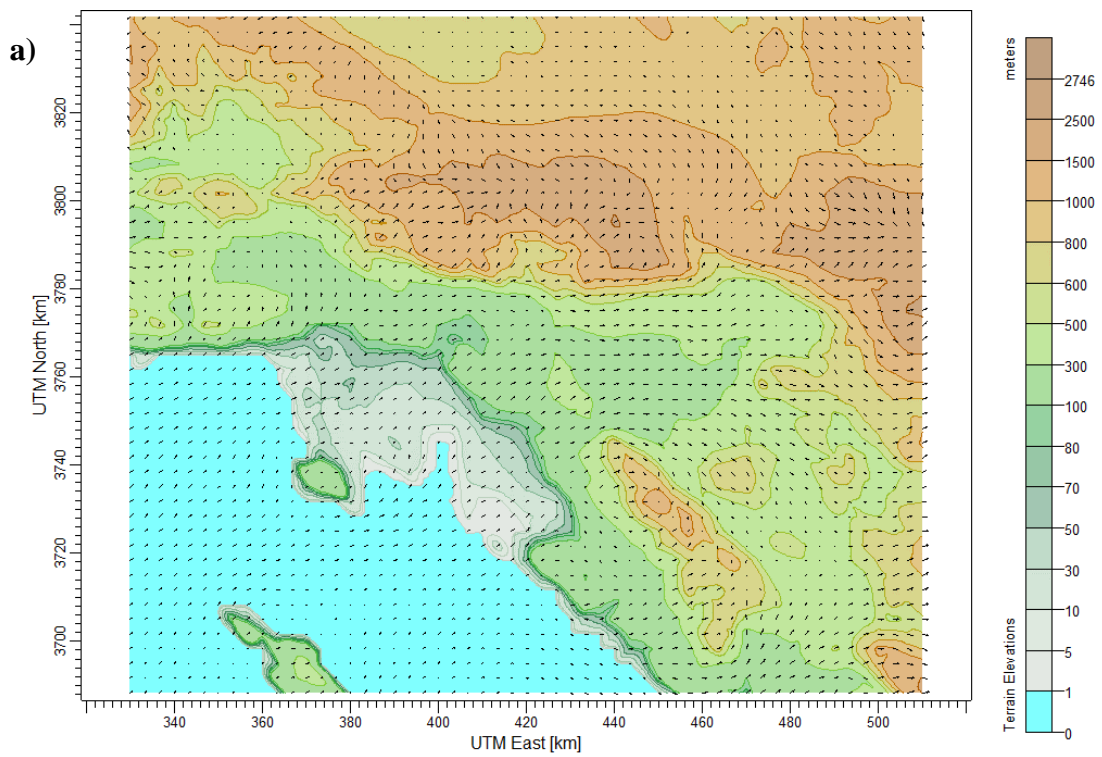
Fig. 18. Continued for (a) 25 October 2007 and (b) 27 October 2007 1900 UTC.

3.5 GIS and CALPUFF Modeling

Fig. 19 displays fires that burned over 175 acres between 20 and 31 October provided by the Air Resources Board. Georeferenced fire "footprints" (polygons of total area burned) were retrieved from an interagency wild and prescribed fire geodatabase (FRAP 2012). Data included location, final extent of the fire perimeter (burn area), timing, and other attributes associated with wildfires. The geodatabase classifies wildfires according to management objective: suppression or non-suppression (wildfire use for resource benefit).

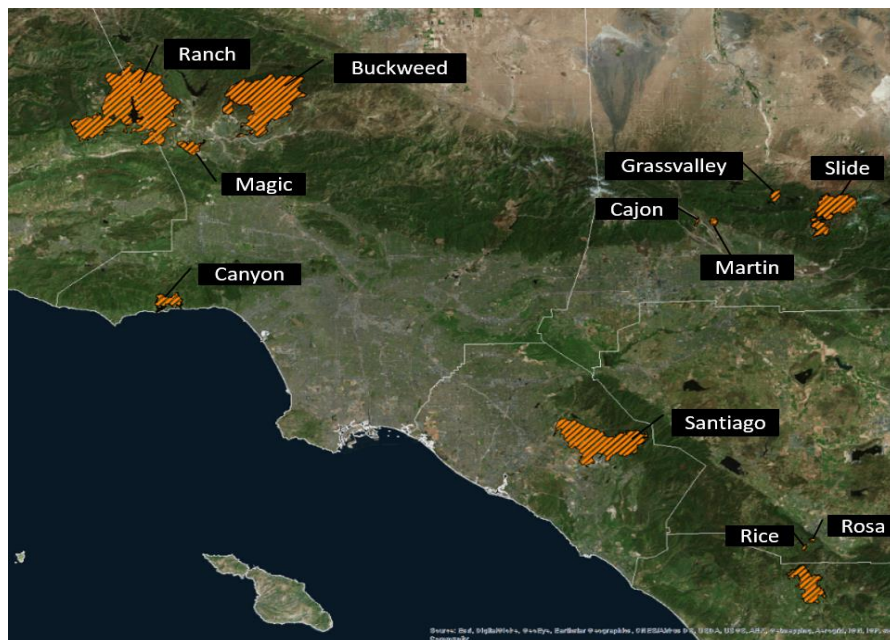**Fig. 19.** GIS "footprints" (polygons of total area burned) of wildfires for Southern California from 20-Oct-07 to 31-Oct-07. (Air Resources Board, 2015).

Satellite imagery by NASA (Fig. 20), shows the behavior of smoke plumes between 23 and 25 October. It is apparent that the smoke plume was being blown offshore on October 23rd (Fig. 20a). On October 24th (Fig. 20b), a shift in wind caused the plume to

diffuse closer to the fires and recirculated the smoke onshore. By the 25th (Fig. 21a), winds are weaker (Fig. 18a), and the offshore marine layer forced the smoke back over land. On October 26th (Fig. 21b), plumes veered northward.
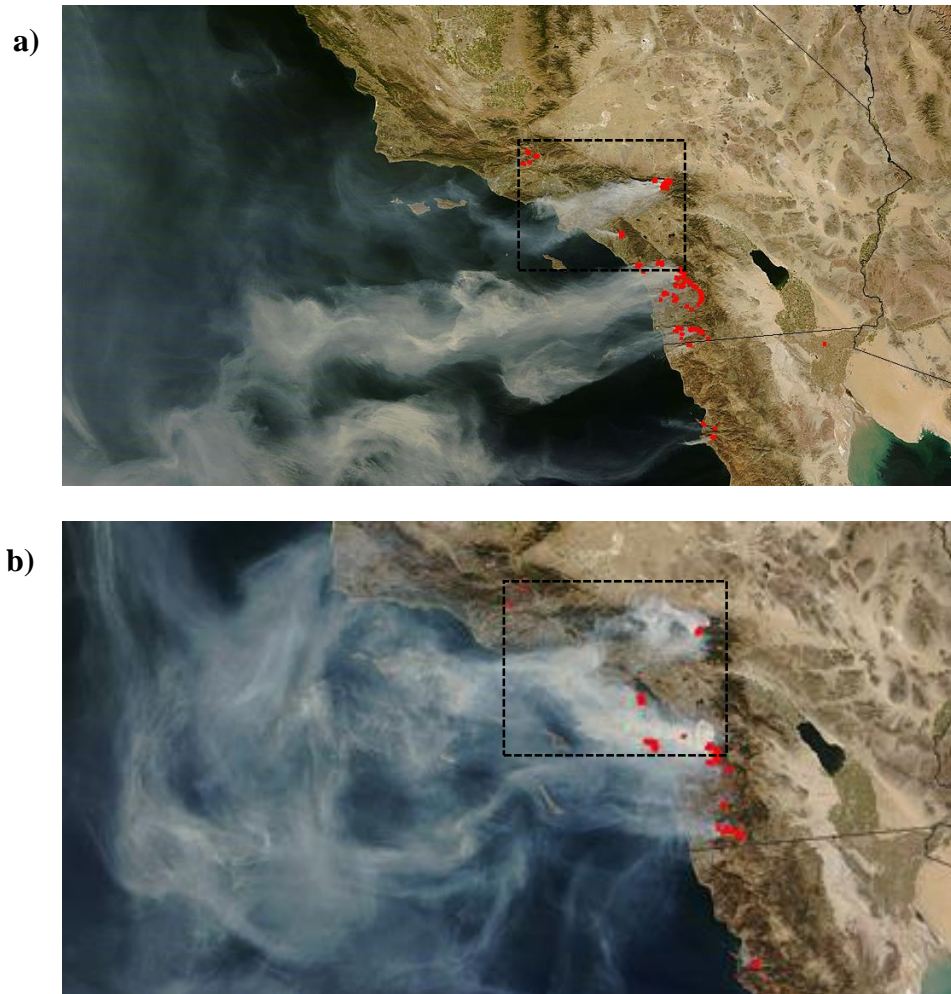

