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Use of Satellite Images to map Spatio-temporal Variability of $PM_{2.5}$ in Air

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Use of Satellite Images to Map Spatio-temporal Variability of $PM_{2.5}$ in Air

Saif Uddin

Abstract

Dust storm episodes are among the most important weather phenomena in arid countries around the world. Fine particulate matter in the air is a major health hazard; besides, dust storms can alter air temperatures as a result of scattering and absorption of solar radiation. The size and type of aerosol have a major influence on radiation, in addition to cloud cover and surface albedo. Heavy dust storms have been reported to result in the lowering of ocean temperatures which may affect primary productivity of seas and oceans, and impact carbon dioxide sequestration. The rates of dust fallout in Kuwait had been reported to be among the highest in the world with mean monthly concentrations as high as 1400 $\mu g\ m^{-3}$. Remote sensing measurements by virtue of their synoptic monitoring capabilities were used to quantify dust on a large spatiotemporal scale. The satellite data set from the Multiangle Imaging Spectro Radio Meter (MISR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) were used for determining the aerosol optical depth (AOD) over land and ocean surfaces through observation at visible and infrared wavelengths. The AODs were used for $PM_{2.5}$ quantification and generation of $PM_{2.5}$ spatio-temporal trends. These data sets were downloaded from the Atmospheric Sciences Data Center of the National Aeronautical and Space Administration (NASA) Langley Research Center (LARC) from 2008 to 2014. The satellite-derived particulate matter (PM) counts were verified by field measurements using an infrared particle counter and high-volume air samplers. One high-volume air sampler (HVAS) equipped with a six-stage cascade impactor was deployed at Abdalli (Iraq-Kuwait Border) and at Kuwait City (KISR). Particulate counts and particulate mass were recorded using Aerocet 531 particle counters at both sites to further calibrate the measurements. The accuracy of the MISR determination was 68% and 62% for MODIS. This satellite data derived $PM_{2.5}$, using AOD can be used as surrogate for PM measurement.

Keywords: Aerosol Optical Depth, Dust, Health, Particulate Matter.

Introduction

Dust storm episodes are among the most important weather phenomena in arid countries around the world (Al-Awadhi, 2005; Chi et al., 2008; Garrison et al., 2006). They are caused by high-energy winds eroding the topsoil in regions with a minimal vegetation cover. Kuwait and other countries in the Middle East experience some of the worst dust storm episodes around the world. Kuwait is particularly susceptible to dust storms because of its low topography, scant vegetative cover, and strong turbulent winds that occur particularly in the summer months (Al-Awadhi, 2005). The rates of dust fallout in Kuwait had been reported to be among the highest in the world (Foda et al., 1985) with mean monthly concentrations as high as 1400 $\mu g\ m^{-3}$.

It is possible to trace the origin of dust and its transport pathway from the nature of the particulate matter (PM). The frequency of dust activity can be related to long- and short-term climate changes (Prasad and Singh, 2007). Climatic processes can also be affected by dust events (Boucher and Haywood, 2001). Air temperatures, for example, may be altered by dust as a result of scattering and absorption of solar radiation (Li et al., 1996; Moulin et al., 1997; Alpert et al., 1998; Miller and Tegen, 1998; Goudie and Middleton, 2001). Suspended dust modifies the short-wave solar radiation transmitted through to the earth and the long-wave infrared radiation emitted to space (Goudie and Middleton, 2001). Also, the size and type of aerosol have a major influence on radiation, in addition to cloud cover and surface albedo. Heavy dust storms have been reported to result in the lowering of ocean temperatures which may affect primary productivity of seas and oceans (Pierson et al., 2003) and impact carbon dioxide sequestration (Ridgwell, 2002). This study utilized satellite data to estimate atmospheric aerosol especially $PM_{2.5}$, which had been reported to have a significant effect on human health (Dockery et al., 1993; Pope and Dockery, 2006; Pope et al., 2002) and on the regional and global climatic changes (Hansen et al., 1998; Hurtado et al., 1996; Ramanathan et al., 2007; Hu et al., 2010). Several reports have indicated that dust serves as a vehicle for long-range transport of associated contaminants including viruses (Griffin, 2007; Reynolds and Pepper, 2000; Williamson et al., 2003; Yates and Yates, 1988), pathogens (Garrison et al., 2006; Griffin, 2007; Griffin et al., 2002), trace metals (Di-Lella et al., 2006), and organic pollutants (Di-Lella et al., 2006; Gevao et al., 2011).

