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Application of New MODIS-Based Aerosol Index for Air Pollution Severity Assessment and Mapping in Upper Northern Thailand

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Abstract

This paper reports capability of a newly-proposed index called the aerosol prediction index (API) in the determination and mapping of near-ground PM_{10} concentrations (at spatial resolution of 500 x 500 m) during the 2009 and 2010 burning seasons in upper northern Thailand. API is a normalized index defined based on the difference in the observed reflectance data at two spectral bands of the MODIS instrument aboard NASA's Terra satellite; Band 3 (blue) and Band 7 (mid-infrared). Initial analysis suggested that API had strong correlation with the corresponding MODIS-AOD and AERONET-AOD with coefficient of determination (R^2) about *0.62* in both cases, and also with the reference PM_{10} data with R^2 of *0.66.* In terms of predictive performance, it exhibited low bias at low PM_{10} condition and achieved impressive prediction accuracy with relative error of 10.78 %. The near-ground PM10 concentration map yielded from the proposed index was proved very useful in the comprehensive assessment of aerosol pollution situation over entire area at fine spatial detail. This task could not be fulfilled from sole use of the ground-based measured data or standard MODIS-AOD product. These findings indicate that API should be a promising tool for the regular monitoring of air pollution severity over the concerned area.

Keywords: particulate matter; aerosol; air pollution; optical depth; MODIS

1. Introduction

Airborne particulate matter (PM), or aerosol, is a broad group of tiny particles that are suspended in the air with variety in size, composition, and origin. PM is a critical air pollutant due to its acute adverse effect on human health and its crucial roles in climatic mechanisms, e.g., rainfall formation or earth's energy balancing (WHO, 2006; Rosenfeld *et al.,* 2014). PM data is commonly assembled through network of ground-based monitoring stations, however, satellite-based observations was also operated since 1970s (Lee *et al.,* 2009). In this case, the PM density is often estimated from a product called aerosol optical depth (AOD), or aerosol optical thickness (AOT). Among which, the mostly-used one is from the MODIS instrument aboard NASA's Terra and Aqua satellites (Engel-Cox *et al.,* 2004). AOD is a dimensionless parameter used to quantify degree to which the aerosol molecules prevent transmission of the sunlight (at a specific wavelength) through atmosphere (along sensor's viewing direction) by absorption or scattering mechanisms. Relationship between AOD data and their associated near-ground PM data is prevalently assumed to have a linear regression form. However, some basic meteorological factors, e.g., relative humidity or mixing layer height, might be included in the analysis to provide more accurate results (Tsai *et al.,* 2011; Zheng et al., 2013).

Apart from the AOD, Ling-jun *et al.* (2007) found that a simple MODIS-based index could predict amount of the PM data in Beijing well. Recently, He *et al.* (2014) reported that their three proposed aerosol indices (difference, ratio, and normalized difference) had strong correlation with the reference AOD data and might be used as a proxy to assess air pollution severity over Beijing. Conceptually similar to the aforementioned reports, main objective of this work is to apply a new MODIS-based index called the aerosol prediction index (API) for the quantification and mapping of the associated near-ground PM data during the 2009 and 2010 fire seasons in upper northern Thailand at fine spatial resolution of 500 m, which cannot be fulfilled from sole use of the ground-based data or the standard MODIS-AOD product.

2. Materials and Methods

2.1. Study area

The study area covers eight provinces of upper northern Thailand including Chiang Mai (CM), Chiang Rai (CR), Lampang (LP), Lamphun (LPH), Mae Hong Son (MHS), Nan (NAN), Phayao (PY), and Phrae (PH), with total area of 88,370 km^2 as illustrated in Fig.1, in which, locations of the 14 air quality measuring stations of the Pollution Control Department (PCD)