Fig. 20. NASA's Terra Satellite passage over southern California on (a) 23-Oct-2007 1825 UTC (b) 24-Oct-2007 1910 UTC.
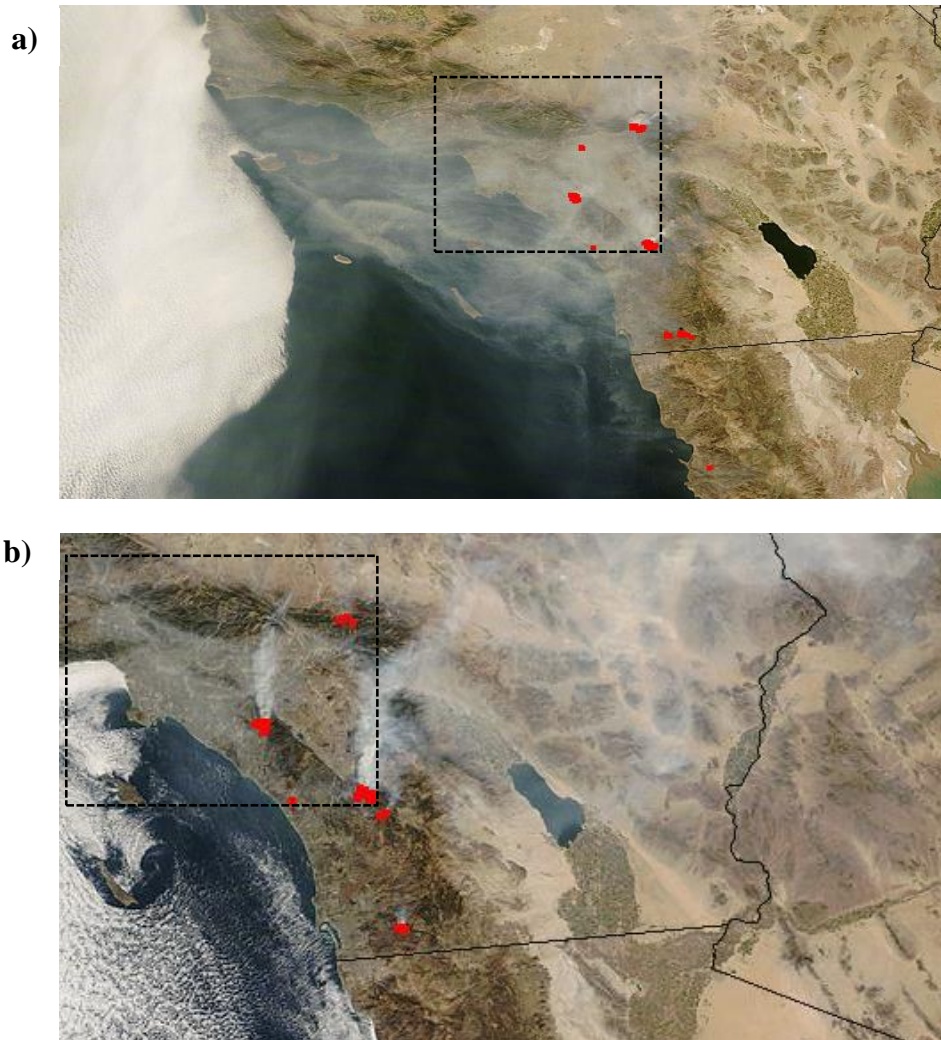
Fig. 21. Continued for (a) 25-Oct-2007 1815 UTC and (b) 26-Oct-2007 1855 UTC.

The plume for all four schemes on October 23rd (Fig. 22), appeared qualitatively similar to the satellite image (Fig. 20a), and their directions were alike. The ISC scheme had the highest levels of PM$_{2.5}$ at the Buckweed and Ranch fire sites, up to 2000 μgm^{-3}. Compared to satellite observations (Fig. 20a), simulations of the plume appeared slightly toward the south. The difference was likely due to wind effects. In addition, it is uncertain from looking at satellite imagery how high the plume was in the atmosphere.
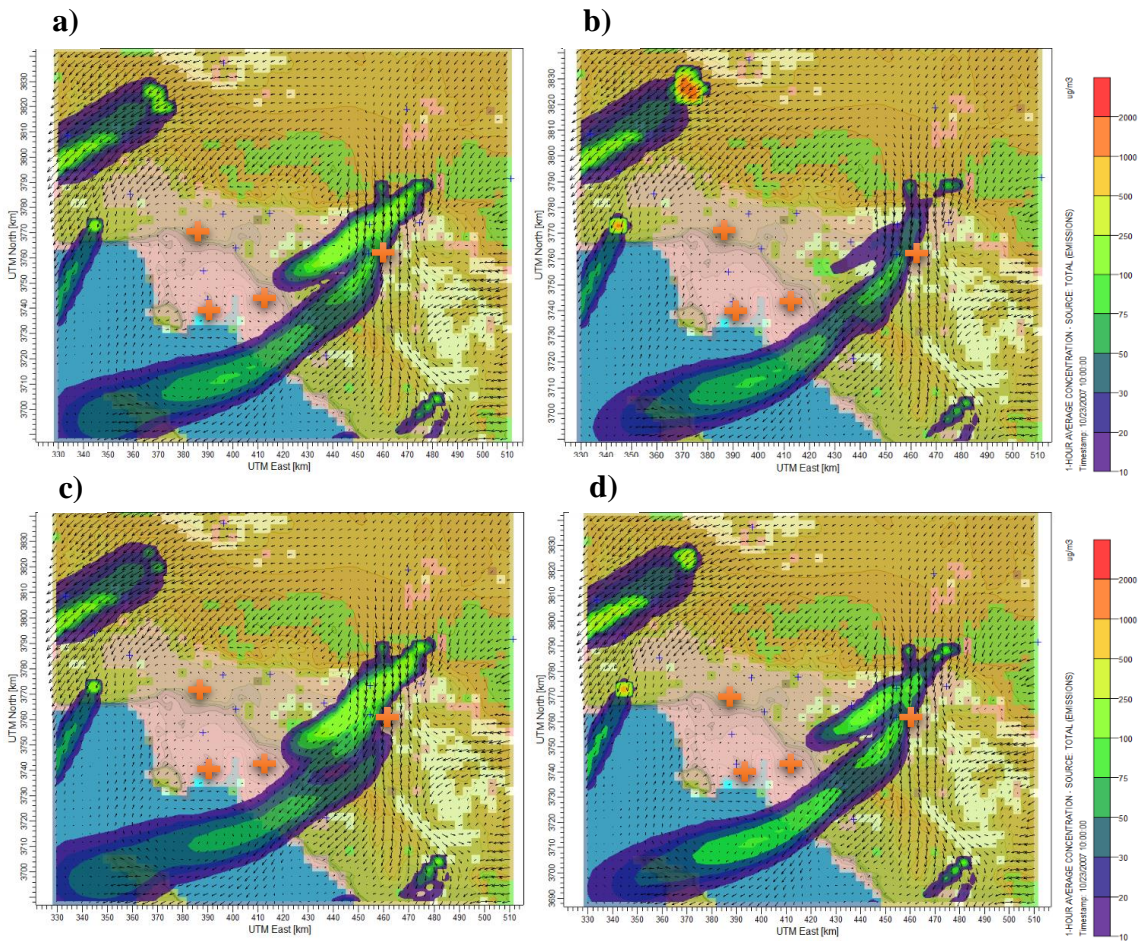
Fig. 22. 23 October 2007 1800 UTC 10-meter height 1-hour average Total Emissions Concentrations for complex terrain effects options (a) No Adjustment (b) ISC Adjustment scheme (c) CALPUFF Adjustment scheme (d) Partial Plume Path Adjustment with wind vectors, land use, and terrain elevations.

