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PREDICTION OF HAZE EPISODE POTENTIAL FOR MOUNTAIN-VALLEY URBAN AREA USING  
SYNOPTIC-CLIMATOLOGICAL MODELING APPROACH

Nguyen Thi Kim Oanh and Ketsiri Leelasakultum

Environmental Engineering and Management, Asian Institute of Technology, Thailand

Abstract: The Chiangmai city of Thailand is located in a complex mountainous area of Northern Thailand. In recent years, the city has been experiencing air pollution haze episodes during the dry season. The most severe haze was observed in March 2007 when the entire city was blanketed with smoke/haze for a few weeks. The 24-h average PM\textsubscript{10} level in the city reached the peak of 396 µg/m\textsuperscript{3}. Recurring haze episodes have become a critical environmental problem that is linked to sharp increases in hospital admissions. This study investigates the main causes of the Chiangmai haze episodes, considering both meteorological and emission sources, with the aim to produce early warning. In the absence of a detailed emission inventory necessary for more comprehensive 3D air pollution model applications for the haze episode warning a synoptic climatological approach is proposed. An automated meteorological classification scheme was developed based on the spatial synoptic index, to identify the most predictive haze-prone meteorological patterns in the area during the months of February-April from 2001-2009. Among the four synoptic patterns that were recognized for the region, pattern 2 was found to prevail on the days with high PM\textsubscript{10} in Chiangmai and occurred with a high frequency in the month of March. This pattern is characterized by presence of vast thermal low pressure cells over Chiangmai and Indian continent with hot, dry and stagnant air over the Northern part of Thailand. All identified as episodic high PM\textsubscript{10} (higher than Thailand air quality standard of 120 µg/m\textsuperscript{3}) in March 2007 were observed to belong to pattern 2. In addition, the increased levels of PM10 in this month coincided with the high emission from biomass burning and seasonal industries. Backward trajectories also show the air masses wandering over the regions of dense fire hotspots, which represented biomass burning, before arriving to Chiangmai on the haze episode days. By utilizing stepwise regression model for PM\textsubscript{10} prediction on the next day, the results of the model were satisfactory for both the dependent set of data of 2007-2009 (R\textsuperscript{2} = 88\%) and the independent sets of data for 2004-2010 (R\textsuperscript{2} = 79 \%). The corrective percentage of “good” ([PM\textsubscript{10} < 40 µg/m\textsuperscript{3}]), “moderate” (40 < [PM\textsubscript{10} ≤ 120 µg/m\textsuperscript{3}) and “haze alerts” ([PM\textsubscript{10} ≥ 120 µg/m\textsuperscript{3}]) air quality category forecasts in Chiangmai are 78%, 81% and 89%, respectively. Based on our analysis, we proposed an episode warning procedure that combines the screening for synoptic pattern 2 during February-April period and prediction for haze alerts day in Chiangmai.

Key words: synoptic classification; monthly emission variation; biomass burning; episodic haze warning; Chiangmai

INTRODUCTION

Air pollution episodes are periods characterized by elevated levels of airborne pollutants, causing a sharp rise in mortality and morbidity. The formation of the episode depends on both meteorological conditions (stagnant air) and increased emission source intensity. Certain topography such as bowl-shaped valleys is known as episode-prone because it restricts the pollution dispersion. This kind of topography is typical in some parts of the Northern Thailand where the Chiangmai province is located. Around 15% of the Chiangmai province is a basin-shaped flat plain, surrounded by mountain ranges in both the western and eastern sides. Most of the population of this province lives in the Chiangmai city, the northern capital of Thailand, located in the basin.

In recent years, Chiangmai has repeatedly experienced air pollution haze episodes during the dry season with the peak around March. Most remarkably severe haze episodes have been observed in year 2007, when the 24-h average PM\textsubscript{10} level in the city reached the peak of 396 µg/m\textsuperscript{3} on March 13. Coincidentally, the number of respiratory patients increased sharply during this time. The total number of respiratory patients recorded from 23 Chiangmai public hospitals in March 2007 (21,336) was much higher than those in March 2006 (16,718), March 2008 (18,025) and April 2007 (15,826).