Remote Sensing-Based Measurements

Remote sensing measurements by virtue of their synoptic monitoring capabilities can be used to quantify dust on a large spatiotemporal scale. Currently, the Multiangle Imaging Spectro Radio Meter (MISR), which can determine AOD over land and ocean surfaces through observation at visible and infrared wavelengths (King et al., 1992, 1999; Kaufman et al., 1997; Diner et al., 1998, 2002; Martonchik et al., 1998, 2002; Kahn et al., 1998, 2005a,

2005b; Liu et al., 2004, 2005, 2007a, 2007b, 2009; Hu et al., 2010) was used. Images over Kuwait and adjacent areas were procured from the National Aeronautics and Space Administration (NASA). The relationship between the MISR AOD and surface $PM_{2.5}$ was established. The $PM_{2.5}$ data was also correlated using in situ measurements at two calibration sites: one in Abdalli and another at the Kuwait Institute for Scientific Research (KISR) Shuwaikh. A high degree of correlation was observed between the MISR AOD and the $PM_{2.5}$ estimates. However, the relationship was empirical due to the complicated dependence on multiple factors, including aerosol chemistry, particulate size distribution, aerosol profile, and most importantly, the atmospheric conditions. Moderate Resolution Imaging Spectroradiometer (MODIS) has fewer and poor retrievals over Kuwait because of high surface albedo. However, with the collection 6 data, the problem was solved, and now, MODIS will be a more useful sensor for PM retrieval. The satellite-based measurements used in AOD as a quantitative measure of PM abundance in the atmospheric column. AOD is dominated by near surface emission sources and can be used to track long-range dust transport pathways caused by a storm event (Seinfeld and Pandis, 1998). AOD retrieved at visible wavelengths is sensitive to 0.1 to 2 μm particle size (Kahn et al., 1998b) and is not affected by gaseous co-pollutants, providing a noisy measurement of fine PM loading over large spatial areas.

Methodology

The methodology proposed by Liu (Liu et al., 2004) for PM estimation using MISR data was used. The method had demonstrated the validity of the MISR AOT with a standard ground level aerosol optical thickness (AOT) measurement from the Aerosol Robotic Network (AERONET). The sensitivity of the MISR AOT measurements from (0.05 to 2.0 μm) had also been reported (Kahn et al., 1998b, 2001; Liu et al., 2005; Hu et al., 2010). Field validation of the $PM_{2.5}$ retrievals from the satellite data sets was carried out at the Abdalli and at KISR's Shuwaikh campus on a weekly basis over the past 36 mo. The samples were collected using a high-volume air sampler (HVAS) fitted with a six-stage cascade impactor. The metrological parameters such as mixing height, relative humidity (RH), air temperature, and wind speed, which could affect $PM_{2.5}$ retrievals, using AOD were also accounted. The rapid update cycle (RUC) model of the Earth System Research (ERS) group was used to integrate the various metrological data sources.

Determination of AOD

MISR's aerosol retrieval algorithmsdoes not depend on explicit radiometric surface properties (Martonick et al., 2004, 16102 – p 1- 4, American geophysical Union). Therefore, MISR can retrieve aerosol properties

over a variety of terrain conditions, including highly reflective surfaces like Kuwait. “Observing continuously at nine distinct zenith angles and in four narrow spectral bands centered at 446, 558, 672, and 866 nm”. MISR repeats its measurements every 16 d in tropical region. Version 22 MISR aerosol data, were used, which has a spatial resolution of 17.6 km. “In this dataset, there are 74 different aerosol mixtures that are constructed from up to 3 of the 8 pre-defined aerosol components (i.e., components 1, 2, 3, 6, 8, 14, 19, and 21)” (Liu, 2009, IEEE, p.177) (Figure 1).

Each MISR aerosol component is defined by size distribution, shape, and single scattering albedo, of which the two (components 19 and 21) are designed for dust particles. “A detailed discussion of the MISR data structure, the aerosol components used to construct the aerosol models and the percentage contribution of each component to total AOD as given elsewhere”(Liu, 2009, IEEE, 177). The MISR aerosol data covering Kuwait and its surrounding areas from 2008 to 2014 were processed. The data were downloaded from the NASA Langley Research Center (LARC) Atmospheric Sciences Data Center.

MISR AOD Validation in the Gulf Region. It has been shown that MISR AOD compares well with AERONET’s observations in desert regions (Martonchik et al., 2004). We have conducted a more comprehensive validation of MISR AOD in the region. The following AERONET sites (Abu Al Bukhoosh, Bahrain, Abu Dhabi, Dhadnah, Hamim, Kuwait University, Mezaira, Mussafa, Solar Village) were identified in the study region with at least one year of operation time. These data of AERONET data were downloaded from the NASA Goddard Space Flight Center (http://aeronet.gsfc.nasa.gov/). MISR AOD maps are generated for the area (Figures 1 and 2).