On October 24th (Fig. 23), most of the plumes diminished and dispersed laterally, likely due to the decrease in Santa Ana winds. Canyon fire (Fig. 19), was fully contained with no plume visible. The CALPUFF scheme appeared to have a greater dispersal impact from the Cajon and Martin fires compared to the other schemes. Ranch, Buckweed, and Magic fires had PM$_{2.5}$ levels close to its source between 250-2000 μgm^{-3}, the highest levels compared to all other fires. Satellite observations (Fig. 20b), showed a

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steady plume recirculation throughout the region, including smoke from the San Diego county fires, but were not visible within the domain.
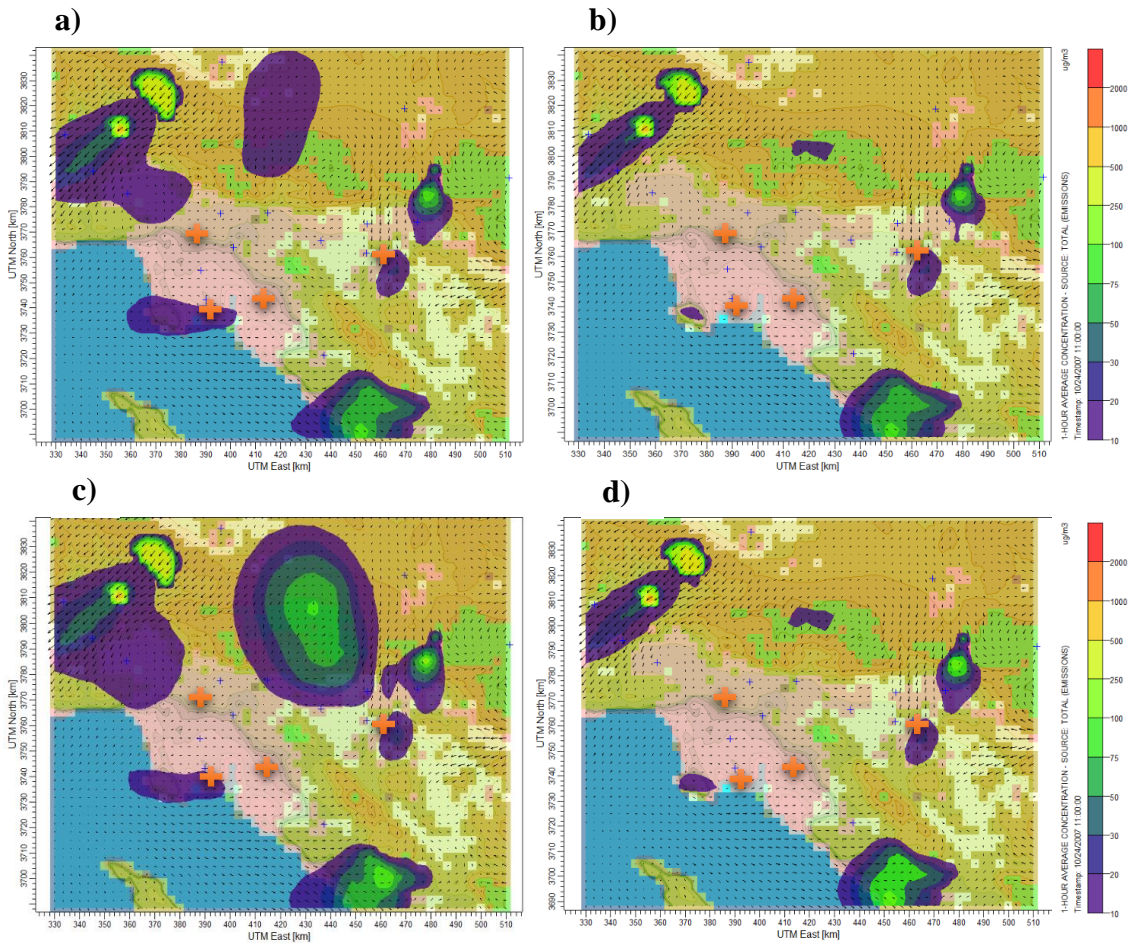
Fig. 23. Continued for 24 October 2007 1900 UTC.

On October 25th (Fig. 24), winds shifted and speeds were close to zero (Fig. 18a). The CALPUFF scheme modeled greater plume dispersal from the Slide and Grassvalley fires that extended to the Orange County coasts. Compared to satellite observations (Fig. 21a), smoke continued to be re-circulated from the San Diego County fires into the domain but such smoke was not visible in the runs. The Rubidoux ground receptor (Fig.

29), showed an increase in PM$_{2.5}$ levels whereas the models did not capture that increase,

likely due to the recirculation of smoke.

Fig. 24. Continued for 25 October 2007 1800 UTC.

By October 26th (Fig. 25), very little of the fires remain, with plumes being shifted

northward consistent with satellite observations (Fig. 21b), and wind observations.

