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Analysis of Aerosol Properties Coupled with Meteorological Parameters over East Asia

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ABSTRACT

This paper investigates the aerosol properties over the major East Asian stations of Beijing, Gosan, Osaka, Taipei, Mukdahan, and Bac-Giang, during the years 2002 - 2008. Aerosol optical thickness (AOT) product from the moderate resolution imaging spectroradiometers (MODIS) onboard the Aqua and Terra satellites are used for this study. The aerosol robotic network (AERONET) ground observations are used to validate the satellite AOT. The daily, monthly, seasonal, and inter-annual AOT variations over the selected locations are described along with meteorological parameters from National Center for Environmental Prediction, National Center for Atmospheric Research (NCEP-NCAR) reanalysis data and Global Precipitation Climatology Center (GPCC) data. Angstrom exponent (AE), and fine mode fraction (FMF) from MODIS and AERONET are used to discuss the size, type and possible particle sources. Seasonal wind patterns from NCEP-NCAR reanalysis data are used to confirm particle transport from the source regions around the study area to the chosen stations. The results suggest that the maximum aerosol loading occurs over Beijing with the daily mean AOT reaching above 2.0. Gosan and Taipei are among the stations having the smallest AOT in most seasons with values below 0.5. Dust influence appears to be significant over Beijing, Osaka, and Gosan and to a lesser extent over Bac-Giang in the spring. Pollution, bio-mass burning, etc. contribute in the summer and spring over all stations. The detailed AOT characteristic over Mukdahan and Bac-Giang are reported for the first time.

Key words: Aerosols, Dust and pollution, Remote sensing of environment, MODIS, Pollution transport

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1. INTRODUCTION

Aerosols play a significant role in the Earth's climate system. They affect the amount of short wave radiation that reaches the ground through scattering and absorption, and also modify cloud properties, often described as having direct and indirect effects on climate (Tanré et al. 1984; Charlson et al. 1992; Kaufman and Nakajima 1993; Huang et al. 2006; Persad et al. 2014). Understanding the aerosol feedback on climate is difficult since aerosol composition, shape and size vary greatly with space and time (Kaufman et al. 2002). Hence, continuous observations with global coverage are necessary, using a network of ground stations or satellite based measurements. Over a global scale, the aerosol robotic network (AERONET) has been widely used to study aerosol characteristics and classify different aerosol types (Holben et al. 2001; Dubovik et al. 2002; Omar et al. 2005; Kaskaoutis et al. 2007; Kambezidis and Kaskaoutis 2008). Satellite measurements by advanced very high resolution radiometer (AVHRR), total ozone mapping spectrometer (TOMS), as well as moderate resolution imaging spectroradiometer (MODIS) have also provided a wealth of information about the spatial and temporal aerosol distribution (Higurashi et al. 2000; Chu et al. 2003; Jeong and Li 2005). Such investigations have revealed large regional contrast in the aerosol amount, size and type, and also their seasonal variations. While satellite coverage offers a global perspective of aerosols and gives valuable information about particle transport, the recent focus has been on the regional characteristics, considering the large uncertainty regarding the amount and distribution of aerosols. This is particularly important in

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understanding how aerosols influence regional and global climate, since different types of sources dominate over different regions and are transported over great distances.

Asia, one of the most populated and heavily industrialized regions, has a major stake in the global aerosol loading (Chu et al. 2003). The ACE-Asia campaign showed that Asian aerosols consist of a mixture of mineral dust and pollutants such as black carbon, sulfates, nitrates, and organics, thus exhibiting a wide range of physical and optical properties (Huebert et al. 2003). The dust and pollution are transported to other regions, affecting the air quality and climate (Eck et al. 2005; Kim et al. 2005; Yi et al. 2014). There is considerable spatial and temporal variability in the amount and type of aerosol particles which impact the local and regional environments differently. Eck et al. (2005) reported a wide range of aerosol loading over selected sites in China, Mongolia, Japan, and South Korea, and noted the presence of pollutants even in the seasons usually dominated by dust storms. Kim et al. (2007) analyzed the natural as well as anthropogenic emissions and the local meteorological parameters to understand the seasonal aerosol distribution over the region. These investigations revealed the aerosol characteristics over the individual stations and indicated the extent and impact of the transport processes, underlining the importance of further studies using long-term data sets and continuous monitoring.

This work is aimed at a detailed investigation of the aerosol properties over major East Asian cities, using seven years of satellite observations, expanding the study area to include Thailand, Vietnam, and Taiwan in addition to China, Japan, and South Korea. There have not been many reports discussing the aerosol properties over Thailand and Vietnam. Further, the analysis of seasonal aerosol characteristics over Taiwan using long-term data is also very limited (Chen et al. 2009). Several studies have been carried out to explain the aerosol variation over China, Japan, and Korea (Chu et al. 2003; Eck et al. 2005; Kim et al. 2005, 2007, 2014; He et al. 2012). The results indicated that dust and pollution are transported from Mongolia and China in the spring. This paper extends that study and discusses the seasonal variation in aerosol optical thickness (AOT) using long-term data. The monthly and annual AOT values over specific stations in the selected countries are described. The differences and similarities in the observed aerosol properties are discussed. The corresponding Angstrom exponent (AE), fine mode fraction (FMF), and meteorological parameter values such as rainfall, humidity, temperature, and soil moisture are used to understand the observed variations.

2. STUDY AREA

The stations selected for the aerosol analysis carried out in this work are marked in Fig. 1, which also gives the average fire counts over the study area in different seasons during 2002 - 2008. The stations are from the East Asian countries of Japan (Osaka), South Korea (Gosan), China (Beijing), Taiwan (Taipei), Thailand (Mukdahan), and Vietnam (Bac-Giang). Among these stations, Osaka, Taipei, and Beijing are urban areas where industrial emissions and motor vehicle pollution are significant. Gosan is located on