Figure 1. *AOD Map for the Study Area Corresponding to 01 April 2008*

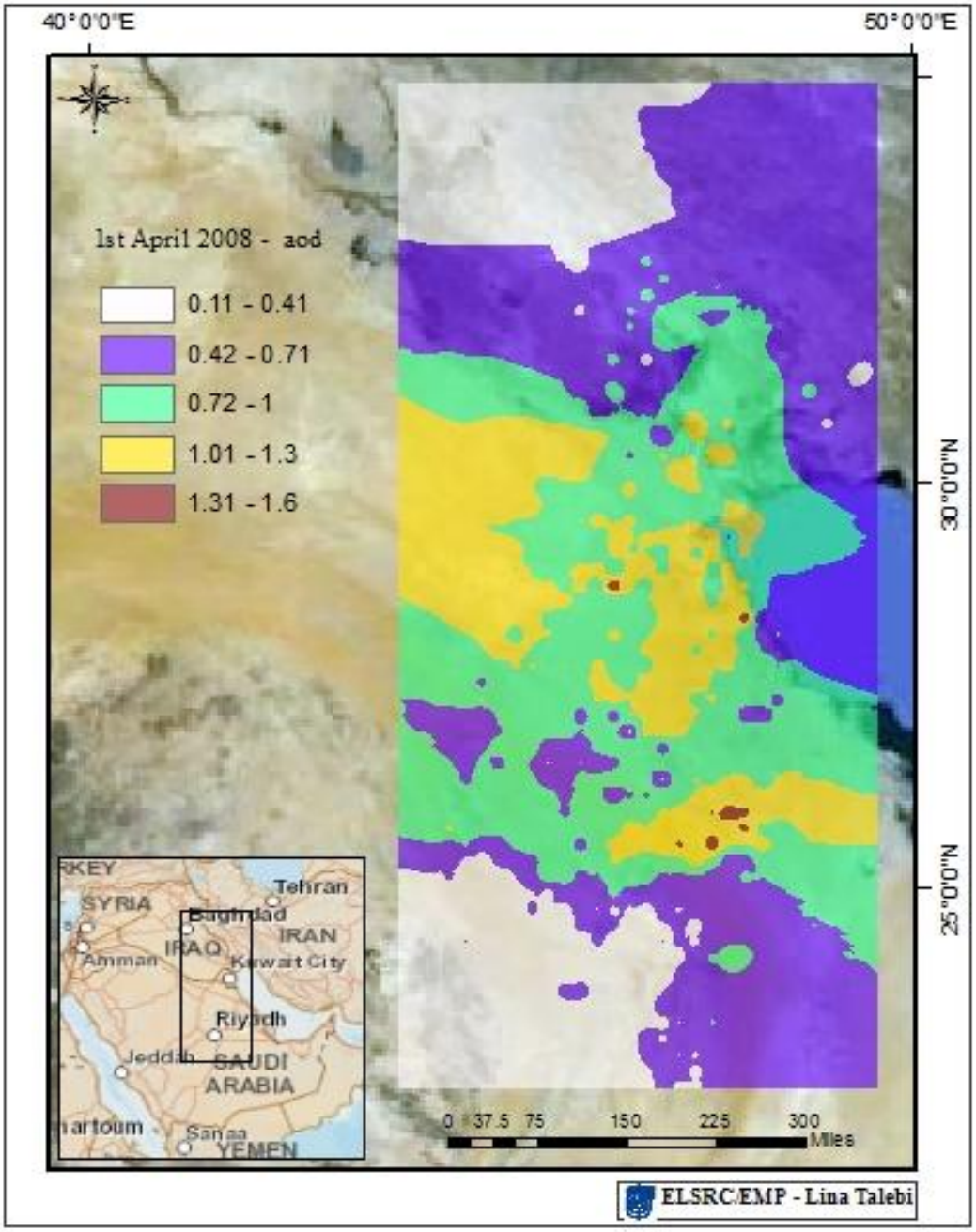
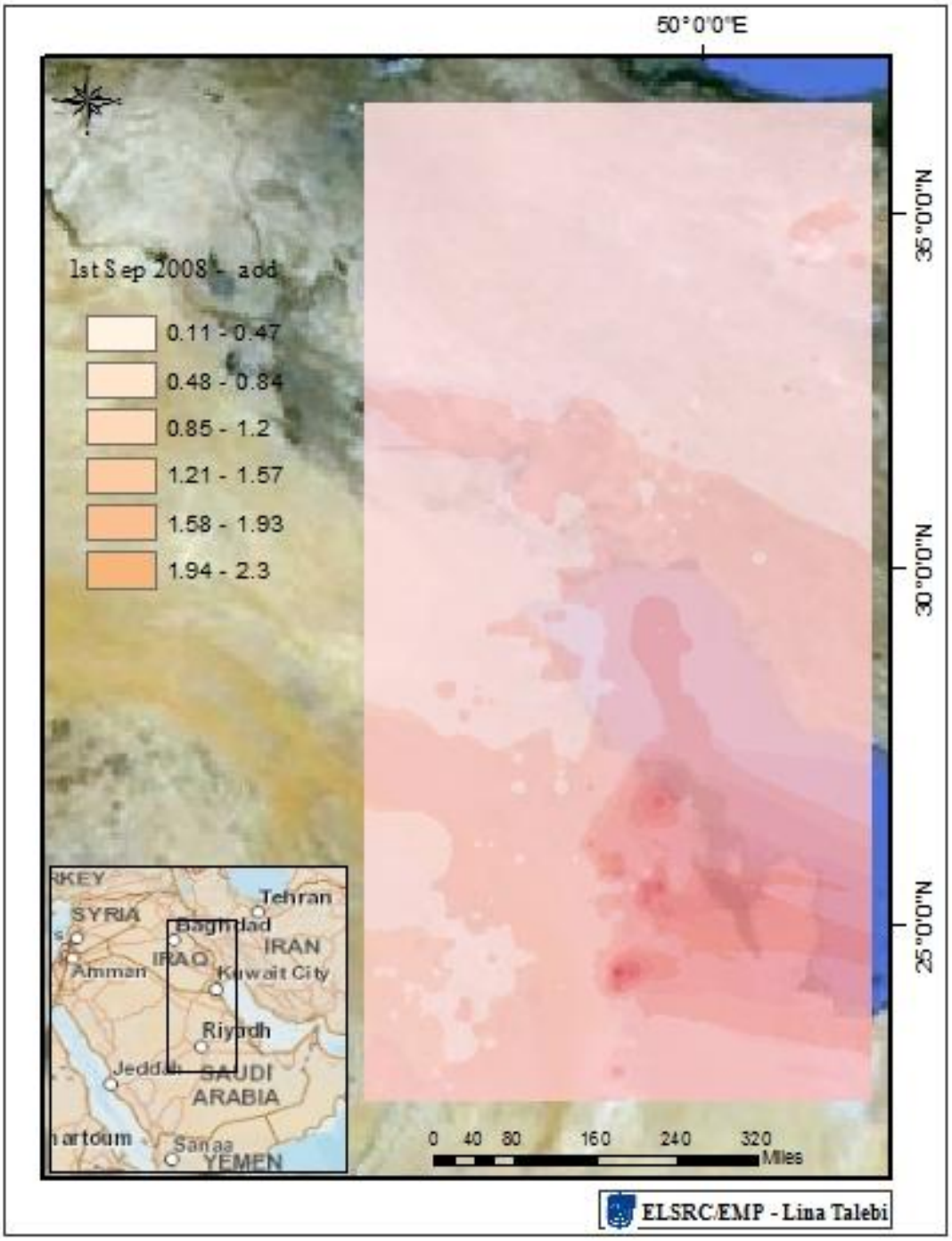