However, the time series (Fig. 26-29), for ground observations showed higher PM$_{2.5}$
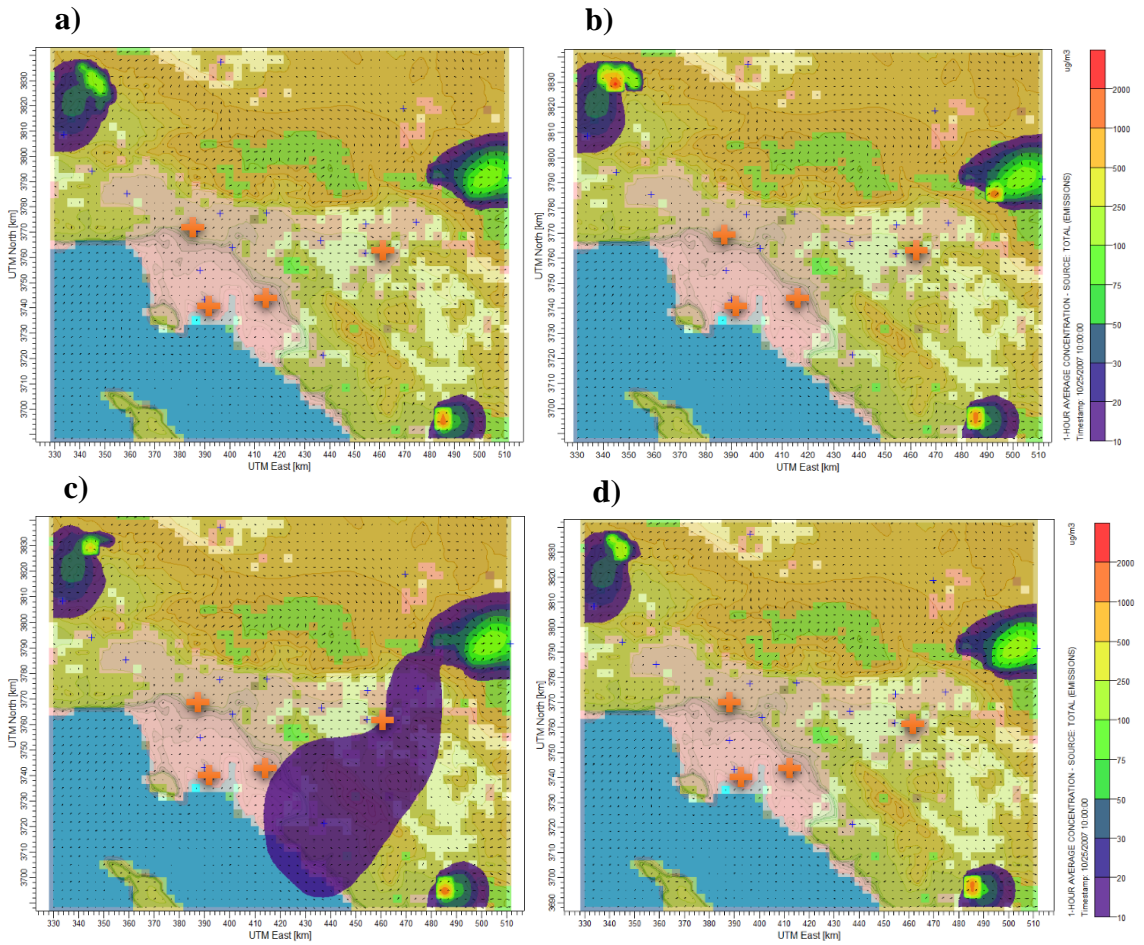
levels than all modeled runs. Because winds shifted northward, smoke from San Diego

county fires made its way into the domain, only visible on satellite but not in any of the runs.
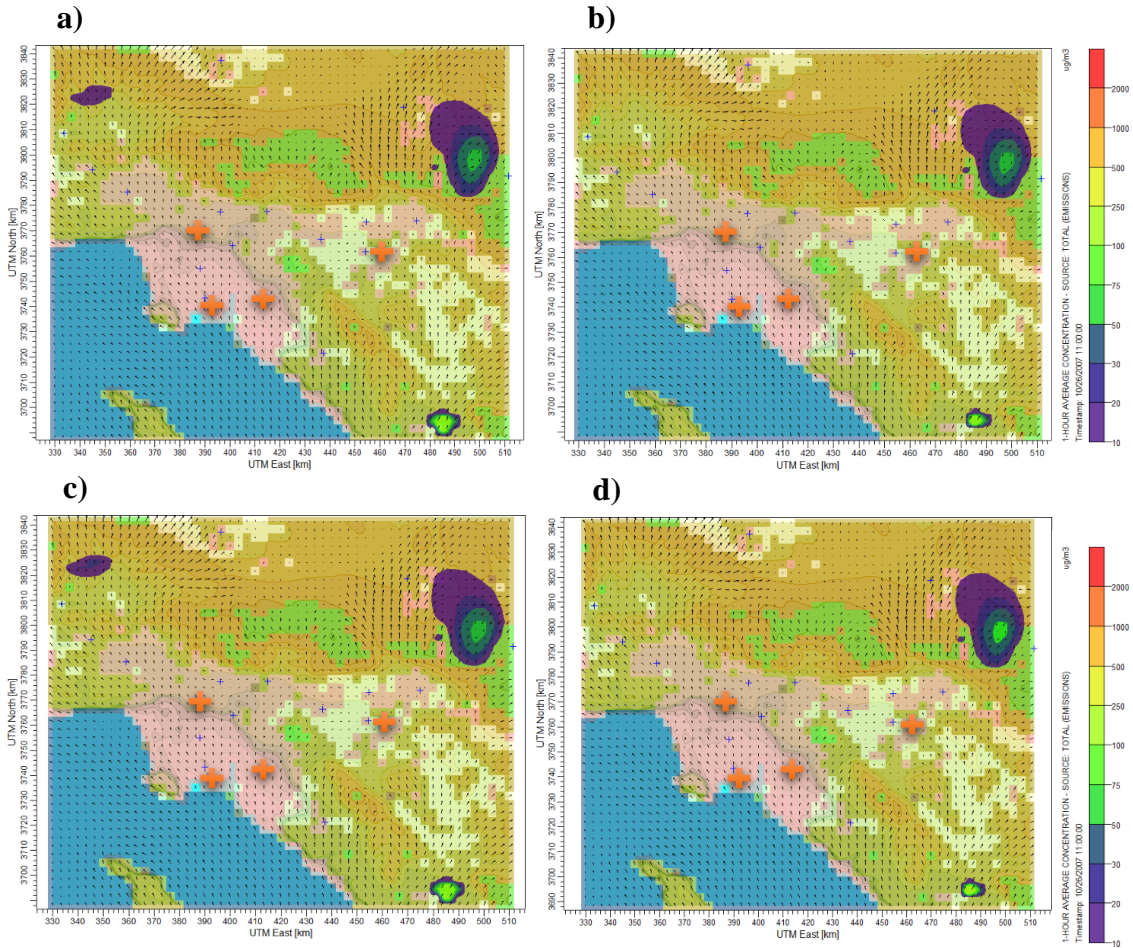
Fig. 25. Continued for 26 October 2007 1900 UTC.

Time series of daily mean PM$_{2.5}$ concentrations and their difference between observed and modeled levels are shown in Fig. 26 through 29 for ground observations and all four terrain adjustment schemes. As reference, the NAAQS for PM$_{2.5}$ was plotted. It is important to note that PM$_{2.5}$ devices vary between filter and continuous monitoring. Filter device measurements are usually conducted every 3rd day as opposed to daily measurements by continuous monitoring devices. Of the 20 receptor points modeled, we

focused on sites that provided 80% or more data for ground observations during the 7-day period. Rubidoux (Fig. 29), was the only site with continuous monitoring and available measurements.