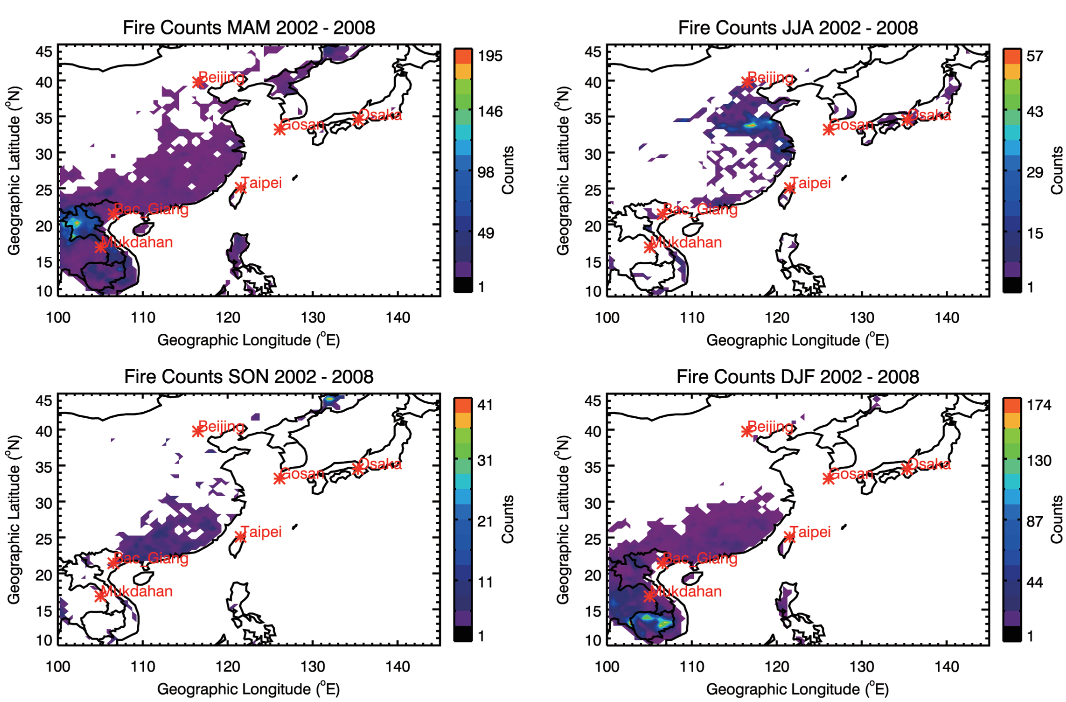

Fig. 1. Study area with MODIS fire counts in different seasons.

JeJu island of South Korea. Mukdahan and Bac-Giang belong to rural communities with the neighboring areas being agricultural land or forest.

The selected locations surround the Inner Mongolian plateau, Taklimakan desert, and Hexi corridor, which are known sources of dust particles, especially in the spring season when dust storms are frequent (Qian et al. 2002; Wang et al. 2004). Another major source of aerosols is pollutants from the rapidly developing industrial regions in the eastern parts of China. Bio-mass burning in the growing seasons and forest fires (Fig. 1), over the area also contribute to the aerosol loading (Eck et al. 2005; Kim et al. 2005, 2007). In addition, Eastern China, Indonesia, Vietnam, and Thailand are also sources of bio-mass burning and pollution (Lelieveld et al. 2001). Depending on the wind pattern, such particles could be transported to other locations and load over the background amount.

3. DATA AND METHODOLOGY

About 7 years of observations by MODIS onboard Aqua and Terra satellites, as well as ground measurements from AERONET were used to study the aerosol characteristics over the selected stations. The MODIS level 2.0 AOT products at 550 nm wavelength were available at a spatial resolution of 10 × 10 km, with one measurement in the morning from Terra and another one in the afternoon from Aqua. The level 2.0 AERONET AOT values at 440 and 675 nm wavelengths were taken whenever measurements were available, depending on the observation conditions over each station. MODIS AOT is derived by measuring the reflected radiation from the surface with the help of pre-computed look-up tables using radiative transfer models (Kaufman et al. 1997; Tanré et al. 1997). AERONET is a global network of ground based radiometers, providing aerosol optical property and aerosol size distribution, making use of direct sun measurements and indirect sky measurements in about 10 different spectral channels (Holben et al. 1998). All of these stations use identical instruments and pre-defined observation sequences. The retrieval is based on the spectral extinction of the solar radiation at the measured wavelength using the Beer-Lambert-Bouguer relationship (Holben et al. 1998).

In addition, AE and FMF from MODIS and AERONET are used to infer the size and type of particles. The MODIS fire count product is used to speculate on the possible forest fire or bio-mass burning activities around the study area. Meteorological parameters from the National Center for Environmental Prediction, National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al. 1996) and Global Precipitation Climatology Center (GPCC) data (Schneider et al. 2011) were used to obtain rainfall, temperature, and relative humidity information over and around the study area. Seasonal wind patterns from NCEP-NCAR reanalysis data were used to understand aerosol particle transport into and away from the region. Note that NCEP-NCAR reanalysis provides global analyses of atmospheric data at a grid resolution of 2.5 × 2.5° using assimilation by incorporating all available data sources. The GPCC data, which provides high accurate reanalysis of precipitation data from global ground stations at 0.5 × 0.5° grid resolution, was used to infer the monthly mean precipitation during the study period over the selected stations.

Before using MODIS and AERONET measurements to study the aerosol properties, it was necessary to check how well they agreed with each other. Both instrument systems differ in spatial and temporal sampling. Note that MODIS scans a large area, while AERONET makes point measurements. Moreover, MODIS gives only two AOT values per day over a given location unlike the AERONET, which is designed to make measurements every 15 minutes depending on the sky condition. Thus, in order to compare MODIS and AERONET AOT, it was necessary to ensure that the data were spatially and temporally coincident. The first step was to determine the MODIS AOT over the AERONET location. For this, the mean of all MODIS measurements within ±25 km of the AERONET location was taken. The second step involved finding the AERONET AOT at the time of MODIS overpass. For this, the average of all AERONET AOT values within ±30 minutes of the MODIS overpass time was used (Ichoku et al. 2002). The AERONET AE in the 440 - 675 nm wavelength range is used to estimate the AOT at 550 nm. Figure 2 gives the total number of MODIS and AERONET data points following the method described above in each month during 2002 - 2008. The AERONET points are taken whenever there is an observation available at the MODIS overpass time. The MODIS has a more concurrent data sample than AERONET during the observation period, except over Beijing where the AERONET sampling is better. However, no data is available after 2008.

4. RESULT

Several investigators used concurrent AERONET measurements to validate MODIS derived AOT, with the results showing good correlation of about 0.8 - 0.9 (Chu et al. 2002; Ichoku et al. 2002; Cheng et al. 2006). All of the spatially and temporally coincident MODIS and AERONET AOT during 2002 - 2008, over all the stations are plotted in Fig. 3a for the present analysis. The overall correlation of the two data sets were reasonably good with a correlation coefficient of 0.90. The MODIS AOT bias over the stations from the AERONET is about -0.04 with a root mean square error of 0.17, using 2250 concurrent data points. Table 1 gives the MODIS-AERONET validation details over each station during 2002 - 2008. The individual stations also have fairly good correlation, with a lowest value of 0.82 over Taipei, and a highest value of 0.94 over Mukdahan and Beijing. Figure 3b gives a similar MODIS AE product