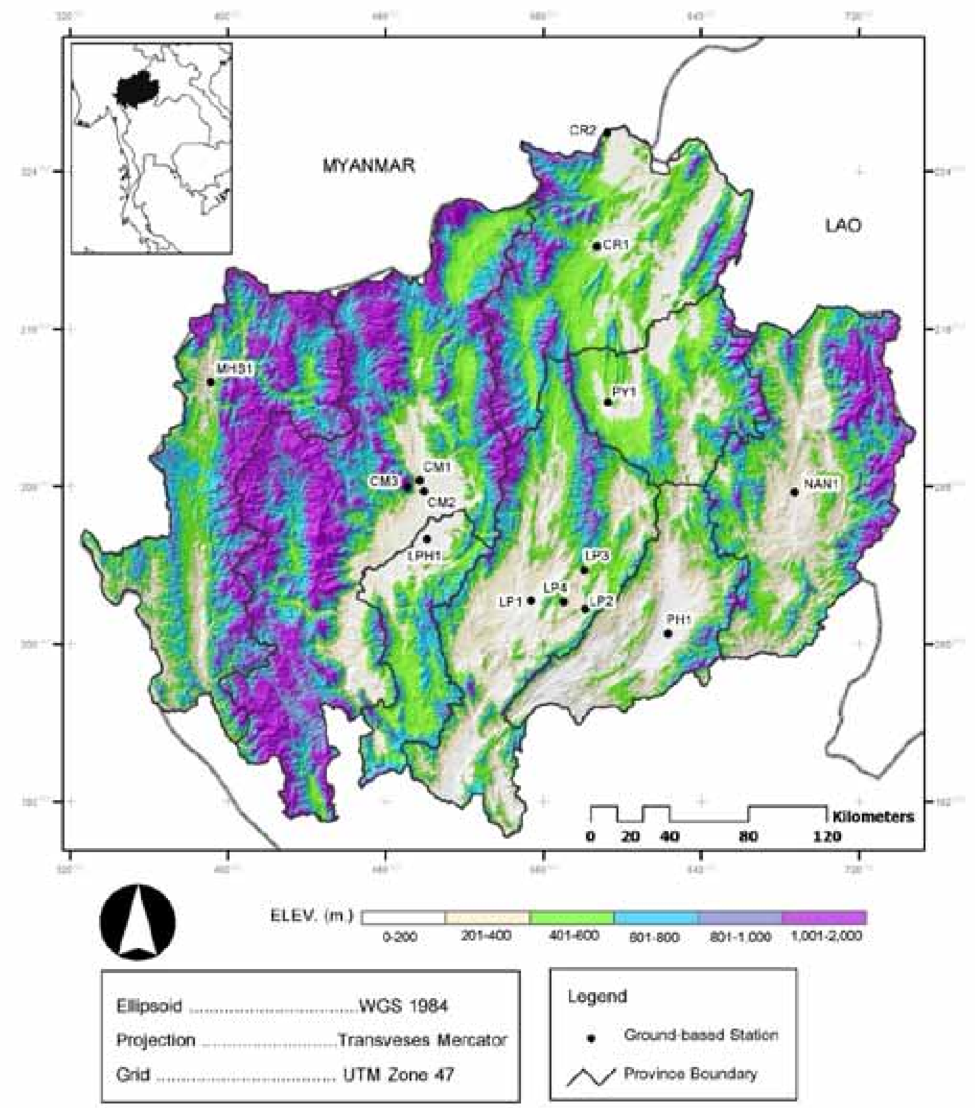

Figure 1. Map of the study area (upper northern Thailand)

used in this study are also presented. The area is bordered by two neighboring countries, Myanmar on the west and Laos on the east. Typical weather is hot and humid under strong influence of the regional monsoon system. Dominant topography is a network of high mountain ranges where forest and agricultural land have occupied about 70% and 25% of the entire region, respectively, while urban and built-up land takes up about 3% (Land Development Department, 2007).

One of the persistent environmental problems of the area is severe air pollution due to rapid increase of the PM amount during the burning season of November to April each year with worst situations usually evidenced in late February and March. Origin of this incidence is often contributed to great rise in total number of the open vegetation burning initiated by farmers living in the area and beyond (mainly for land clearance purpose), supported by the appropriate climatic conditions, e.g., dry and stable air (Oanh and Leelasakultum, 2011).

2.2. Data description

2.2.1. MODIS data

The Moderate-resolution Imaging Spectroradiometer (MODIS) is a key instrument on board NASA's Terra (EOS AM) and Aqua (EOS PM) satellites which are currently operating at altitude of 700 km along the near-polar orbit. Both sensors can observe the entire Earth's surface and atmosphere every 1 to 2 days through 36 spectral bands (located at 0.4-14.4 μm) with spatial resolution of 250 m (Bands 1-2), 500 m (Bands 3-7), 1 km (Bands 8-36) (MODIS Web, 2014). Two types of the MODIS data were applied in this study: (1) measured radiance (or reflectance) data (MOD021KM-Level 1B) in blue band (Band 3: 459-479 nm) and mid-infrared (MIR) band (Band 7: 2105-2155 nm), (2) standard AOD data observed at 550 nm (MOD04-Level 2) with resolution of 10 km (at nadir). These data were downloaded from the NASA's

LAADS website (http://ladsweb.nascom.nasa.gov/index.html). Only MODIS data from Terra platform during the 2009 and 2010 burning seasons were used in the study due to their better qualities compared to those of the Aqua one.

2.2.2. Ground-based PM_{10} data

Two groups of the small PM particles called PM_{10} and PM*2.5* are usually monitored at present due to their prominently harmful effect on human health (WHO, 2006). These names are referred to the PM particles with equivalent aerodynamic diameter of less than 10 µm and 2.5 µm, respectively. However, only PM_{10} data were included in this study as data of $PM_{2.5}$ in the area were not available. The hourly ground-based PM_{10} data measured at 14 monitoring stations (Fig. 1) were acquired from the Pollution Control Department (PCD), however, only data that match the most with the satellite overpass time at each station (i.e. around 10:30 am LST) were chosen for further analysis. These data were split into 2 groups; the first one was used for identifying relationship between the proposed index (API) and reference PM_{10} data (240 samples) and the second was applied to validate applicability of the resulted relationship (71 samples). Referred data in each group were chosen randomly to achieve sufficient variety in amount of the PM_{10} data (from low to high) and in locations of the used measuring stations (regarding to the 14 stations available).