Background values were computed per county by using the average $PM_{2.5}$ for all October months (2007-2009). The following formula was used to find the difference between ground observation and modeled $PM_{2.5}$:

$$\Delta=Observed\text{-}(modeled+background) \tag{2}$$

The most significant differences in estimates were visible between October 22nd and October 24th. These differences were due to the small displacements in the dispersion of the plume. At the Anaheim site (Fig. 26), the CALPUFF scheme overestimated emissions on October 23rd by a factor of nearly 2, greater than all other schemes. CALPUFF again overestimated emissions at Los Angeles (Fig. 27), by a factor of 1 and Long Beach (Fig. 28), by a factor of 1.5. At the Rubidoux site (Fig. 29), the No Adjustment scheme had the greatest overestimation by a factor of over 2. The ISC scheme was the most conservative at Anaheim, Los Angeles, and Long Beach. The No Adjustment scheme was closest to the observed values at Anaheim and Long Beach, Partial Plume Path scheme at Los Angeles, and ISC scheme at Rubidoux.
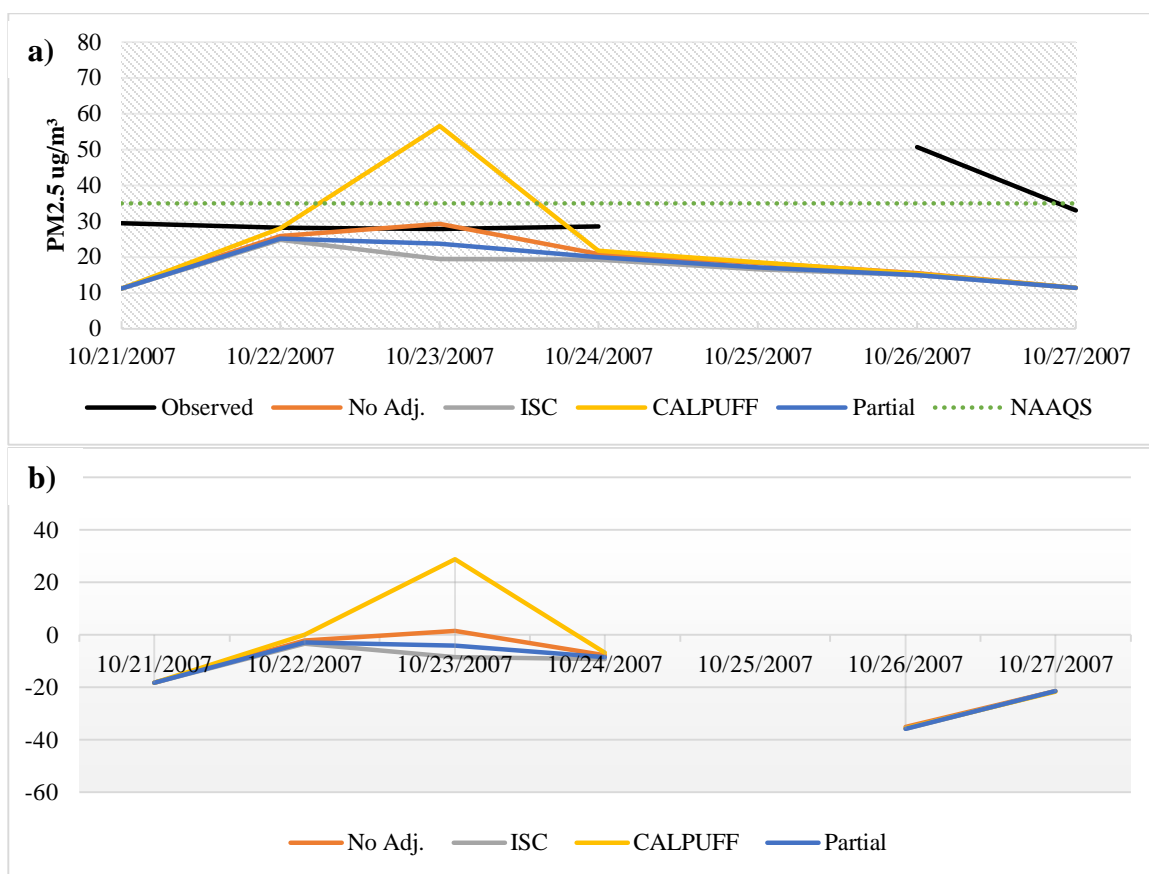
Fig. 26. (a)24-hour averaged time series of observed and modeled PM$_{2.5}$ concentrations and (b) difference between observed and modeled concentrations for receptor site Anaheim from 21-Oct-07 to 27-Oct-07.

On October 24th Anaheim, Long Beach, and Rubidoux, had predicted emissions for all four schemes at differences less than 10 µgm^{-3} from ground observations. At the Los Angeles site ISC and Partial Plume Path schemes performed best at differences less than 4 µgm^{-3}.

From October 25th and onward, all schemes had a similar trend with a near equivalent underestimation from the observed values by a factor of 1.5. These predictions included emissions from the wildfires within the domain but not the emissions from the 359,670 acres that burned in the San Diego region (Fig. 21).
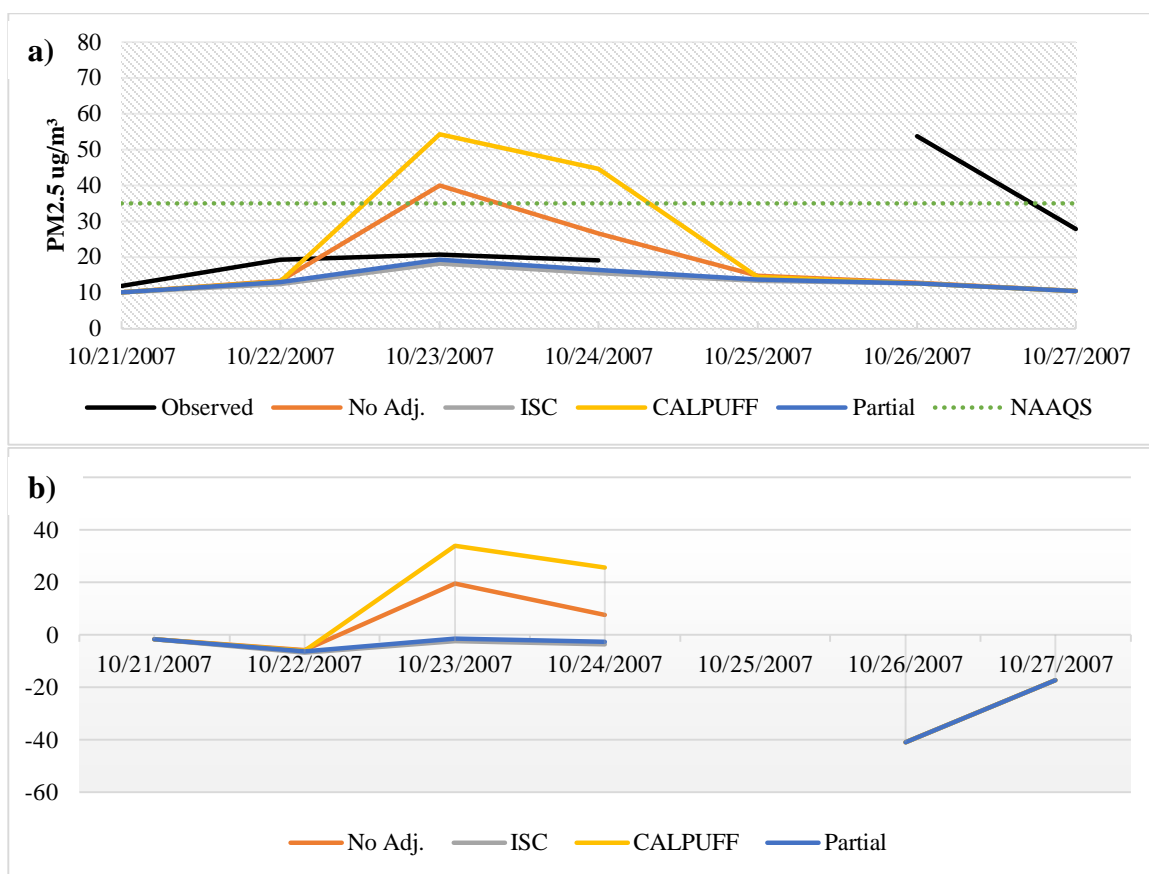
Fig. 27. Continued for Los Angeles.