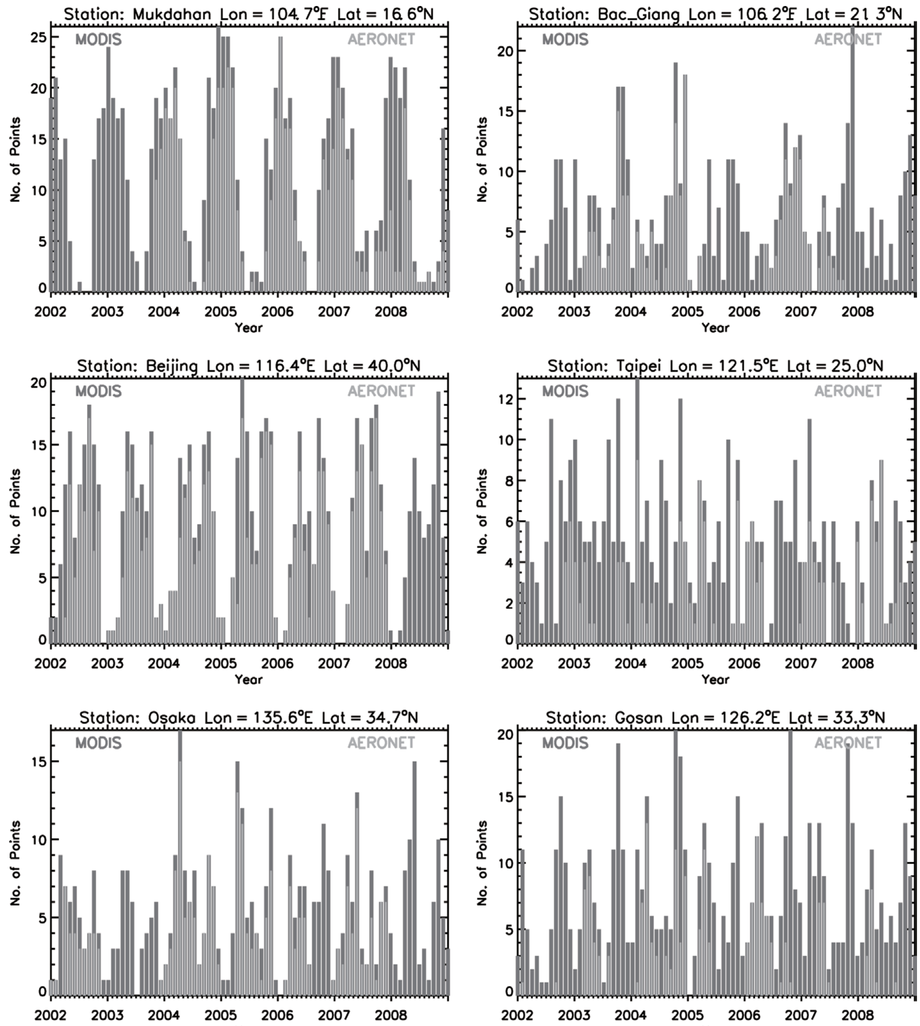

Fig. 2. Number of MODIS and AERONET data points for each month during 2002 - 2008. The AERONET data at the time of MODIS over pass are used.

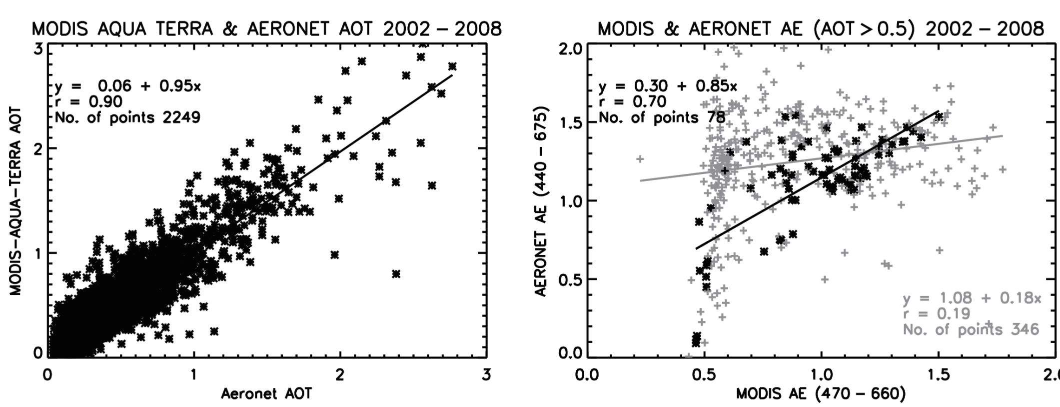

Fig. 3. Scatter plot of spatially and temporally coincident MODIS and AERONET AOT as well as AE over selected stations during 2002 - 2008. For the AE correlation, the '+' symbols in gray color give the correlation of all data points, whereas the asterisk symbols correlation considering only those points with MODIS AOT > 0.5.

Table 1. Validation of MODIS and AERONET over the selected stations. The number of data points (N), correlation coefficient (R), slope (m), and intercept (c) of the linear regression are given.

Station	N	R	m	c
Mukdahan	689	0.94	0.88	-0.04
Bac-Giang	313	0.88	0.82	0.17
Beijing	791	0.94	0.98	0.16
Taipei	188	0.82	0.68	0.05
Gosan	100	0.94	0.91	0.07
Osaka	168	0.87	1.20	0.11
All	2249	0.90	0.95	0.06

validation with that of the corresponding AERONET AE. The light gray points show that the correlation is very poor with a coefficient below 0.2. Note that the MODIS AE values were calculated using the AOT at 470 and 660 nm wavelengths. Thus, to have a meaningful comparison, the AERONET AOT at the 440 and 675 nm wavelength pairs were used to calculate the corresponding AE in Fig. 3b. This was done because AE estimated using AOT at different spectral regions might have different characteristics (Schuster et al. 2006). However, Fig. 3b (gray points) shows that little agreement occurs even within a similar spectral range. It has been shown that the aerosol size parameters estimated from MODIS could be less accurate when the AOT is small (Remer et al. 2002, 2005; Kleidman et al. 2005). In order to find a better correlation between the two, the AE values were estimated using a different AOT threshold. It was found that the correlation improves significantly when the AOT is greater. The dark asterisk symbols in Fig. 3b give the correlation using only those points with AOT $\geq$ 0.5. The correlation is about 0.7 in this case. The poor aerosol size representation estimated from MODIS is attributed to its lesser sensitivity at low AOT due to calibration errors and surface reflectance assumptions (Kleidman et al. 2005; Remer et al. 2005).

After having found that both the MODIS and AERONET AOT are well correlated, the daily, monthly and annual variations over the six selected stations were analyzed further. Figure 4 displays the daily mean MODIS and AERONET AOT values during 2002 - 2008. For the daily mean values, only those AERONET AOT at the MODIS overpass time were used. The AOT values were greatest over Beijing in all years, with some of the values apparently greater than 2.0. Bac-Giang also showed larger AOT values. Over other stations the AOT values were below 1.5. The MODIS observations show that over Taipei and Gosan, the AOT values are the smallest of all stations and remain mostly below 1.0 in all years. Figure 4 also reveals the seasonal AOT behavior, which depends on individual locations. Although both the MODIS and AERONET show similar variations, the magnitudes are slightly different. One of the reasons for the difference could be the applied spatial and temporal sampling, which probably resulted in more smoothening of the MODIS data. The daily mean AE values corresponding to the AOT values are given in Fig. 5. The seasonal variation can also be seen in the AE values, with values ranging between 0.5 to about 1.8. This indicates that the aerosol properties are different in different seasons, with fine mode (larger AE values, mostly greater than 1.0) and/or coarse mode (smaller AE, with values below 1.0) particles dominating. However, over Taipei the seasonal variation appears to be not so significant with the AE values mostly between 1.3 - 1.8, which occasionally drops to about 1.0. This suggests that over Taipei fine mode particles dominate in all seasons.

In order to understand the intra-annual AOT variation as well as AE, the monthly mean values averaged over the 7 years for each station are plotted in Fig. 6. Since not much difference occurs in the monthly mean AOT and AE for Aqua and Terra, only the average values are given in the figure. The monthly pattern, as well as the magnitude of AOT variation is different for different stations. Mukdahan and Bac-Giang show a double peak pattern, with peaks in March (spring) and September-October (autumn), and smaller values in the summer and winter months. The spring peak is more prominent than that in autumn. The monthly mean AOT over Bac-Giang is mostly greater than 0.5, while over Mukdahan the mean AOT is below 0.5 except in the month of March. The maximum and minimum monthly mean MODIS AOT over Mukdahan are 0.60 ± 0.16 and 0.18 ± 0.05, respectively in March and December months, while the corresponding values over Bac-Giang are 1.06 ± 0.03 and 0.50 ± 0.17, and are recorded in the months of March and May. In December the monthly mean AOT over Bac-Giang is about 0.66 ± 0.10.