2.2.3. AERONET-AOD data

AERONET (Aerosols Robotic Network) is a network of solar radiance measurement established by NASA and France's PHOTONS group. It has been in operation since 1993 for the observation of AOD worldwide from expansive network of about 600 ground-based sun photometers including 9 stations in Thailand (AERONET, 2014). AERONET-AOD product is often used as a reference for validating most satellite-based AOD data (including MODIS-AOD) due to its high accuracy and assured quality. In this work, AERONET-AOD (Level 2) product at 440 nm from the active station in Chiang Mai's downtown was downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov) to assess correlation with the proposed index. Through the temporal resolution of this AOD product is 15 minutes but only data that match the most to the satellite overpass time at the stated AERONET station (i.e. 10:30 am LST) were chosen for further analysis.

2.3. Derivation of an index

A new MODIS-based index called aerosol prediction index (API) was defined based on the relevant MODIS reflectance data using the following relation:

$$API = \frac{Blue - 0.25MIR}{Blue + 0.25MIR} \quad (1)$$

where Blue and MIR are measured radiance of the MODIS's blue band (Band 3) and mid-infrared band (Band 7), respectively. This given definition of API was devised based on prior knowledge that the blue band is normally most sensitive to the variation of PM amount in the atmosphere whereas the MIR band is rather insensitive to such changes (Remer *et al.,* 2005). Therefore, difference in the observed reflectance radiances of these bands on a particular date should principally correlate with actual amount of the existing aerosol pollution on that date. The constant term (0.25) was added to make the API values become near zero on the aerosol-free date (i.e. dates with $PM_{10} \approx 0$) as suggested by an initial analysis and the theoretical basis (Kaufman *et al.,* 1997). Possible values of the API are limited to -1 to 1 (normalized values) in which the positive values closer to 1 shall indicate higher amount of the existing PM10 data in the lower atmosphere while the negative values have no definite meaning.

To find potential association between the API and the reference PM_{10} data, the linear regression relationship was assumed and the coefficient of determination (R^2) was applied to assess the correlation level seen in the found relationship. Validity of the predicted PM10 data from the adopted relationship was evaluated from the resulted mean absolute error (MAE):

$$\text{MAE (\%)} = \frac{1}{n}\left[\sum_{i=1}^{n} \frac{\left|PM_{API,i} - PM_{REF,i}\right|}{PM_{REF,i}} x100\%\right] \quad (2)$$

where $PM_{API,i}$ and $PM_{REF,i}$ are the i^{th} pair of the derived and reference PM_{10} data, respectively, while n is total number of the relevant data pairs in use (n = 71 in this case).

3. Results and Discussion

3.1. Relationships of API with reference ground-based PM_{10} data

High aerosol pollution was evidenced on several dates during the 2009 and 2010 fire seasons especially in March and early April (see Fig. 2 for example). The MODIS reflectance data during these periods were acquired from their source stated earlier for the calculation of API values detailed in Eq. 1. At this stage, focus of the study was on image pixels that locate

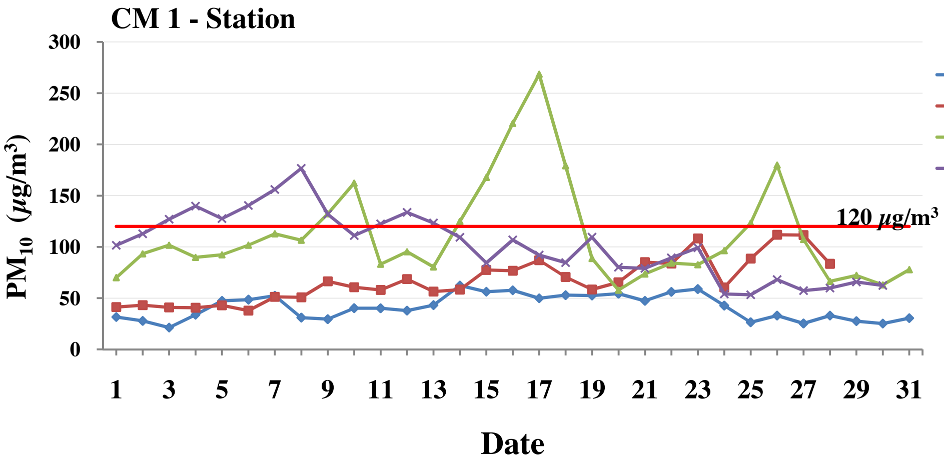

Figure 2. Daily record of PM_{10} data at the CM1 (Chiang Mai Provincial Hall) station during 2010 fire season. Critical value of 120 μg/m^3 set by the PCD is also shown as a reference.

directly over the 14 air monitoring stations in use. Derived API data were then compared with their corresponding hourly PM_{10} data. The yielded result is shown in Fig. 3 with 240 samples included in the analysis from which the following linear relationship was found:

$$PM_{10} = 300.6API + 4.527, \quad (3)$$

with coefficient of determination (R^2) of 0.661, which is comparable to, or better than, those reported in several works that used MODIS-AOD as sole predictor (Table 1). The established relationship shown above also produces small bias in the prediction under low-PM condition as when API = 0, the output PM10 data would become 4.527 μg/m^3 which is highly close to the ideal value of 0 μg/m^3 expected from the adopted assumption.