Strictly looking at performance of the models two types of observations were noted. First, all four sites were evaluated daily between 21 and 27 October. The scheme with the smallest difference between the observed value and the modeled value on that day was marked. CALPUFF scheme performed best at the Anaheim and Long Beach sites, Partial Plume Path performed best at Los Angeles, ISC scheme performed best at Rubidoux. Second, we looked at individual days for all receptors whose ground observations were given between 21 and 27 October and noted all schemes whose difference were closest to the observed value and below 10 μgm^{-3}. Out of 19 available

ground observations CALPUFF scheme performed best in 8 instances, No Adjustment and Partial Plume Path schemes tied at second with 4 instances each, and ISC scheme with 3.
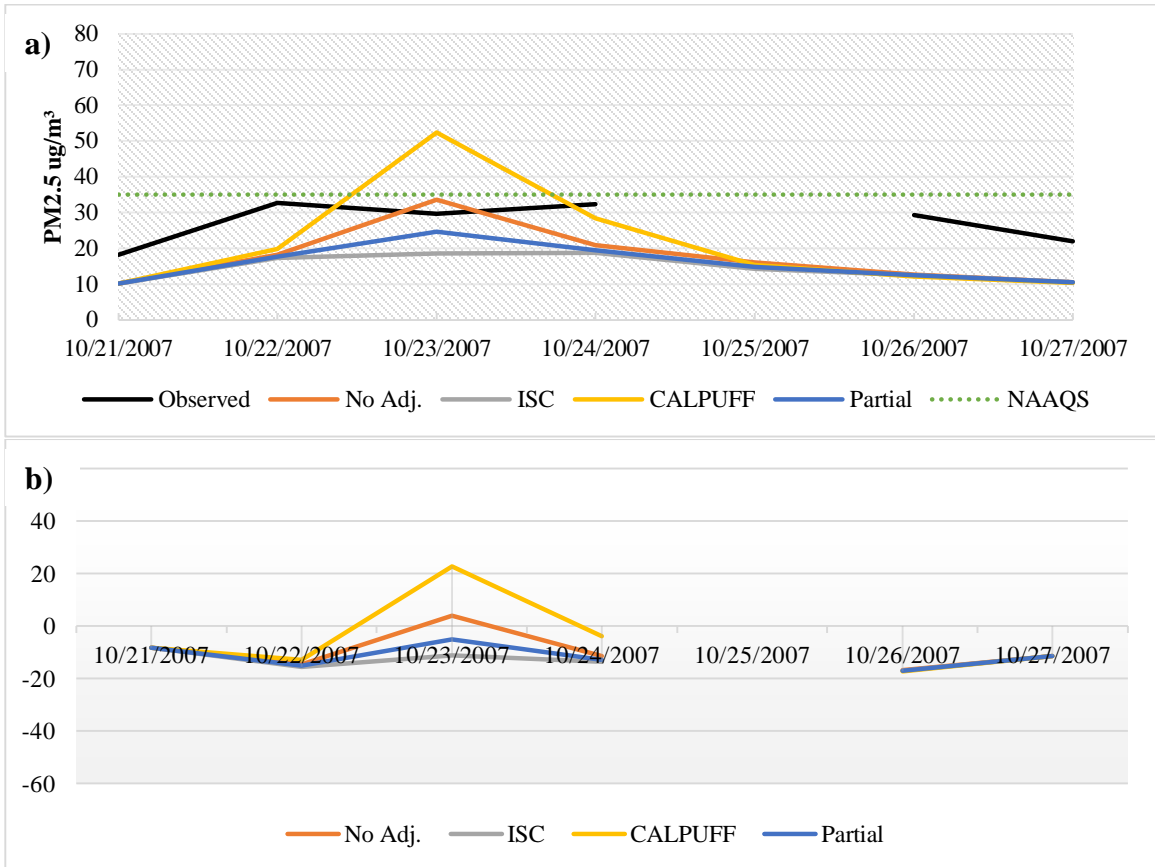
Fig. 28. Continued for Long Beach.
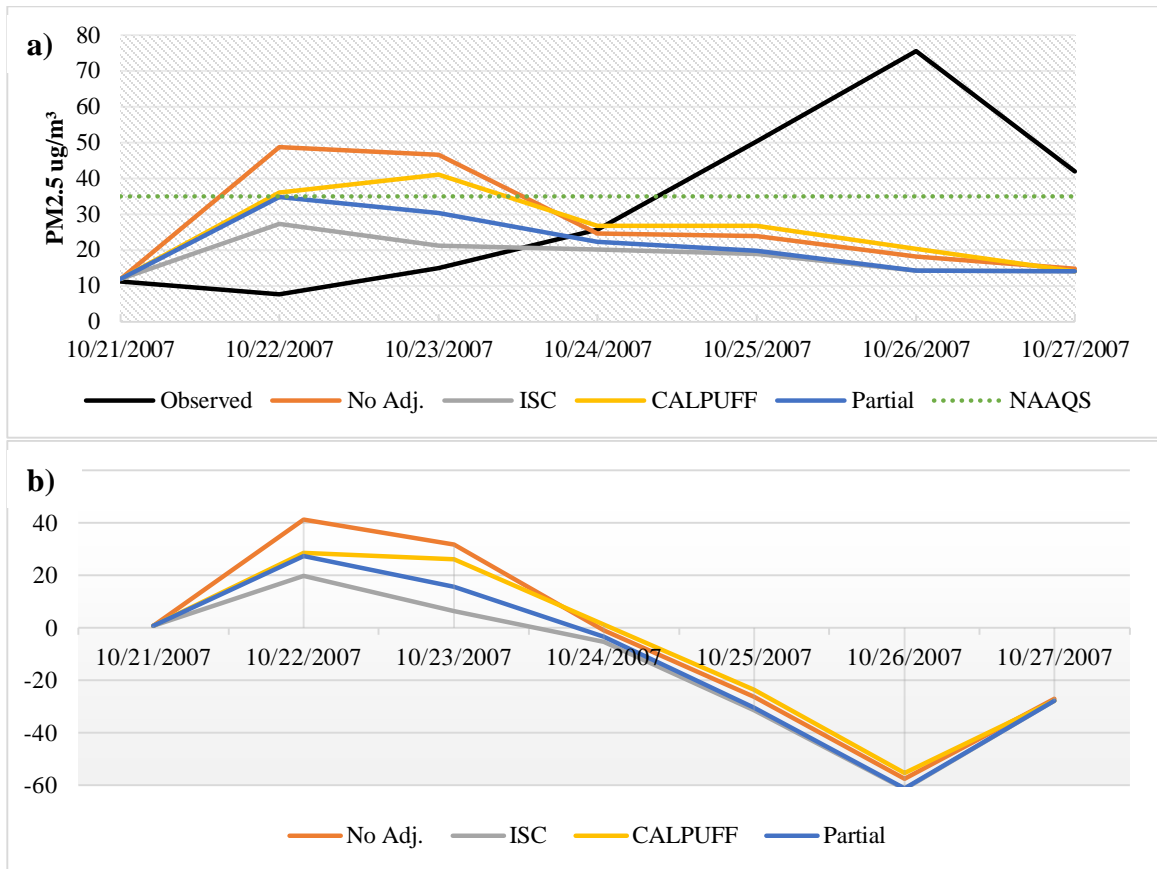
Fig. 29. Continued for Rubidoux.