Figure 2. *AOD Map for the Study Area Corresponding to 01 September 2008*



Sampling and Particulate Quantification

The sampling campaign was initiated in April 2012. Size-segregated aerosol samples were collected using a six-stage high volume cascade impactor (Tisch Environmental, Inc) on the premises of KISR (29^o 20.227 N; 47^o 54.208 E) and Abdalli (30^o 02.312N; 47^o 49.589E). The sampler was located about 2 m above the ground. Over each sampling period that lasted 24 h, approximately 815±5 m^3 of air was drawn through the cascade impactor at a constant flow rate of 0.855 m^3/min to trap various aerodynamic particles on different filters. The particles were separated into the aerodynamic diameter (Dp) sizes ranges such as the following: < 0.39 (backup high-volume filter), 0.39 to 0.69, 0.69 to 1.3, 1.3 to 2.1, 2.1 to 4.2, 4.2 to 10.2 and > 10.2 μm. In addition to the weekly sampling, the samples were also collected on all dusty days to capture the spatiotemporal variations in the PM concentrations.

In addition to the *in situ* HVAS sampling, a noninvasive infrared (IR)-based measurement was also taken up for both particulate count and particulate mass determination using a Metone Aerocet 531 particle mass profiler and counter, which takes hourly measurements and logs the data in the built-in data logger.

Calibration of Field and Laboratory Equipment

Air volumes for each sample collected were determined using a flowmeter with a flow tantalizer, in addition to a Magnehelic gauge (Tisch Environmental, Inc.). Calibrations were done in accordance with the manufacturer's guidelines. The calibrations were performed upon installation of the sampler, and at least once every quarter.

Model Development for $PM_{2.5}$ Estimation

Given the scarcity of ground level $PM_{2.5}$ measurements in the study region, a technique that can estimate regional $PM_{2.5}$ concentrations without ground data support becomes an important tool. MISR has eight aerosol components that are indicative of different contributions to ground-level $PM_{2.5}$ concentrations; the total MISR column AOD was disassembled into species-related fractions using the AOD value associated with, and the three aerosol components defined by each of the 74 aerosol mixtures (Eq. 1). The fractional AOD of a MISR aerosol component is defined as the average contribution of this component to a total AOD. For example, if MISR does not observe the presence of any dust particles in a 17.6-km pixel, the fractional AODs for dust components (i.e., 19 and 21) would be zero. By definition, the sum of all the significant fractional AODs is equal to the total column AOD.

$$Fractional\,AOD_{i\,(i\,=\,1,\,8)} = \frac{\sum_{j=1}^{74} AOD_{mixture\_j} \times Fraction_{component\ i\ in\ mixture\_j}}{No.\,of\ Successful\,Mixtures} \quad (1)$$