To verify validity of the yielded relationship in Eq. 3, predicted values of the PM_{10} data from the reference set of API data (71 samples in total) were compared with actual PM_{10} data observed at the 14 ground-based stations in use (Fig. 4). In this process, the relative error in average of 10.78% between these two PM datasets was found which indicates impressive predictive performance of the API at this stage. However, as stated earlier, inclusion of some relevant meteorological parameters (e.g., mixing height or air humidity) in the analysis might be able to improve prediction efficiency of the regression model accomplished in this study. Another interesting issue is the applicability of the used API to other areas that have different environmental characteristics to one examined here (forest-dominant scenario) which

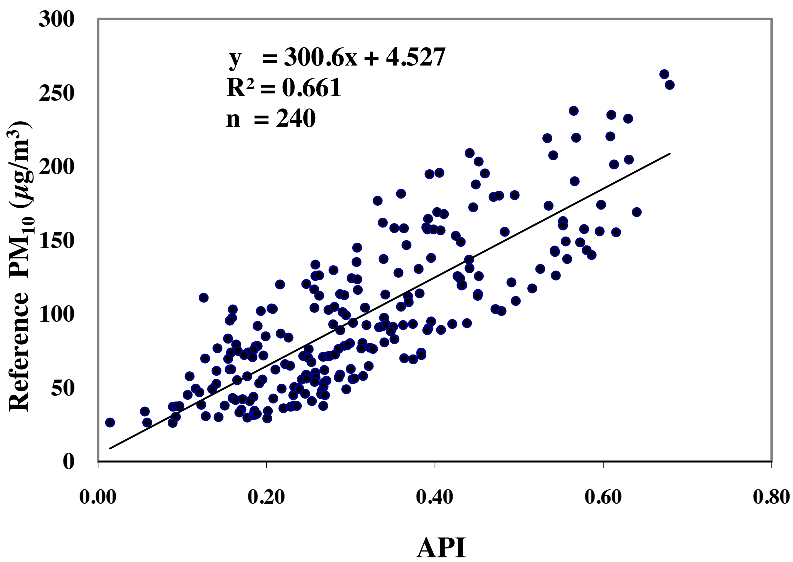

Figure 3. Relationship between the API and reference near-ground PM_{10} data (R^2 = *0.661*). Here *x* and *y* variables represent the API and the reference PM_{10} data, respectively.

Table 1. Examples of report on relationships between MODIS-AOD and reference PM_{10} data compared to the use of API achieved in this study.

Variable		Relationship	Correlation		Source
X	y		R	R^2	
AOD	PM_{10}	y = 302.3x - 54.4	0.82	-	Li *et al.* (2005)
AOD	PM_{10}	y = 69x + 20.0	0.57	-	Dinoi *et al.* (2010)
AOD	PM_{10}	y = 119.09x + 22.684	-	0.75 (summer)	Zha *et al.* (2010)
AOD	PM_{10}	y = 90.413x + 52.368	-	0.22 (winter)	
AOD	PM_{10}	y = 66.344x + 91.529	-	0.21	Kanabkaew (2013)
API	PM_{10}	y = 300.6x + 4.527	-	0.66	This study

should be explored more in future work. It should be noted here that, one obvious limitation of the regression model expressed in Eq. 3 is that it is valid for the prediction of PM_{10} data of less than about 300 $\mu g/m^3$ only (as API must be always ≤ 1). In reality, this problem should not be a serious shortcoming for the study in the chosen area as amount of observed PM_{10} density in the past rarely exceeded this value except on a few dates that were extraordinary polluted. But, for other areas, this model might have to be adjusted to suit more with the actual aerosol pollution situation over those areas.

3.2. Relationships of API with MODIS-AOD and AERONET-AOD

In addition, the derived API had exhibited strong correlation with their corresponding MODIS-AOD and AERONET-AOD data with R^2 of *0.620* and *0.616*, respectively, in which their relationship can be expressed as follows (Figs. 5 and 6):

$$\text{MODIS-AOD} = 1.5122API - 0.0618, \quad (4)$$

$$AERONET\text{-}AOD = 2.7082API - 0.0278. \quad (5)$$

These results indicate that API might be applied, in replacement of the normal MODIS-AOD, for producing map of the near-ground PM_{10} data over the concerned area with distinguished spatial resolution of 500 m (about 20 times higher than that derived from the MODIS-AOD). This kind of data is necessary for the effective evaluation of air pollution situation at urban or provincial level for health warning and mitigation purposes. Moreover, if mutual relationship between amount of the PM_{10} and $PM_{2.5}$ over the area is available, map of the $PM_{2.5}$ can also be made from the initial PM_{10} map to provide more knowledge on the public health impact as $PM_{2.5}$ is believed to have much higher danger to human health than PM_{10} (WHO, 2006).