The AE values also exhibit a similar two-peak variation over these two stations with larger AE in spring and autumn and smaller values in summer and winter. The AE over Mukdahan is about 1.5 during spring and between 1.0 - 1.3 in the autumn and winter months. In the summer months the AE values are in the 0.8 - 1.0 range. The FMF also exhibits very similar variation as that of AE. Note that the FMF from MODIS and AERONET differ, especially in the autumn and winter months, with the AERONET FMF showing higher values than the MODIS. However, the overall tendency of both observations is similar. Over Bac-Giang the MODIS AE values are between 0.6 - 0.8 during the summer (June - July) and winter (November - February) months. The value sharply rises to about 1.3 - 1.4 in April, and attains a secondary peak of about 1.2 - 1.3 in September. Unlike Mukdahan, the MODIS and AERONET AE over Bac-Giang disagree in magnitude, though the monthly variation arguably exhibits a similar tendency. The AERONET AE is greater than 1.0 in all months and has a peak value of about 1.5 in April - May. The summer months reveal a decreasing trend, except in July when the value is higher. It can be seen that the MODIS and AERONET FMF also exhibit a discrepancy similar to that in the AE values. While the AERONET FMF shows smaller size particles dominating in all months, the MODIS FMF presents smaller particles in summer and winter and larger particles in the spring and autumn seasons, with the peak occurring in April. Bridhikitti and Overcamp (2011) observed fine mode particles over these stations in the spring and autumn months. However, a detailed investigation of the monthly mean AOT variation as described here, using multi-year data over Mukdahan and Bac-Giang was not carried out before.

The monthly mean pattern over Beijing shows a single AOT peak in June, with a maximum value of 1.23 ± 0.20, and relatively larger values (> 0.5) during April - September. In other months the values are below 0.5. The AERONET AOT varies similar to that of MODIS, but the values are slightly smaller with a maximum value of 0.93 ± 0.24. The MODIS AE values are about 0.6 - 0.7 in the months of October - April and there is a gradual increase from May, reaching a peak value of about 1.2 - 1.3 in August and decreasing thereafter. The AERONET AE, in contrast to the AOT, is greater than the MODIS. The values are mostly above 1.0, showing a reduction in spring, peaking again in July - August and decreasing in winter. Note that the AE appears to slightly increase in the early winter month of November. The MODIS FMF reveals a similar monthly pattern as that of the corresponding AE, suggesting the presence of smaller particles in summer and larger particles in other seasons. Eck et al. (2005), using 2 years of AERONET data during 2001 - 2003, reported a similar AOT variation over Beijing, with monthly mean in the range 0.4 - 1.10, peaking in the month of June. Their AE result, while exhibiting a similar tendency, showed a peak in June, similar to the AOT. Kim et al. (2007) also showed a similar monthly

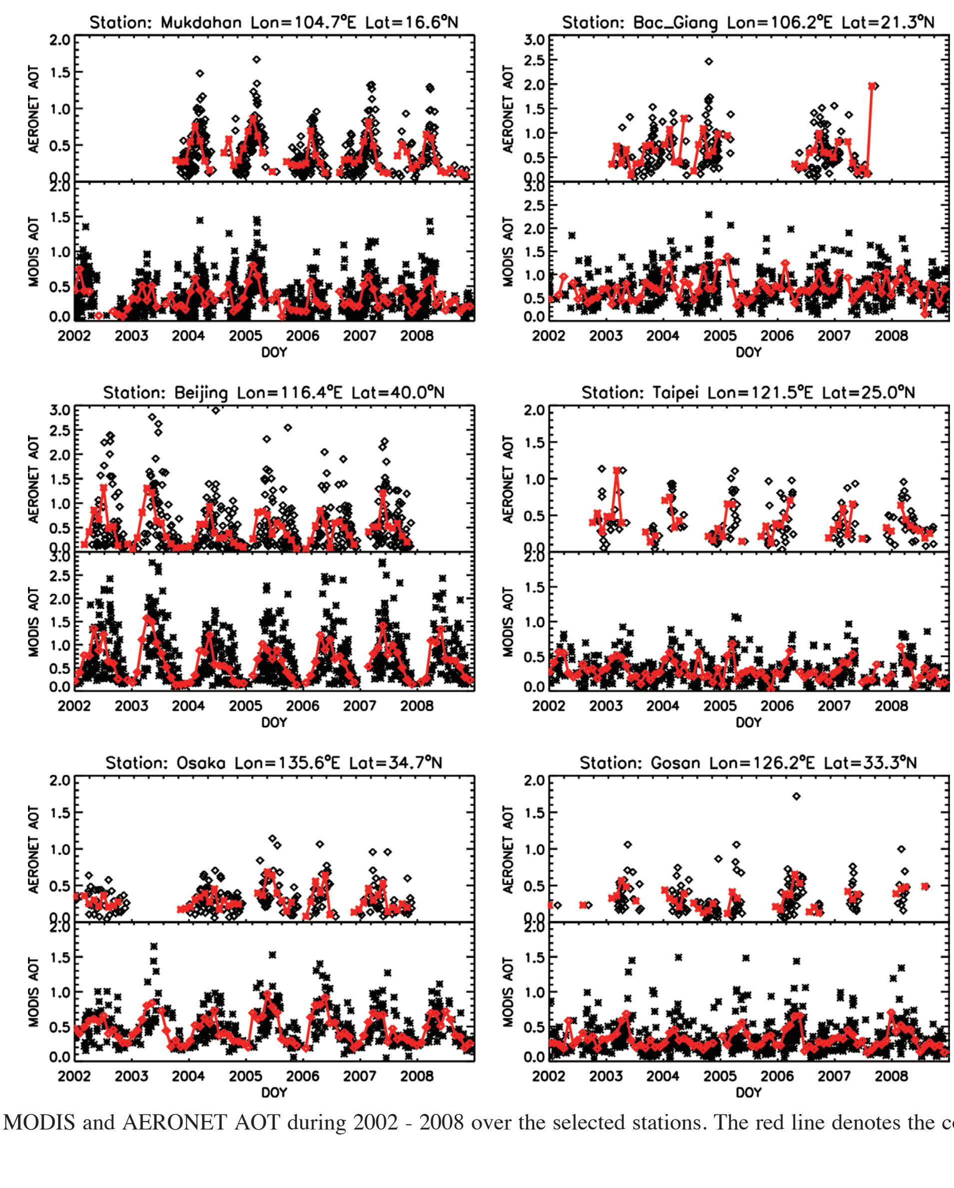

Fig. 4. Daily mean MODIS and AERONET AOT during 2002 - 2008 over the selected stations. The red line denotes the corresponding monthly mean values.