Then, the simulated AOD and $PM_{2.5}$ concentrations from GEOS-Chem model were used to define a physically consistent relationship between AOD and surface level $PM_{2.5}$ concentration (Eq. 2). GC surface [$PM_{2.5}$] in Eq. 2 refers to the sum of GEOS-Chem fine particle species concentrations within one kilometer from the surface, and GC column dust AOD refers to the sum of GEOS-Chem total AOD in all 35 layers. A similar analysis for dust particles were performed.

$$[PM2.5] = \frac{GC\ Surface\ [PM2.5]}{GC\ Column\ AOD} \times MISR\ AOD$$

$$[Dust] = \frac{GC\ Surface\ [Dust]}{GC\ Column\ Dust\ AOD} \times MISR\ dust\ AOD \quad (2)$$

This technique had been demonstrated previously using the early version MISR and GEOS-Chem data in the US (Liu et al., 2004) and was successfully utilized in the present study. The annual MISR $PM_{2.5}$ concentrations exhibited an improved agreement with the ground measurements in terms of spatial pattern as compared to simulated $PM_{2.5}$ concentrations. The annual average MISR $PM_{2.5}$ concentrations had a good linear relationship with the ground measurements ($r = 0.69$, linear regression slope = 0.87), and the estimated intercept was insignificant ($p = 0.81$).

High-resolution spatial statistical models were developed using ground $PM_{2.5}$ measurements from the two sites in the study region and Collection 6 MODIS 10-km AOD data. Given the limited ground data support (one site in Abdalli, KISR, and Wafra each), a linear mixed effects model was developed similar to, but more advanced than that presented in Lee et al. (2011). This random intercept, random slope model can be expressed as follows:

$$[PM2.5]_{i,j} = (\alpha + u_j) + (\beta_1 + v_j) \times MODIS\ AOD_{i,j} + (\beta_2 + \omega_j) \times MODIS\ AOD_{i,j-1} + \varepsilon_{i,j} \quad (3)$$

where $[PM2.5]_{i,j}$ is the daily PM2.5 concentration at monitoring site i on day j; MODIS $AOD_{i,j}$ is the average of Collection 6 Terra and Aqua MODIS AOD in the 10 km x 10 km grid cell corresponding to monitoring site i on day j; α and u_j are the fixed and random intercepts, respectively; β_1 and v_j are the fixed and random slopes on same day AOD, respectively; β_2 and ω_j are the fixed and random slopes on previous day AOD, respectively; $\varepsilon_{i,j} \sim N(0, \sigma^2)$ is the error term at site i and on day j. In this statistical model, the AOD fixed effect represents the average effect of AOD on PM2.5 for all study days. The AOD random effects explain the daily variability in the PM2.5-AOD relationship.

Given the limited number of monitoring sites, a random intercept was not included for the site.

Because no previous studies have been done for desert regions, other statistical model format was explored. A generalized additive model (Liu et al,, 2012b) was tried as well (Eq. 4):

$$PM_{2.5} = N\left(\mu + f_{AOD}(AOD) + f_{AOD2}\left(AOD_{lag}\right) + f_{RH}(RH) + f_{TEMP}(TEMP) + \beta_1 \times precip + \beta_2 \times precip_{lag} + \beta_3 \times weekend\right) \quad (4)$$

Where all the covariates on the right hand side of Eq. (3) are averaged spatially and therefore only vary with time; μ is the model intercept; f_{AOD}(AOD) is the smooth regression term describing the association between AOD and $PM_{2.5}$; f_{AOD2}(AOD_lag) is the smooth regression term, describing the association between mean AOD of previous two days and $PM_{2.5}$, f_{RH}(RH) and f_{TEMP}(TEMP) are smooth regression terms, describing the impact of domain-averaged relative humidity (RH), and surface air temperature (TEMP) on the AOD–$PM_{2.5}$ association, respectively. The inclusion of lag AOD term reflects the fact that urban aerosol has a general lifetime of a few days without major scavenging events. Precipitation on a given day (precip) and precipitation on the previous day (precip_lag) are both modeled as a binary variable (0=no rain, 1=rain). The weekend effect is reflected here as a binary variable (weekend=1 if Friday and Saturday, =0 otherwise).

Results and Discussion

The $PM_{2.5}$ concentrations were estimated using the models developed (Figure 3) which showed a high correlation with the point measurements. The total suspended PM in each size fraction measured at the sampling site at KISR between April and October 2012 are given in Figure 4; whereas, the time-series plot of the total suspended particulate matter (TSP) over the same period is given in Figure 5. A summary of the particle-size distribution for the entire study period, expressed as the average particle concentration in each size range, is given in Figure 6. The mean (and range) in TSP concentrations for the entire study period was 1400 (140 to 8500) μg/m^3. If the concentrations measured on the 6th of March were excluded, as this sample was collected during a major dust storm episode in Kuwait, the mean (and range) in TSP that is typical for this site would be 1040 (140 to 2750) μg/m^3. The TSP concentrations in this study were higher than those reported in Chicago (27.7 μg/m^3) and Lake Michigan in the United States (Offenberg and Baker, 1999), Mumbai (119 to 216 μg/m^3, (Venkataraman et al., 1999), rural Taiwan (182 to 238 μg/m^3, (Wu et al., 2006), and in Thessaloniki in Greece (243 μg/m^3) (Chrysikou et al., 2009), and in Hamilton, Ontario Canada (58–121 μg/m^3) (Katz and Chan, 1980). These high TSP values measured in Kuwait may be due in part, to the fact that Kuwait is a desert country where high-energy winds