3.3. PM_{10} mapping from API data

To demonstrate potential use of the API in producing detailed PM_{10} map for the entire study area,

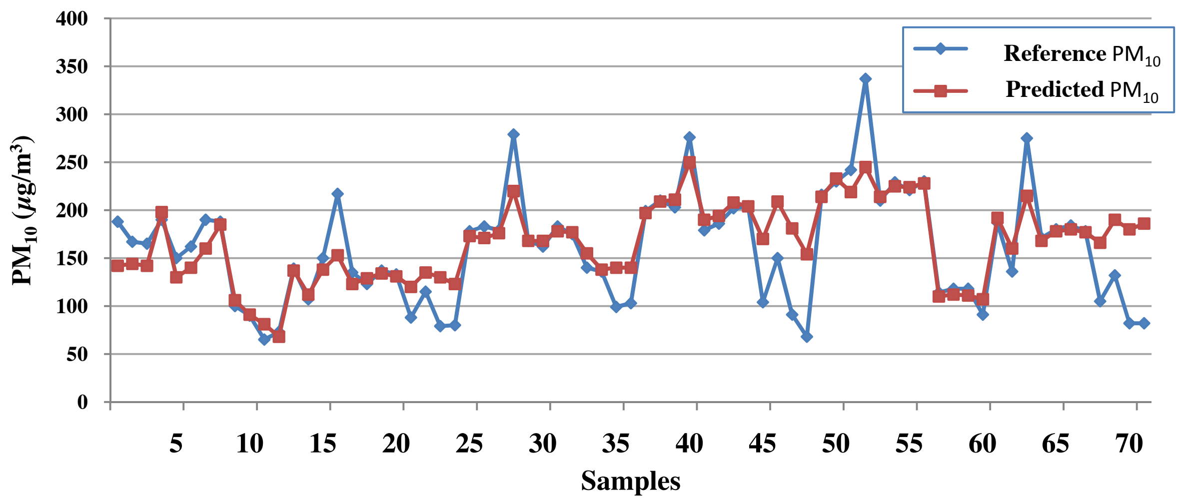

Figure 4. Comparison between predicted and reference PM_{10} data (relative error = 10.78 %).

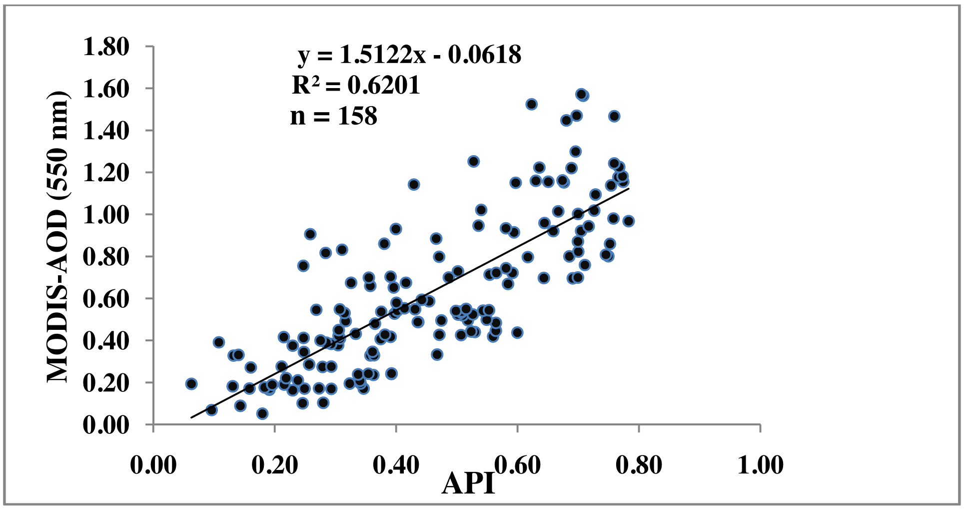

Figure 5. Relationship between the API and MODIS-AOD data (R^2 = *0.620*)

the heavily-polluted date of 8th April 2010 (with average PM_{10} data over the area of 233.71 μg/m^3), was chosen as a case study. Fig. 7 presents the MODIS true-color image on this date while Fig. 8 shows the MODIS-AOD map of the same date. Appearance of thick smoke plume over the area, especially on the eastern part, is clearly visible in the used image while its intensity could be approximated from the associated AOD map (on scale of 0-1.5). Similarly, Figs. 9 and 10 portray PM_{10} distributing pattern over the area in terms of the API (on scale of 0-1) and its predicted PM_{10} density (on scale of 0-300 μg/m^3). It can be primarily concluded from these results that the most polluted areas in several provinces (e.g., Lampang, Phayao, Nan) on that date were not situated over the locations of their respective monitoring station. This finding indicates that usual evaluation of aerosol pollution by relying on ground-based measurements alone is insufficient to reveal actual situation over the entire area and the satellite-based observation should be applied as a complementary source to the analysis.