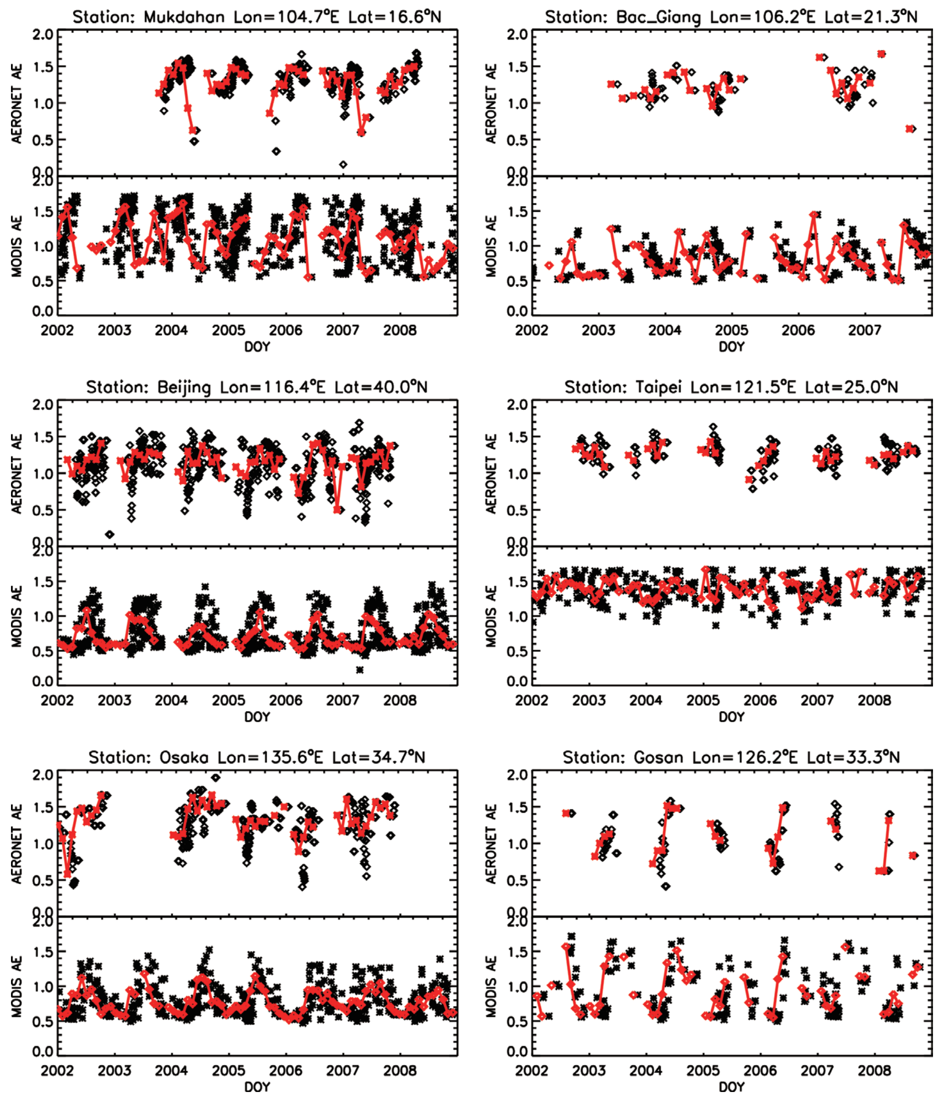

Fig. 5. Daily mean MODIS and AERONET AE during 2002 - 2008 over the selected stations. The red line denotes the corresponding monthly mean values.

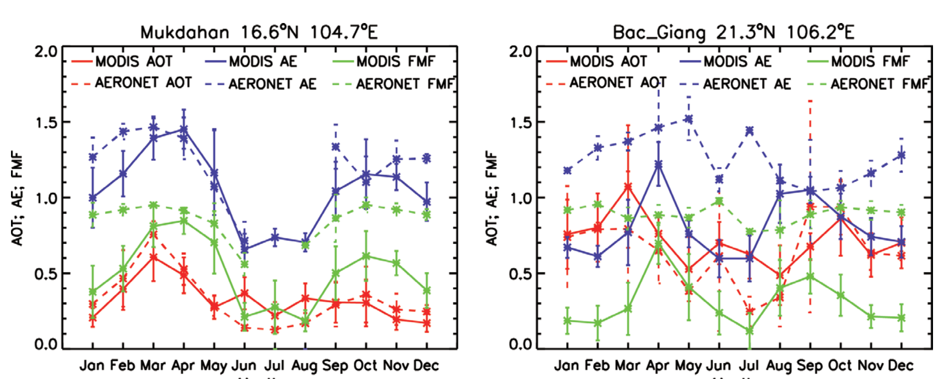

Fig. 6. Monthly mean MODIS and AERONET AOT, AE, and FMF during 2002 - 2008 over the selected stations.

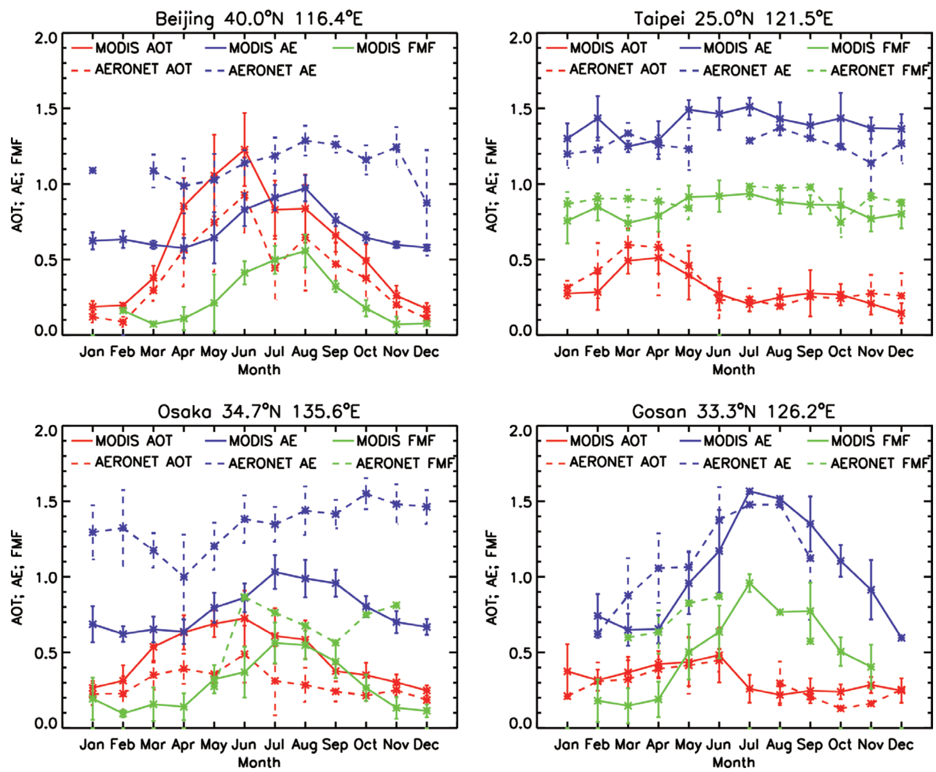

Fig. 6. (Continued)

mean pattern over Beijing from 2000 - 2005, with values between 0.5 - 1.0. The AE variation in their study is similar to that reported here. Further studies by Yu et al. (2009), using AERONET also shows similar seasonal aerosol optical properties over Beijing.