The onset of severe haze episodes such as that of March 2007 is the cumulative effect of many individual factors. A thorough analysis of the underlying causes and the development of a predictive scientific (air-pollution) model would provide helpful measures that allow for the anticipation and/or complete prevention of any future episodes. Application of a complex 3D air pollution modelling system would be desirable however lack of an adequate emission inventory presents the greatest obstacle for this modelling approach. Complex model systems such as CMAQ-MM5 (Ngheim and Kim Oanh, 2008) or UAM-V/SAIMM (Kim Oanh and Zhang, 2004)\textsuperscript{7} were successfully applied in the region but mainly for general air quality management purposes using annual emission inventory data that are not suitable for episode simulation. While development of necessary emission inventory with adequate spatial and temporal distributions for episode prediction is much desired such an effort needs time and resources to be realized. In this study we propose to use an alternative approach, namely, the synoptic climatological for haze episode warning and PM10 pollution prediction for Chiangmai. We examine in detail the abnormality in the emission sources and meteorological conditions that were associated with the March 2007 episode. Furthermore, the haze warning system was developed that is based on the prediction of the most unfavourable meteorological conditions (for emission dispersion) and a statistical model for PM\textsubscript{10} level prediction for Chiangmai.

METHODODOLOGY

The meteorological conditions in the study area and monthly variations in emission strength of major sources were examined simultaneously to identify the abnormalities that led to episodic high PM pollution in the months of February-April 2007.

a. Meteorological classification

We classified the meteorological conditions governing over Northern Thailand during the haze prevalent months (February, March, April) into homogenous patterns. The meteorological data was collected from a spatial weather station network: 4 stations in Thailand (Chiangmai, Bangkok, Nongkhai and Nakhonpanom) and 3 stations in China (Yibin, Wuhu and Haikou) with the station locations shown in Figure 1. Hence, the spatial synoptic index (SSI) approach was used. This is
similar to the approach presented in Kim Oanh et al. (2005) which was proven to successfully classify the major synoptic patterns governing the Northern Thailand but for the winter months from November to January.

The synoptic classification scheme in this study was developed based on surface meteorological observations at 7:00 LST (or 00:00 GMT) for the months of February-April for the past 8 years (2001-2008) the weather stations shown in Figure 1. The data were collected from the Thailand Meteorological Department (TMD), the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html) and the University Corporation for Atmospheric Research (UCAR) website (http://dss.ucar.edu/). The data processing procedure was done similarly to that reported by Kim Oanh et al. (2005). First, a trial set of meteorological variables was selected and the principal component analysis (PCA) was conducted for its correlation matrix using SPSS. Further, the principal components (PC) with eigenvalue >1.0 after Varimax rotation and with at least one loading above 0.5 were retained for the K-means clustering analysis. Total selected PC should collectively explain more than 70 % of the original data variance. Next, the K-mean clustering classified all the days of February, March and April of 2001-2008 into a certain number of meteorological patterns (3, 4, 5, or 6). Several trial sets of meteorological variables were examined until the best match between the patterns produced by the automatic scheme and the actual synoptic charts was found.

The final set of meteorological parameters used in this study consisted of 18 variables that could be grouped into 3 subsets. The first subset primarily included the meteorological variables of Chiangmai: cloud cover (Cl_cm), temperature dew point (Td_cm), morning mixing height (MorningMH_cm), visibility (Vis_cm), wind direction index (WDI_cm), wind speed (Wsp_cm), and sea level pressure (SLP_cm). The second subset included variables related to sea level pressure in the selected stations: Bangkok (SLP_bkk), Nakhonphanom (SLP_np), Yibin (SLP_ybC), Wuhan (SLP_whC) and Haikou (SLP_hkC). The third subset comprised variables related to the pressure horizontal gradients between Chiangmai and other stations: Bangkok, Nongkhai, Nakhonphanom, Wuhan, Yibin and Haikou (PG1_bkkcm, PG2_nkcm, PG3_npcm, PG4_whcm, PG5_ybcm, PG6_hkcm). To remove the discontinuity of the wind direction (WD) angle at 360° the wind direction index (WDI) was used to represent the wind direction, which was calculated using equation (1).

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\text{Wind Direction Index (WDI)} = 1+\sin \left(\theta + \frac{\pi}{4}\right)
\]

Where, \( \theta \) is the wind direction

b. Monthly fluctuation in emission

Monthly fluctuations in major emission sources (traffic, industries, and biomass open burning) were analyzed for Chiangmai and 5 surrounding provinces (Mae Hong Son, Tak, Lamphun, Lampang, and Chiang Rai which are further referred to as 6 Northern provinces) using surrogate parameters of the emission intensity.

The collected surrogate data consisted of monthly petroleum wholesale from the Department of Energy Business, monthly productivity of industries from questionnaires survey, monthly burning pixels from Web Fire Mapper, monthly crop harvest areas (rice, maize, sorghum, bean, cassava) for the six provinces and their harvest time from Office of Agriculture Economic, Thailand in year 2007. In addition, daily hotspot counts or fire detections from both Terra and Aqua satellite at confidence level 50% were collected from Web Fire Mapper (http://maps.geog.umd.edu/) for the region near Chiangmai (within a circle of 150 km radius) and to the west of Chiangmai (16°00-25°8´N; 92°37´-97°37´E) (Figure 1).