often result in localized or regional dust storms. The rates of dust fallout in Kuwait have been reported to be one of the highest in the world (Foda et al., 1985). The particle size distribution was bimodal with the major peak located in the < 0.63-μm fraction, constituting about 85% (range 44 to 94%) of the PM in air. Another small, but distinct peak occurred in the particle size fraction > 10 μm. Particles smaller than 3.0 μm are easily transported through the respiratory tract into the bronchioles and alveoli of the lungs and are therefore a human health risk.

One of the most important indicators of air quality in most industrialized countries in the world, according to the World Health Organization (WHO) is the concentration of PM in the air (WHO, 2005). These standards however, often ignore the concentrations of toxic compounds such as PAHs, trace metals, and other contaminants, some of which are carcinogens, that are associated with these particles. This may be due to inadequate information on the concentrations of the associated contaminants that are required for risk assessments. It has been shown in several studies that an inverse relationship exists between particle size and pollutant concentration (Lewis, et al., 1999). The inhalable (< 10 μm) and respirable (< 2.5 μm) fractions of PM, which remain suspended in the air the longest, are thought to be the most important fractions associated with respiratory illnesses. Many studies have linked long-term exposure to PM with adverse health effects, such as cardiovascular disease, chronic respiratory illnesses, and cancer. To better understand the risks posed by particle inhalation, it is important to understand the distribution of pollutants in various size fractions.