The AOT pattern over Taipei is more-or-less similar to that over Mukdahan, with a peak in spring (0.50 ± 0.10), and a less pronounced peak in autumn (0.29 ± 0.15). However, the monthly mean variation in AE over Taipei is very different, with the value at about 1.4 - 1.6 in all months indicating that mostly smaller size particles contribute to the observed aerosols. As in the case of Mukdahan, over Taipei also there is a fairly good agreement between MODIS and AERONET AE and also FMF. However, in spring MODIS AE (also FMF) tend to slightly decrease, while AERONET AE suggests an opposite tendency, though both agree in magnitude. Chen et al. (2009) reported a similar seasonal AOT variation over Taipei using about two years of AERONET observations. Their AE variation agrees with that of the AERONET result described here.

Osaka and Gosan have a similar AOT seasonal variation, with both showing a single peak in the month of June. The MODIS and AERONET AOT and AE values more or less agree over Gosan, while it is not the case over Osaka. Note that the AERONET AOT exhibit similar monthly variation in magnitude over both stations (also for the case of MODIS AOT over Gosan), with the maximum value not greater than 0.5. However, the MODIS AOT over estimates the AERONET values over Osaka, with AOT > 0.5 during March - August, with a peak value of about 0.70 ± 0.18 in June. The MODIS AE over Osaka is between 0.7 - 0.8 during December - April and gradually increases from May, attaining the peak value of 1.2 - 1.3 during July - September and decreasing thereafter. The corresponding AERONET AE behaves differently, with values greater than 1.0 in all months. There is a significant decrease in spring, registering the lowest value (1.0) in April. The AERONET AE then gradually increases, reaching a peak of about 1.5 in October, showing a slight decrease in winter. The seasonal AE variation is more pronounced over Gosan, showing maximum summer to winter difference. The MODIS and AERONET AE mostly agree in magnitude, except in March and April when they show opposite tendency, similar to that over Taipei. The MODIS AE is about 0.6 during March - April, whereas the corresponding AERONET values are 0.9 and 1.1, respectively. Both measurements show higher values of about 1.4 - 1.6 during June - August, with a peak in July, and gradually decreasing afterwards.

The AOT range over Gosan agrees with that reported by Kim et al. (2007) using AERONET measurements. Over Osaka, the AERONET observations at 670 nm in 2002 by Sano et al. (2003) showed peaks in spring and summer seasons and lesser values during winter. Funasaka et al. (2003) noted an enhancement in total and coarse mode particles in spring using surface observations over Osaka. The spring time AOT enhancement and corresponding lower AE agrees with this, although it must be noted that surface and total column measurements could as well be very different. The AERONET values over Shirahama, a nearby station, given by Eck et al. (2005) and Kim et al. (2007) are also similar to that over Osaka, except that the peak value is only about 0.4 - 0.5. Note that the AERONET AE values over Gosan by Kim et al. (2007), appear to be different from those in Fig. 6. Their result shows a decrease in AE in the spring season. There is no pronounced peak in July and instead a small peak exists in September. Table 2 summarizes the monthly mean maximum and minimum AOT, AE, and FMF, averaged for both Aqua and Terra, with the corresponding month of occurrence over all stations.

5. DISCUSSION

The monthly mean and seasonal AOT variations over the selected stations described above include two components, the background aerosols and those transported from remote or nearby locations. Thus, in order to understand the AOT patterns, it is necessary to identify these different contributions. It is also important to know the possible sources of these aerosols, whether natural or anthropogenic, to examine the implications on climate. The observed variations are discussed below based on the present understanding of the major sources and types over the study area (Chueinta et al. 2000; Lelieveld et al. 2001; Sun et al. 2001; Qian et al. 2002; Kim et al. 2004, 2007; Wang et al. 2004; Eck et al. 2005; Lin et al. 2005; Lin et al. 2011; Reid et al. 2013).

5.1 Dust Particles

It has been reported that dust storms occur frequently over the Inner Mongolian plateau, Taklimakan desert and Hexi corridor (Sun et al. 2001; Wang et al. 2004). Several investigations have shown the influence of dust particles on the aerosol loading over the region (Eck et al. 2005; Kim et al. 2005, 2014; Lin et al. 2005; Mukai et al. 2006; Lee et al. 2007; He et al. 2012), especially in the February - May months. The aerosol loading observed over Beijing, Osaka, and Gosan, in these months is related to such dust storm events. Figure 7 suggests a strong westerly at the 850 hPa level in the spring season over this area from dust sources in China. The effect is pronounced over Beijing, which is an immediate downwind site to the source locations. The lower AE (about 0.6 - 0.8) and FMF (about 0.1 - 0.2) values over these stations indicate the dominance of coarse mode particles.

The AE over Mukdahan and Bac-Giang are relatively larger (> 1.0) in the spring, suggesting the dominance of smaller size particles. This indicates that there is probably less dust transport influence over these locations. There is no indication of any possibility for wind driven dust particle transport to Bac-Giang or Mukdahan during spring from desert sources over China (Fig. 7). However, over Bac-Giang, it can be seen that while the AOT peaks in the month of March, the AE records its highest value during April - May. Thus, it is possible that there is some sort of large particle transport in March, influencing the AOT and AE values. The wind-pattern in Fig. 7 indicates the possibility for particle transport from the desert regions of Northern India. This possibility for dust transport from the Indian sub-continent is discussed by Kim et al. (2005). Although the influence of spring dust transport has been reported over Taiwan, (Chiang et al. 2004; Nee et al. 2007), the multi-year monthly mean AERONET AE does not reveal any decrease in this period. The relatively larger magnitudes indicate that the dust event frequency might not be very significant over Taipei when considering the average picture. The seasonal mean wind also do not reveal much possibility for dust transport to Taipei in the spring months. Nevertheless, there is a slight decrease (about 7%) in the MODIS AE as well as FMF values in March - April. Individual dust transport events could still be important, but they do not affect the average values.

Note that MODIS and AERONET AE are not well correlated over some stations and hence interpreting MODIS AE must be performed with further verification. For example, considerable difference exists in the MODIS and AERONET AE magnitudes over Bac-Giang in spite of an overall similarity in the seasonal tendency. This difference in the MODIS and AERONET AE could also be seen over Beijing as well as Osaka. Further, the MODIS and AERONET AOTs over these stations also differ slightly, although the variation is within the statistical deviation. However, fairly good agreement exists between the two observations over the other three stations (Fig. 6). The difference in the MODIS and AERONENT AE could result from differences in the corresponding AOT estimations. The MODIS and AERONET AOT relationship in Table 1 show good correlation over the stations. However, the linear regression intercept is relatively larger over Bac-Giang, Beijing, and Osaka, compared to that for Mukdahan, Taipei, and Gosan. The intercept values probably suggest some bias in the MODIS and AERONET AOT over these stations. The satellite estimations are based on the aerosol backscattering, whereas the ground instruments measure the aerosol forward scattering. It has been shown that the error in AE measurements depends on the relative errors in AOT at the two wavelengths used for the calculation, although using multiple wavelengths minimizes the error (Wagner and Silva 2008). Instrument calibration error is regarded as one of the main contributors to the AOT error. The uncertainty in AOT and AE satellite measurements depend on the aerosol models used in the respective retrieval algorithms as well as the particle shape assumptions. A detailed investigation of the MODIS and AERONET validation is necessary to comprehend the differences over certain locations. Such

Table 2. Monthly mean maximum and minimum AOT, AE, and FMF from MODIS during 2002 -2008 with the corresponding month of occurrence.