In order to link with the regional source regions, five-day backward trajectories for the most severe haze periods (PM10>120 \( \mu g/m^3 \)) were analyzed using the HYSPLIT model (http://www.arl.noaa.gov/ready/hysplit4.html). The analyzed trajectories started at 00 UTC (7:00 LST) and 500 m above ground level over the Chiangmai meteorological station (WMO ID 48327 at 18°47’ N and 98°59’ E).

RESULTS AND DISCUSSION

a. Synoptic meteorological patterns

The PCA, conducted on the final set of 18 meteorological variables, produced the first five PC that collectively explain 81 % of the variance in the raw data set. Afterwards, K-means clustering technique was applied on the component score matrix (714 days * 5 PC) and produced four clusters corresponding to four synoptic patterns. They are distinguished from each other in terms of the mean values of meteorological variables and typical synoptic charts (Figure 2).
b. PM$_{10}$ levels in different synoptic meteorology patterns

Average and ranges of PM$_{10}$ in Chiangmai associated with the four identified synoptic patterns during February-April of 2001-2008 were analyzed. The highest PM$_{10}$ level is observed in pattern 2 (97±54 µg/m$^3$), second highest is in pattern 4 (89±42 µg/m$^3$), followed by pattern 3 (79±41 µg/m$^3$) and the lowest is pattern 1 (40±15 µg/m$^3$). The numbers of days exceeding the 24h PM$_{10}$ NAAQS of 120 µg/m$^3$ are also ranked from pattern 2 (85 days), to pattern 4 (43 days), pattern 3 (15 days) and final pattern 1 (0 day).

Wind directions in patterns 1, 2 and 4 are mainly from the west. Low wind conditions especially were observed for pattern 2 and 4 which are linked to the high levels of PM$_{10}$ these two patterns. In particular, clear sky, light wind, low mixing height, and low dew point observed in these patterns could stimulate the formation of ground-based radiative inversion which would combine with subsidence inversion typical for a high pressure system. In terms of stagnant air conditions, pattern 2 and 4 seem to be quite similar. However, the surface and upper air temperatures in pattern 2 are higher than pattern 4, which is mainly observed in February. Within pattern 2 (highest PM10 levels), most strong haze episode days in 2004 and 2007 are identified as outliers, while none is seen in pattern 4. This suggests that other factors may contribute to the high build up of air pollution in pattern 2 which could be related to the intensity of emission sources in and surrounding the Chiangmai province, and the regional transport of pollutants.

Figure 2. Examples of regional surface synoptic maps at 07.00 LST for four synoptic patterns: (I) pattern 1 (30 April 2007), (II) pattern 2 (13 March 2007), (III) pattern 3 (27 March 2007), (IV) pattern 4 (1 February 2007)

c. Investigation into Emission and meteorology in March 2007 haze episode

1) Monthly fluctuations in emission

Detail emission inventory would require local specific emission factors and detail activity data that are not available at the present time for Chiangmai therefore surrogate/proxy parameters were used to indicate the intensity of major sources in the 6 Northern provinces. The results showed that the monthly petroleum wholesale did not fluctuate much, and in March 2007 only 8% of the total was recorded. Whereas, two types of industries: tobacco and brick kilns, had high productivity in March, especially the tobacco curing (38% of the total is in March). The forest fires, represented by the burning pixel, were highest in March 2007 (62%). This agreed with the 2002 emission inventory for the Chiangmai city which shows that forest fire was the main contributor of the total SPM emission (PCD, 2002). Overlaying the fire hotspots on MODIS satellite imageries and land use in the Northern region of Thailand by using ArcView GIS for the period of highest numbers of hotspots (March 9-15, 2007) showed that 80% of hotspots were detected in the forest areas and 20% were in the agriculture areas. Thus, the most remarkable emission source increase in March 2007 was biomass burning (forest fire and agroresidue burning) followed by seasonal industries.

2) Daily meteorology and emission

The synoptic patterns for each day during the period from February-April 2007 show that all of the episode days in March 2007 belong to pattern 2 (Figure 3).
Figure 3. Relationship between daily hotspot counts (y1) and PM$_{10}$ levels in Chiangmai.

Note: area with radius 150 km around Chiangmai is shown as a circle and area of 150-557 km is marked as rectangle in Figure 1. Synoptic patterns are shown in the top of Figure 3.