Fig. 30 through 32 show observed and modeled concentrations for all receptors on October 23rd. Four receptors had ground observations (Fig. 30), on this date with PM$_{2.5}$ levels between 11 and 30 μgm^{-3}.
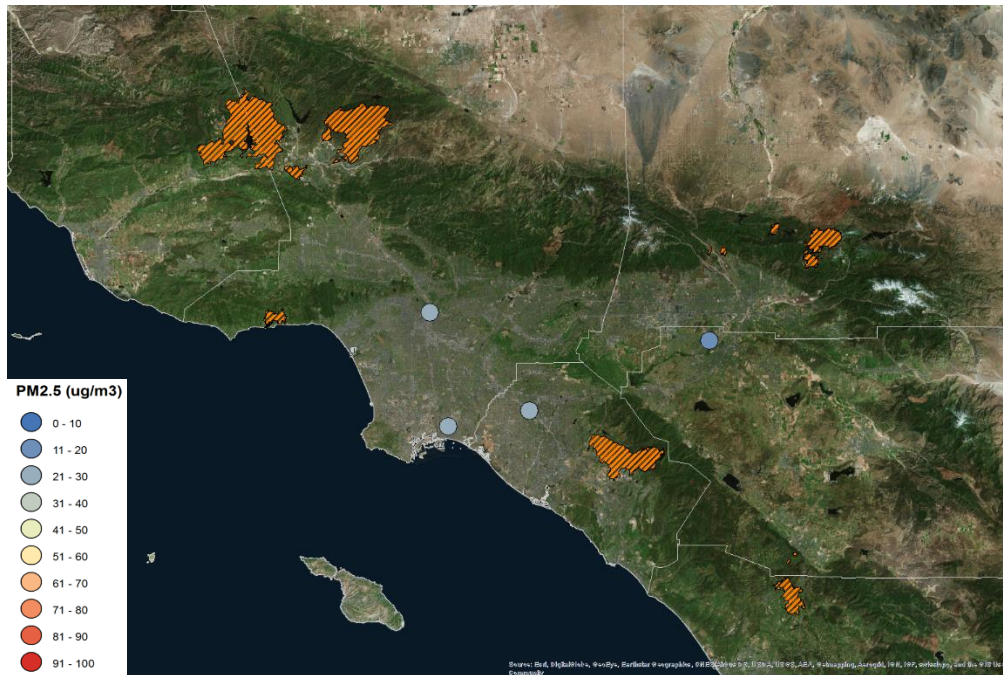
Fig. 30. 23 October 2007 24-hour average PM$_{2.5}$ concentration values at selected receptors (μg/m³) for ground observations.

The ISC (Fig. 31b), and Partial Plume Path (Fig. 32b), schemes had levels between 11 and 40 μgm^{-3} throughout the region. The No Adjustment (Fig. 31a), and CALPUFF (Fig. 32a), schemes had more clearly defined areas of impact with levels modeled up to 100 μgm^{-3}.
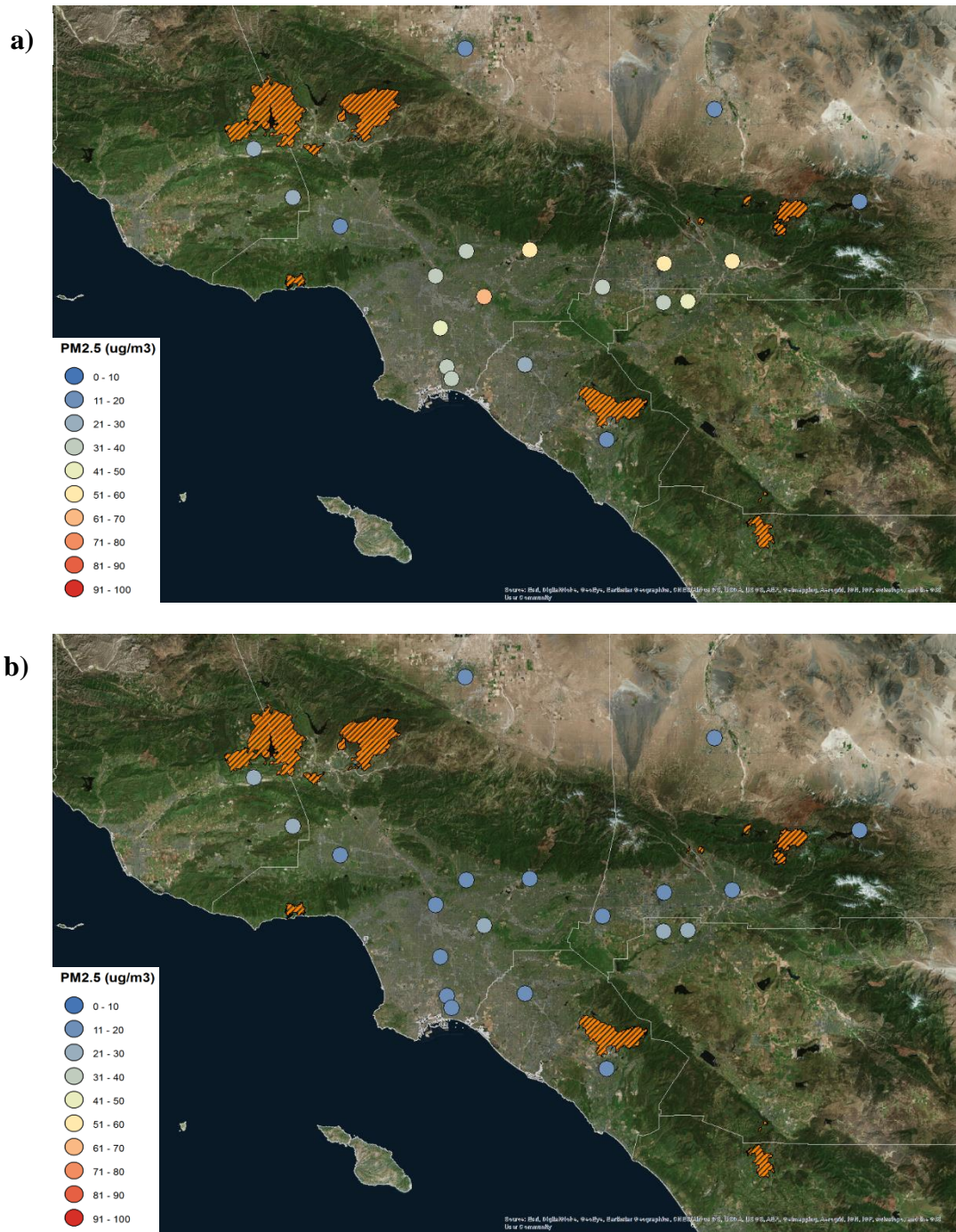
Fig. 31. Continued for (a) No Adjustment Scheme and (b) ISC Adjustment Scheme.
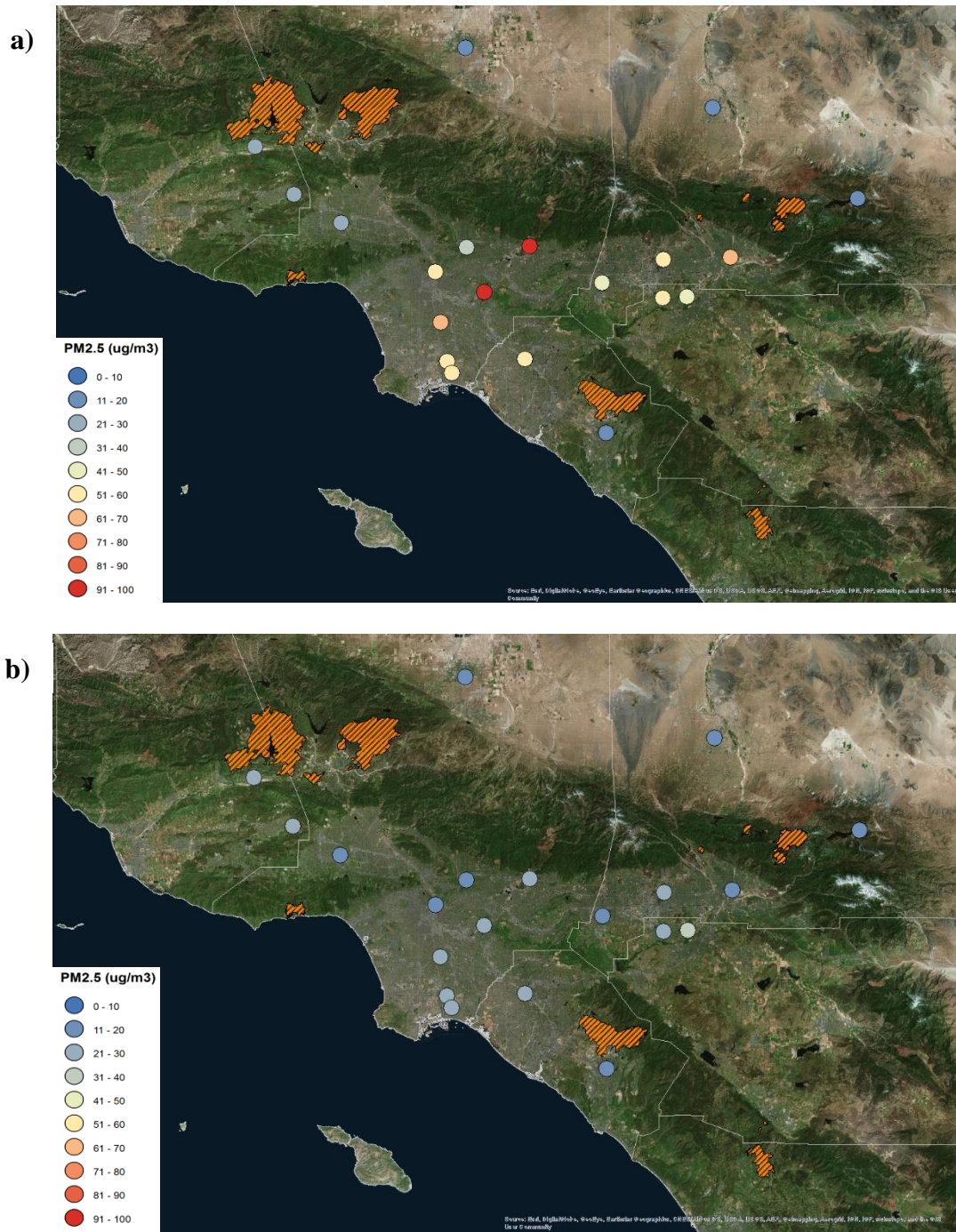
Fig. 32. Continued for (a) CALPUFF Adjustment Scheme and (b) Partial Plume Path Scheme.