4. Conclusions

This paper introduces a new index called the aerosol prediction index (API) for being a primary indicator of PM_{10} pollution intensity over an area of interest. The index was proved to have good linear correlation with the reference ground-based PM_{10} data (R^2 = *0.661*) with low bias at low aerosol condition. It was also found to correlate well with the corresponding MODIS-AOD and AERONET-AOD (R^2 of *0.620* and *0.616*, respectively. The impressive prediction accuracy of the adopted regression model was also evidenced with relative error of 10.78%. These properties along with the remarkably fine spatial resolution (of 500 m)

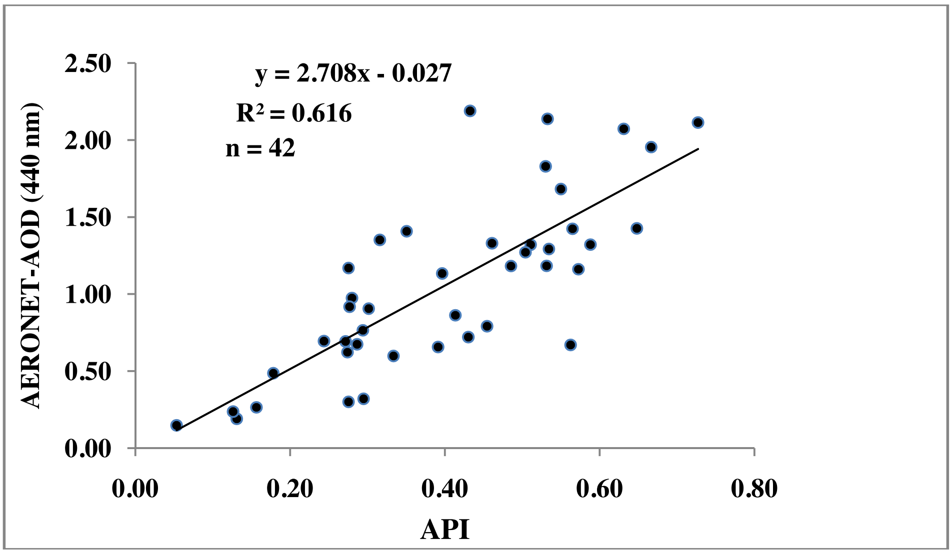

Figure 6. Relationship between the API and AERONET-AOD data (R^2 = *0.616*)