Figure 3 shows that the days with pattern 2 were associated with high PM$_{10}$ and also with high number of hotspot counts. We used the daily hotspot counts within a radius of 150 km (northern Thailand) surrounding the Chiangmai weather station (ID 48327) and the west area (557 km x 1009 km) of Chiangmai (Figure 1) as surrogates for the intensity of biomass burning emission around Chiangmai and that on the intensive burning area on the west of the city. Note that WDI in Table 1 show westerly is prevalent in three patterns 1, 2 and 4 that there is possibility that the biomass burning emission may be transported to Chiangmai under this prevalent wind. However, the division between local biomass burning and regional biomass burning influences is more geographical in this study and would not be able to give a quantitative answer to the share of the sources to air quality in Chiangmai. A complex 3D air quality modelling system is required to adequately answer this question.

High numbers of hotspots in both surrounding areas and the western region of Chiangmai were observed daily during March 1-April 4, 2007. However, on March 5 and 12, the PM$_{10}$ levels in Chiangmai were still high despite low hotspot numbers being observed (both days had low cloudiness). This could be explained by analyzing the five-day backward trajectories, which found that majority of air mass took longer time to move over the Southeast Asia continent before arriving to Chiangmai. The slow motion of the air masses indicated the stagnant conditions that trap air masses over the areas with dense hotspots to pick up the burning emission. In addition, the air mass trajectories are directly linked to synoptic scale wind and hence to synoptic patterns. During March 21-22, a ridge was found to be extending in Northern Thailand and pattern 4 was present, coinciding with the air mass pathway through the South China Sea, Vietnam and the Northeast of Thailand before arriving at Chiangmai. This pathway avoided the region of dense hotspots, consequently, PM10 levels decreased suddenly. Thus, meteorological patterns can link both the stagnant conditions (local and regional) and the air mass pathway (regional transport), both of which are important in the formation of haze episode in Chiangmai.

d. Episode warning

Identification of the synoptic pattern of a given day by the developed automated meteorological classification scheme is proposed as a prerequisite for implementing episodic controls. When occurrences of pattern 2 are noticed during March period measures for minimization of emission should be implemented, especially for unnecessary open burning of solid waste in community and agriculture area and prescribed forest fires.

Model forecasting daily 24h PM$_{10}$ in Chiangmai was developed based on the data of the episodic days in February-April of 2007-2009 that provided 99 data points for the step wise regression analysis. Only days of synoptic pattern 2 were considered. All available dependent variables were entered into the stepwise linear regression analysis. We input all available data, namely meteorological data, emission surrogate data and levels of PM$_{10}$ in previous days. The stepwise procedure examines all previously entered variables and removes any variable whose F statistic is not significant. In this study the significant level for retention is F = 0.15. The resulting regression model is presented in equation (2).

$$[\text{PM}_{10}] = -2838.526 + 0.781 \ T_{\text{PM}_{10}} - 0.006 \ \text{Vis} - 1.56 \ \text{Hum} + 3.01 \ \text{SLP} - 0.164 \ Y_{\text{PM10}} + 0.674 \ PG4$$

(2)

Where,

$[\text{PM}_{10}]$ is the next day 24-h PM$_{10}$ forecast averaged for 2 stations in Chiangmai
$T_{\text{PM}_{10}}$ is 24-h PM$_{10}$ averaged for 2 stations in Chiangmai of present day (µg/m$^3$)
Vis is the visibility (m) in Chiangmai measured at 07:00 LST of present day
Hum is the relative humidity (%) in Chiangmai at 07:00 LST of present day
SLP is the sea level pressure (mb) in Chiangmai at 07:00 LST of present day
$Y_{\text{PM10}}$ is 24-h PM$_{10}$ averaged for 2 stations in Chiangmai of the previous day, and
PG4 is pressure gradient between Wuhan and Chiangmai of present day

A linear relationship between the observed and predicted values was obtained with $R^2$ of 89% and RMSE (root mean square error) of 21.9 µg/m$^3$. The model performed satisfactorily when tested with data sets of year 2004 - 2010 (until March 10, 2010) with $R^2$ of 79% and RMSE of 24.1 µg/m$^3$, respectively.
CONCLUSIONS
Meteorology and emission intensity are interrelated and both play important roles in the Chiangmai haze episode formation. Our findings indicate that pattern 2, typically with light wind and strong inversion, is most likely to be linked to haze episodes in March 2007. High monthly emission in March 2007 due to open burning (forest fire and agro-residue) and seasonal industries of 6 Northern provinces in February-April period are also causally linked to the high frequency of haze occurrences during this month. The developed PM$_{10}$ model performed satisfactorily on both development and test data sets for 7 years (2004-2010) can be used for the haze episode prediction if pattern 2 is identified. Advanced haze warning can also be distributed by the local authorities to help residents better prepare to cope with the high pollution levels. Details of both meteorological and emission factors should be considered to successfully manage episodes in a selected area. Further efforts should be concentrated to prepare detailed emission inventory as the input of an operational model system to predict air quality in the area.

REFERENCES