5. Conclusion and Future Work

Three years' worth of data was analyzed to find the association between daily asthma emergency department visits and exposure to O_3, NO_2, CO, $PM_{2.5}$, dew point temperature, air temperature, and winds during wildfire peaks. Two datasets per county were created to perform correlations. The first dataset included daily rates for all variables while the second dataset excluded all fire events that took place within that county. Among all the variables, the most significant correlation was that of asthma and $PM_{2.5}$. This pair's correlation decreased considerably from the original dataset to the modified dataset during fall of 2007 given in Table 6. It is clear that fires contributed to the higher correlation between $PM_{2.5}$ and asthma ED visits during this period. However, fires are not the sole reason for increases in asthma ED visits. Other factors like stress and emotion or respiratory infections could have contributed as well.

Furthermore, from Table 3 we know that the average number of asthma ED visits has increased over time. It is yet to be determined if this increase is due to fire events or other environmental or political influences. The data provided in this research may suggest designs in future studies on understanding the relationship between fires and health such as acres burned and asthma ED visits.

An outbreak of wildfires took place during the last 10 days of October 2007. Using this information, the wildfires were simulated using BlueSky's air modeling framework to assess the accuracy of $PM_{2.5}$ concentrations produced by the WRF/CALMET/CALPUFF pathway. This pathway (Table 2), was uniquely chosen since it had not been used before to simulate wildfires in Southern California.

A sensitivity analysis was conducted for the different terrain effect schemes. Results from this model framework proved to be accurate within 10 μgm^{-3} on October 24th for all schemes, but varied for all other dates. From October 26th and onward, $PM_{2.5}$ underestimations were likely a result of the absence of modeled wildfires. A noteworthy amount of burned acres from wildfires in San Diego County were not included in the domain. Future work will include resizing the domain to include these fires, potentially providing an improved estimation of $PM_{2.5}$ levels.

In addition, uncertainties in the pathway contributed to the variability of $PM_{2.5}$ estimates. The ICS-209 summary relies heavily on information entered at the incident or dispatch level. Inadequacies include missing, incomplete, or incorrect records and untimely submission of final reports (Thompson et al. 2013). The information provided by this report is used for import into FEPS and thus needed for more accurate modeling, most importantly the daily perimeter growth of the fire. However, FEPS has its own limitations such as errors in characterizing fuels and fuel consumption (Hardy et al., 2001; Peterson, 1987; Peterson & Sandberg, 1988). This surfaces from FEPS's usage of NFDRS which classifies fuel beds and fuel loads by region. Any variation in fuel loading can contribute up to 80% of the error associated with estimating emissions (Peterson, 1987; Peterson & Sandberg, 1988).

The area source plume rise option in CALPUFF is designed to calculate the rise of buoyant plumes resulting from forest fires. However, complex terrain features influence meteorological conditions like temperature and wind patterns, creating a slight deviation in the location of the modeled plume and inexact concentration estimates. This

is a direct result from WRF output that is regularly updated to provide more precise data that could help improve CALPUFF's modeling.

In conclusion, this study created a methodology that confirmed the association between asthma and increased levels of $PM_{2.5}$ and explored a framework in BlueSky not previously used in the 2007 wildfires of Southern California.

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APPENDIX A.

Models and Acronyms

Acronym or model	Description
AQS	Air Quality System
AQMIS	Air Quality and Meteorological Information System
ARB	California Air Resources Board
BlueSky	BlueSky smoke modeling framework
CALFIRE	California Department of Forestry and Fire Protection
CALMET	Diagnostic 3-D meteorological processor for CALPUFF
CALPUFF	Gaussian puff dispersion model
CDC	Centers for Disease Control
CH4	Methane
CO	Carbon Monoxide
DISC	NASA Data and Information Services Center
ED	Emergency Department
EPA	US Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FEPS	Fire Emissions Production Simulator
GACC	Geographic Area Coordination Center
GES	NASA Goddard Earth Sciences
GIS	Geographic Information System
ICD	International Classification of Diseases
ICS-209	Incident Command System 209 reports
MM5	Mesoscale Meteorological model Version 5
MODIS	Moderate Resolution Imaging Spectroradiometer
NAAQS	National Ambient Air Quality Standards
NAM	North American Mesoscale Forecasting System

NASA	US National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Predictions
NFDRS	US National Fire Danger Rating System
NOAA	US National Oceanic and Atmospheric Administration
NO2	Nitrogen Dioxide
OSHPD	Office of Statewide Health Planning and Development
PM	Particulate Matter
PPM	Parts per million
RMA	Riverside Municipal Airport
RRTM	Rapid Radiative Transfer Model
SCAQMD	South Coast Air Quality Management District
SLAMS	State or Local Air Monitoring Stations
SMARTFIRE	Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation
SMOKE	Sparse Matrix Operator Kernel Emissions
SO2	Sulfur Dioxide
USDA	US Department of Agriculture
USC	University Southern California
WONDER	CDC Wide-ranging Online Data for Epidemiologic Research
WRF	Weather Research and Forecasting meteorological model