Station	AOT		AE / FMF	
	Max	Min	Max	Min
Mukdahan	0.6 ± 0.16 (3)	0.18 ± 0.05 (12)	1.59 / 0.85 (4)	0.79 / 0.15 (8)
Bac-Giang	1.06 ± 0.03 (3)	0.50 ± 0.17 (5)	1.35 / 0.69 (4)	0.69 / 0.11 (6 - 7)
Beijing	1.2 ± 0.21 (6)	0.19 ± 0.03 (1)	1.16 / 0.55 (8)	0.62 / 0.07 (4, 11 - 12)
Taipei	0.50 ± 0.01 (4)	0.17 ± 0.05 (12)	1.64 / 0.90 (7)	1.43 / 0.73 (12 - 3)
Osaka	0.71 ± 0.18 (6)	0.26 ± 0.04 (1)	1.3 / 0.6 (8 - 9)	0.71 / 0.09 (12, 2)
Gosan	0.49 ± 0.17 (6)	0.21 ± 0.05 (8)	1.56 / 1.0 (7)	0.70 / 0.17 (2 - 4)

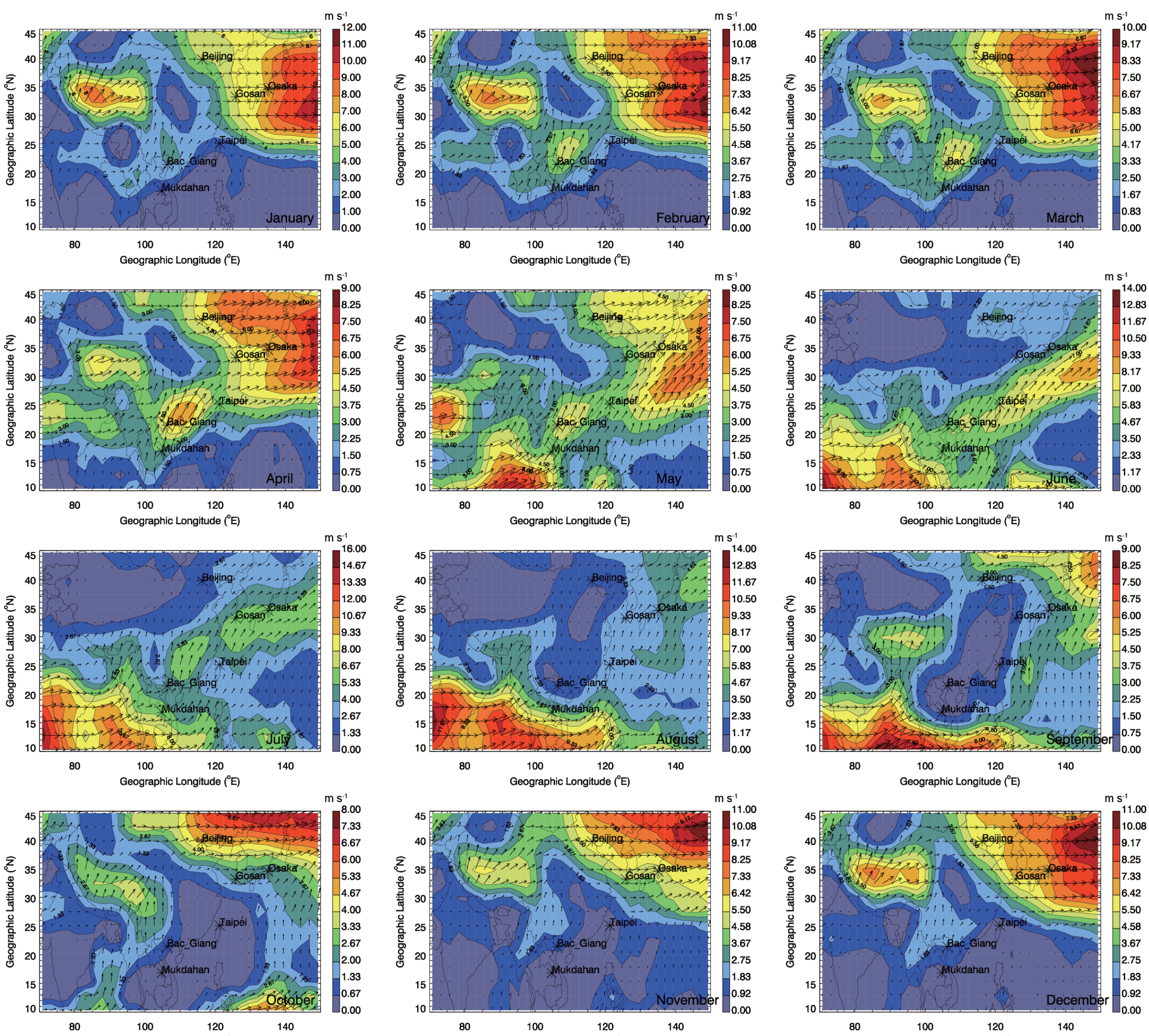

Fig. 7. Monthly mean NCEP-NCAR reanalysis wind at 850 hPa during 2002 - 2008 over the study area.

an analysis would be beyond the scope of this study and is being carried out separately, including a wider network of AERONET stations. In the current analysis whenever there is a disagreement in the MODIS and AERONET values, the AERONET is used to discuss the variations.

5.2 Smoke and Pollution

Another major contribution to the aerosol loading comes from pollution and smoke particles. Kim et al. (2007) studied frequent bio-mass burning in the eastern coastal areas of China in the month of June. He et al. (2012) reported the pollution and bio-mass particles in the North and East parts of China. Kambezidis and Kaskaoutis (2008) showed that the regions dominated by bio-mass burning present pronounced AOT peaks in the August - September months. Lelieveld et al. (2001) reported an increased aerosol loading in the dry season of August and October due to agricultural burning. A detailed account of bio-mass burning activities over South East Asia was given by Reid et al. (2013). Mukdahan and Bac-Giang are rural areas, surrounded by forest and agricultural land. Bio-mass burning, grass land burning and forest fires could contribute to the observed aerosol loading over these stations, especially in spring. The MODIS fire counts (Fig. 1, Reid et al. 2013) also suggest biomass burning or forest fire events occurring over the region in spring. The larger AE values in spring over the two stations indicate that smaller sized particles dominate the aerosols. FMF values of 0.5 or more further confirm that the majority of these particles are smaller in size. Bridhikitti and Overcamp (2011) suggested bio-mass burning activities for the fine mode particles over these stations. The prevailing South-Westerly in spring could transport smoke and pollution from the Indian continent, Indonesia and the Philippines to these regions (Fig. 7). The increase in AE over Mukdahan in autumn also suggests a loading of smaller particles in August - October. Forest fire events occur over the area in the dry winter months.