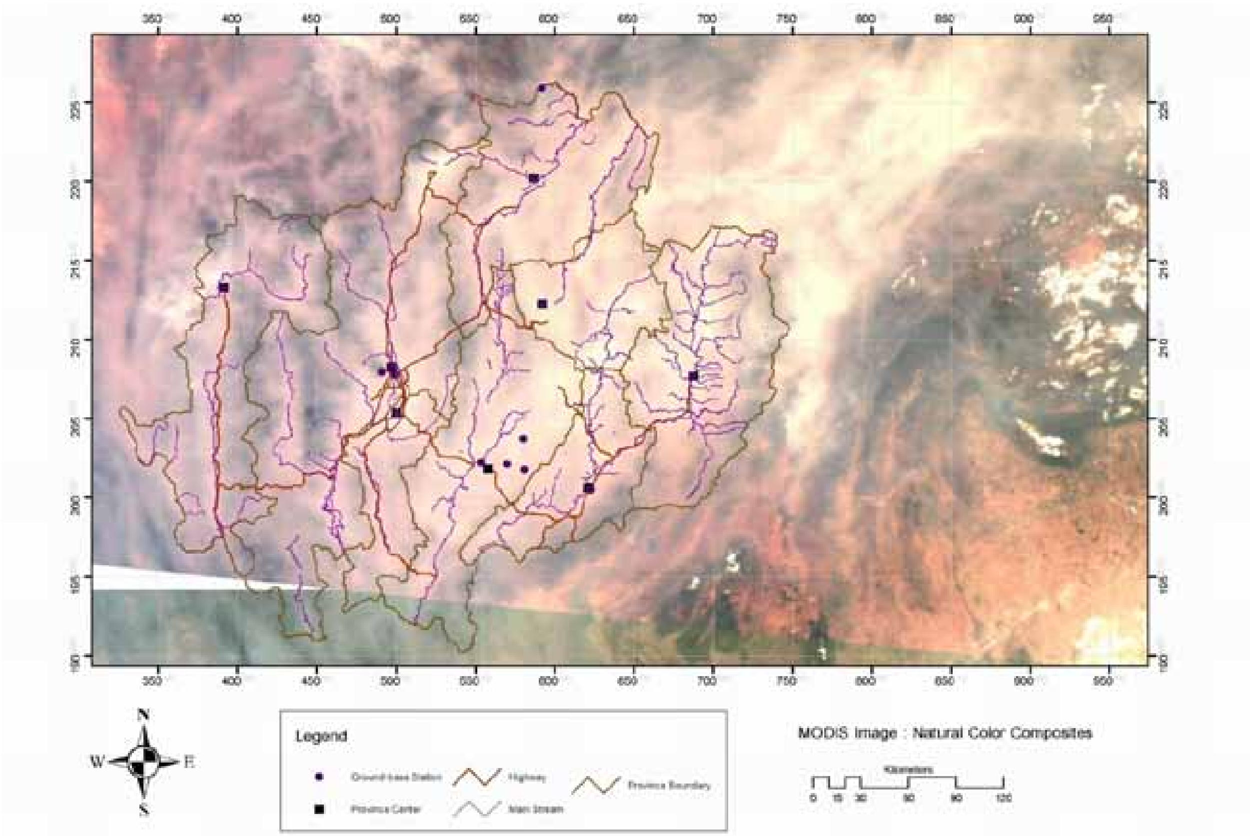

Figure 7. MODIS image of the study area on 8th April 2010. The landmarks, i.e. province center, highway and main stream, are also displayed.

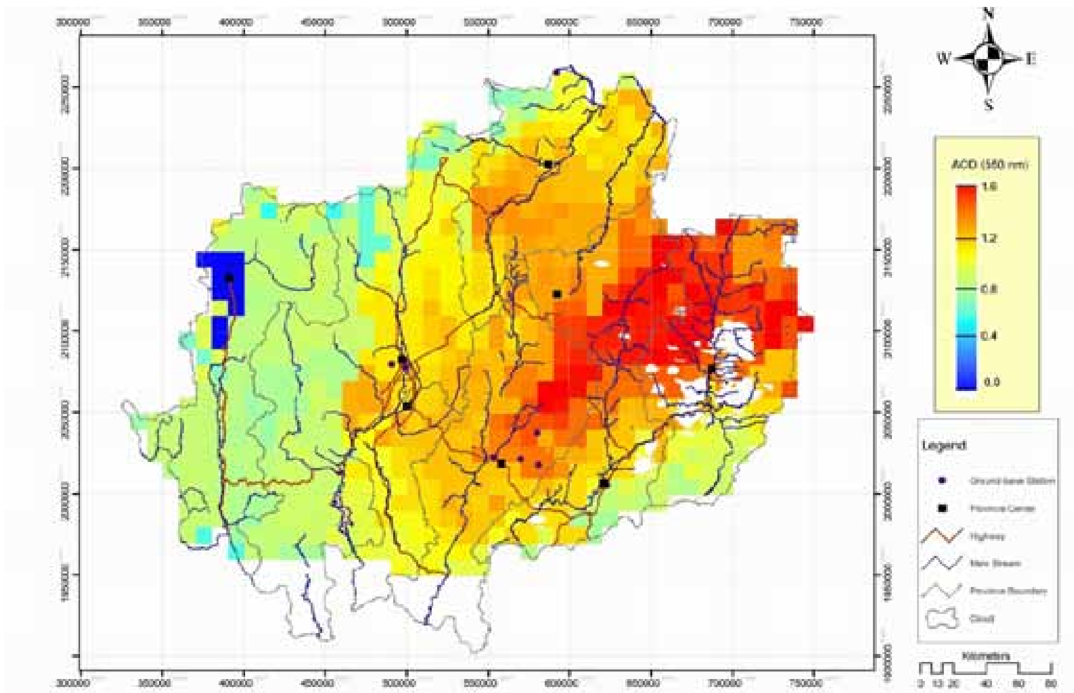

Figure 8. Map of the MODIS-AOD on 8th April 2010 (at spatial resolution of 10 km)