Figure 3. *PM2.5 Concentrations Using Satellite Datasets*

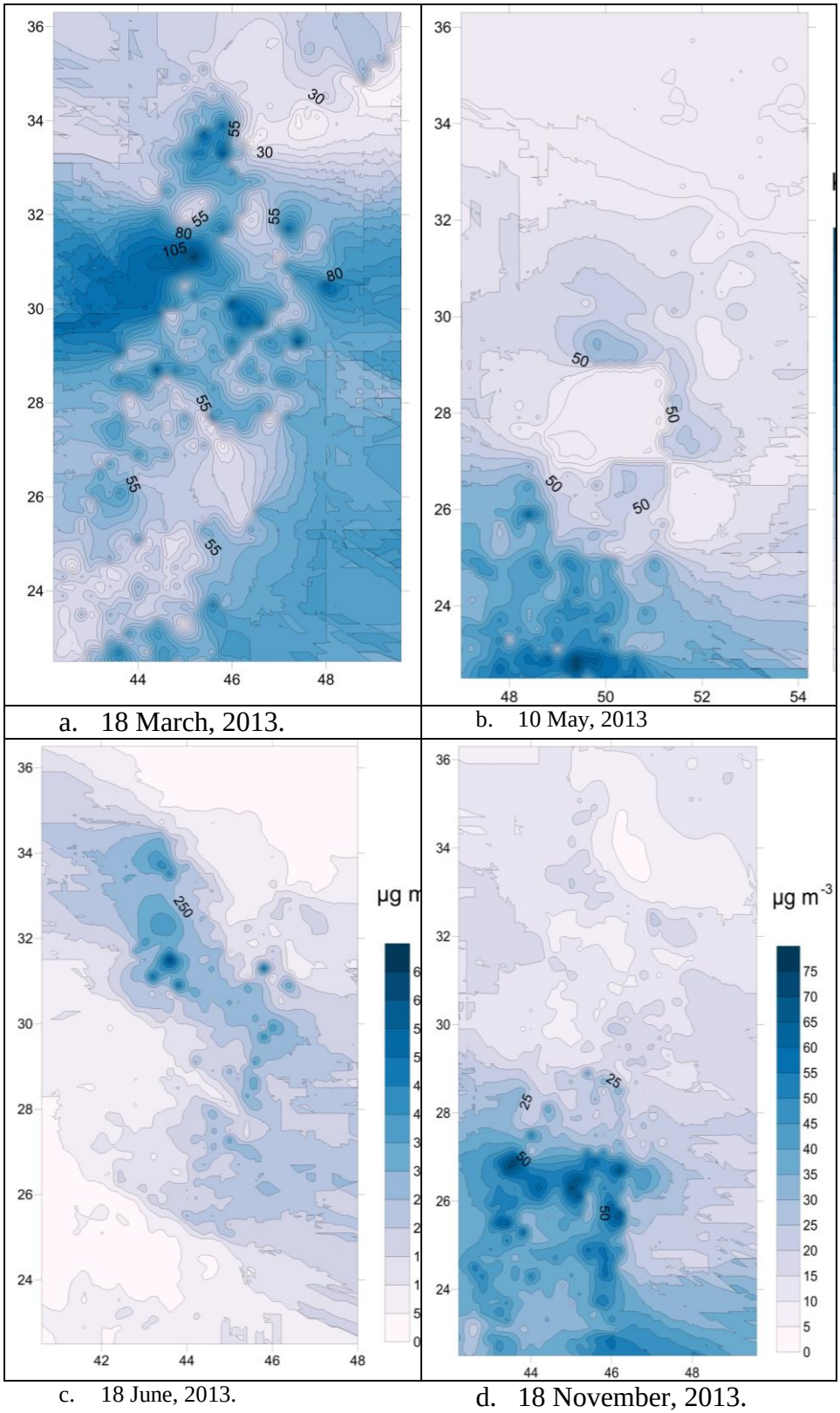


Figure 4. *Atmospheric Concentrations of Particles in Different Impactor Size Ranges in the Air at KISR in Kuwait City between April and August 2012*

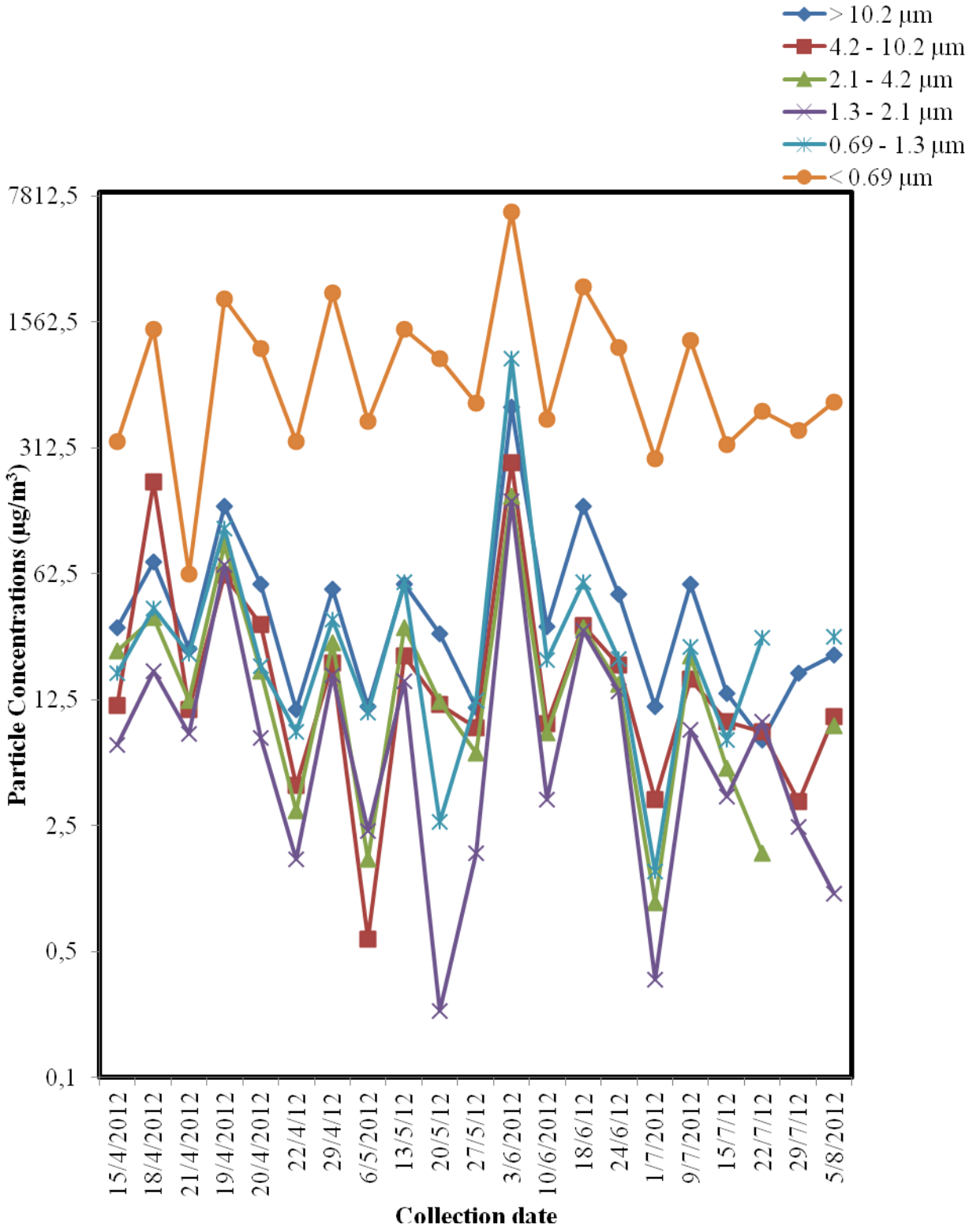


Figure 5. *The Total Suspended Particle Concentrations in Different Impactor Size Ranges in the Air at KISR in Kuwait City between April and August 2012*