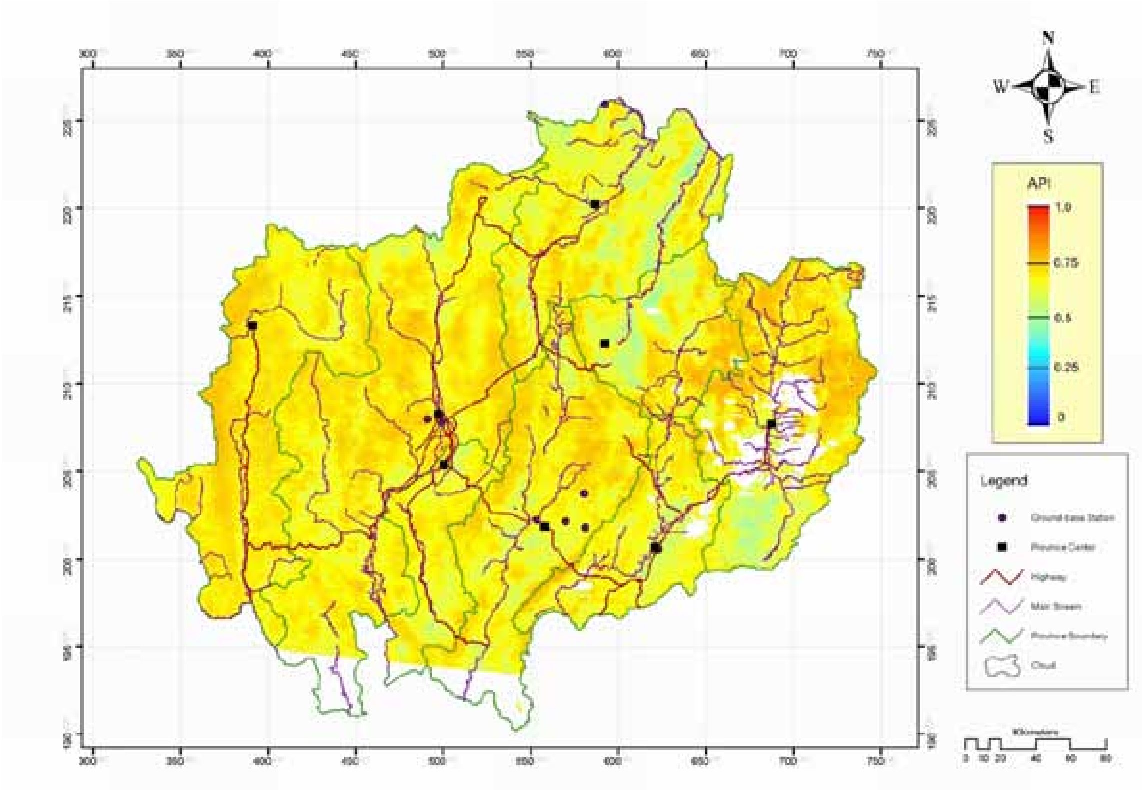

Figure 9. Map of the derived API on 8th April 2010 (at spatial resolution of 500 m).

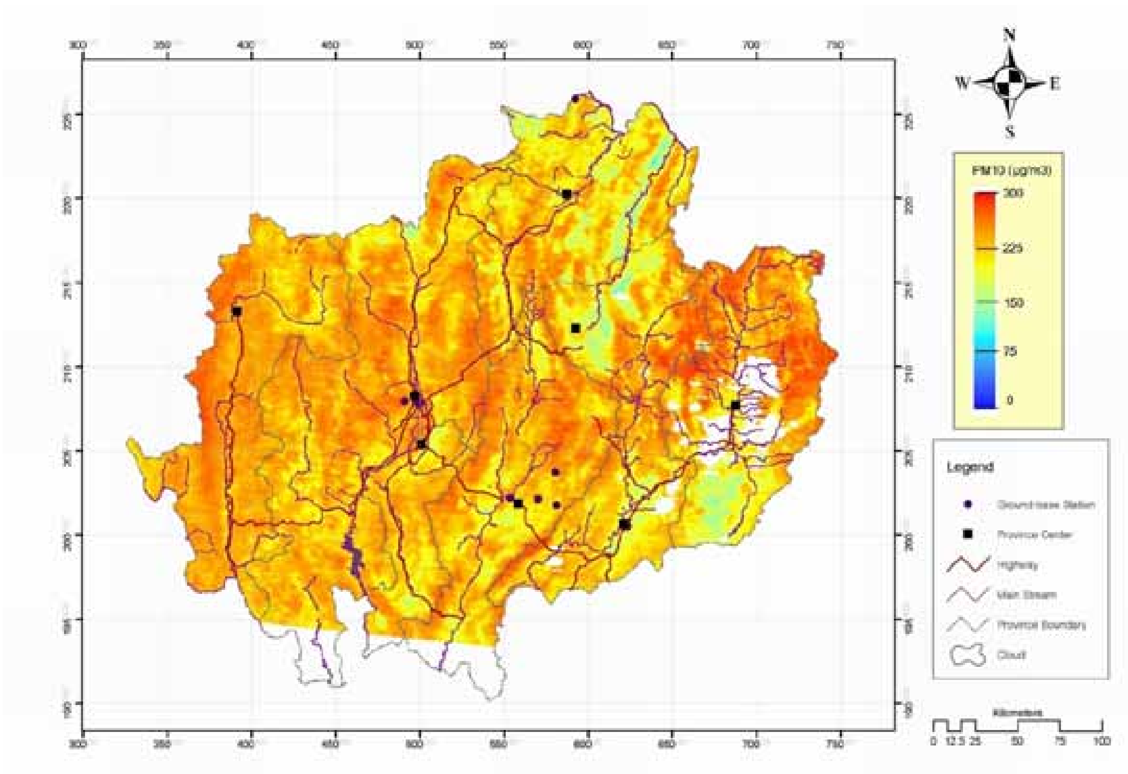

Figure 10. Map of the predicted PM_{10} on 8th April 2010 (at spatial resolution of 500 m).

make API very useful for the production of the PM_{10} map over a concerned area which cannot be achieved by sole use of the traditional ground-based measurements or standard MODIS-AOD product. Further studies for improving the prediction performance of the index by inclusion of some metrological parameters in the analysis and for examining applicability of the index in areas with different environments are also recommended. In addition, increasing in number of the reference ground-based PM_{10} data to represent the whole area more realistically is also preferable especially data that come from the rural environment.

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