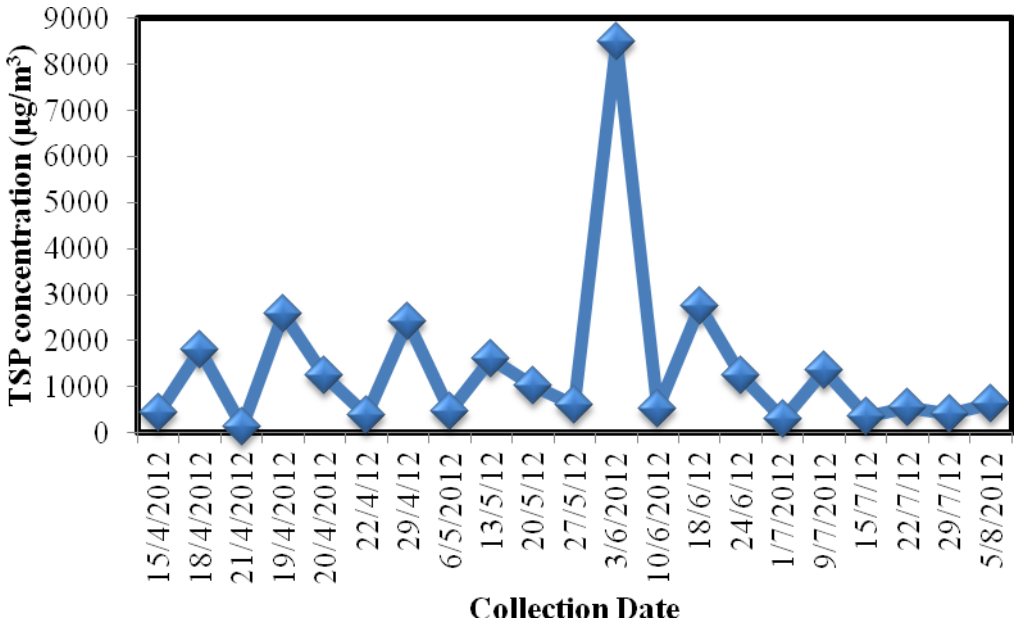
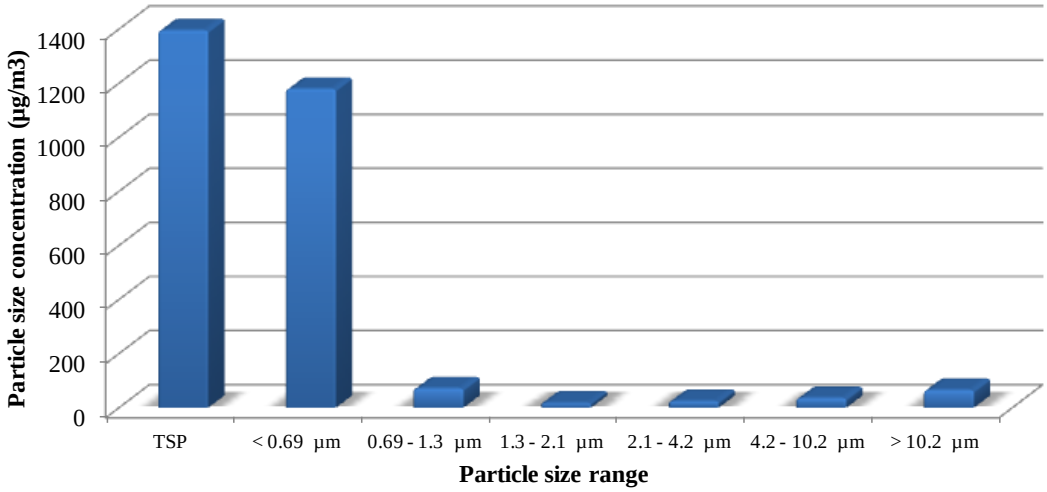


Figure 6. *Average Particle Concentrations in Different Size Ranges and the Total Suspended Particulate Matter in the Air at KISR in Kuwait City between April and August 2012*



Conclusions

This study provided the basic model framework and the setup which can be populated by continuous data collection both using HVAS and AEROCET

particle counter. The accuracy of the MISR showed a systematic underestimate, which by additional data collected can be integrated into the model. The calibration of Collection 6 for MODIS will also provide an additional opportunity to use MODIS as a reliable satellite for PM estimation. The $PM_{2.5}$ concentration from the satellite images were well-correlated with the measured data both from the IR mass and particle counter and the high volume air sampler. The accuracy of the MISR determination was close to 68% and 62% for MODIS. There was a systematic underestimation of PM using both MISR and MODIS data, currently, possibly due to very high back scatter. But still, these sensors provide a very reasonable estimate of $PM_{2.5}$ concentration on a large spatiotemporal scale.

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