The larger AOT and AE over Beijing in June - August also indicate the loading of fine mode particle from pollution, bio-mass burning and/or forest fire (Eck et al. 2005; Kim et al. 2007). The AE over Osaka and Gosan also increase from June - July. The large AE values in September - October over these stations indicate that smaller particles dominate the aerosols. The smoke and pollution from East and North-East China could be transported to these stations (Kim et al. 2005). He et al. (2012) suggested that pollution and bio-mass burning contribute to aerosols over the eastern parts of China. The large AE values over Taipei, with FMF > 0.5, suggest that fine mode particles dominate in all seasons. The average AOT over 2002 - 2008 does not indicate any aerosol loading in any particular month or season. Thus, most of the observed aerosols might belong to background particles from industrial and motor-vehicle emissions.

5.3 Seasonal Variation with Meteorological Parameters

The seasonal variation in aerosol size, as inferred from the AE and FMF values, provides important information about the major aerosol types and the possible sources. In other words, the observed differences in the seasonal pattern over different stations could be used to understand the aerosol loading over these locations in different seasons. The aerosol characteristics over a given location are also influenced by meteorological parameters such as precipitation, temperature, humidity, wind pattern, etc. The monthly mean precipitation values from the GPCC data at locations nearest to the selected stations are given in Table 3. Further,

Table 3. Monthly mean precipitation (mm) over the selected stations from GPCC data.

Month	Mukdahan	Bac-Giang	Beijing	Taipei	Gosan	Osaka
January	1.9	19.2	2.2	92.8	55.6	46.8
February	27.7	20.6	4.0	150.3	57.6	62.9
March	57.7	21.4	13.2	204.9	90.2	92.8
April	55.5	81.5	23.2	147.7	107.4	101.8
May	223.9	201.9	42.4	252.4	165.9	154.7
June	226.5	185.5	75.2	262.1	174.7	144.8
July	351.8	257.8	109.8	155.5	230.3	176.5
August	357.1	265.8	81.2	310.1	251.8	128.6
September	261.7	178.3	57.5	350.2	216.8	138.7
October	94.4	66.8	30.8	140.2	73.3	127.8
November	19.1	81.9	8.2	96.4	66.8	75.8
December	2.9	24.1	3.0	86.5	49.6	68.0

the NCEP-NCAR precipitation, relative humidity and temperature data are plotted in Figs. 8 - 10.

Note that very dry conditions exist over the northern parts of China in the spring, with the relative humidity decreasing from 50% to below 20% (Fig. 9). Similar dry conditions are also seen over Beijing with humidity between 40 - 50% in the spring. Such dry weather might favor dust storms through local convections (Qian et al. 2002), resulting in the observed loading over Beijing, Osaka, and Gosan in the spring. In the summer months relative humidity increases with all stations receiving a significant amount of precipitation. The observed decrease in AOT in the summer might thus result from particle wash out. The relatively smaller decrease in AOT over Beijing in the summer months, compared to other stations, might be due to the smaller amount of rainfall over that region. Since Beijing lies in the vicinity of major source regions, the continuous loading might also reduce any wash out effect. The increase in AE over Beijing, Osaka, and Gosan in the rainy season could also be related to the washout, which is likely to remove larger sized particles, in addition to the emission and/or transport of fine mode particles as discussed above.

While all other stations show larger AE values in the summer months, indicating smaller sized particles, there is

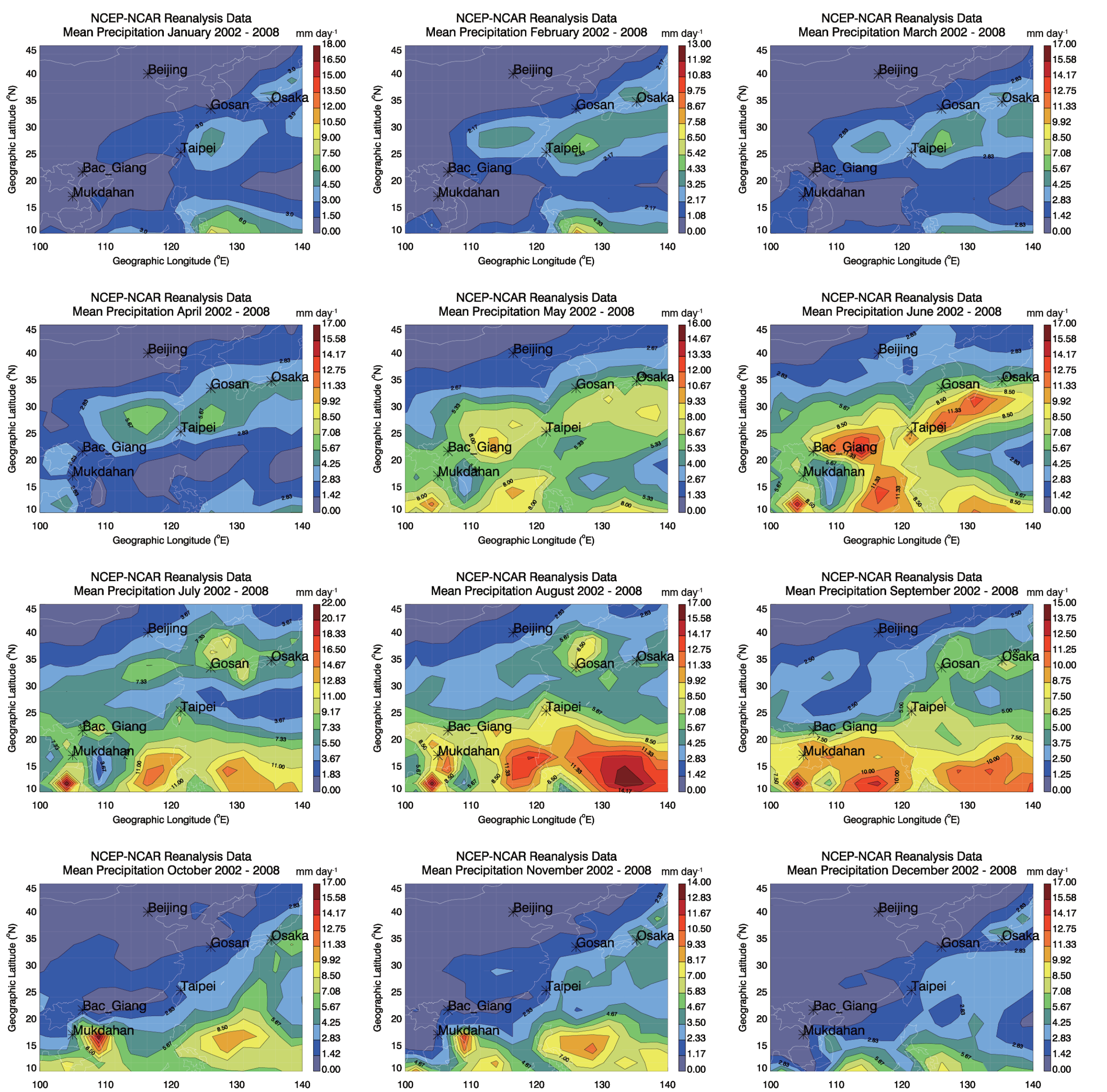

Fig. 8. Monthly mean NCEP-NCAR reanalysis precipitation data during 2002 - 2008 over the study area.

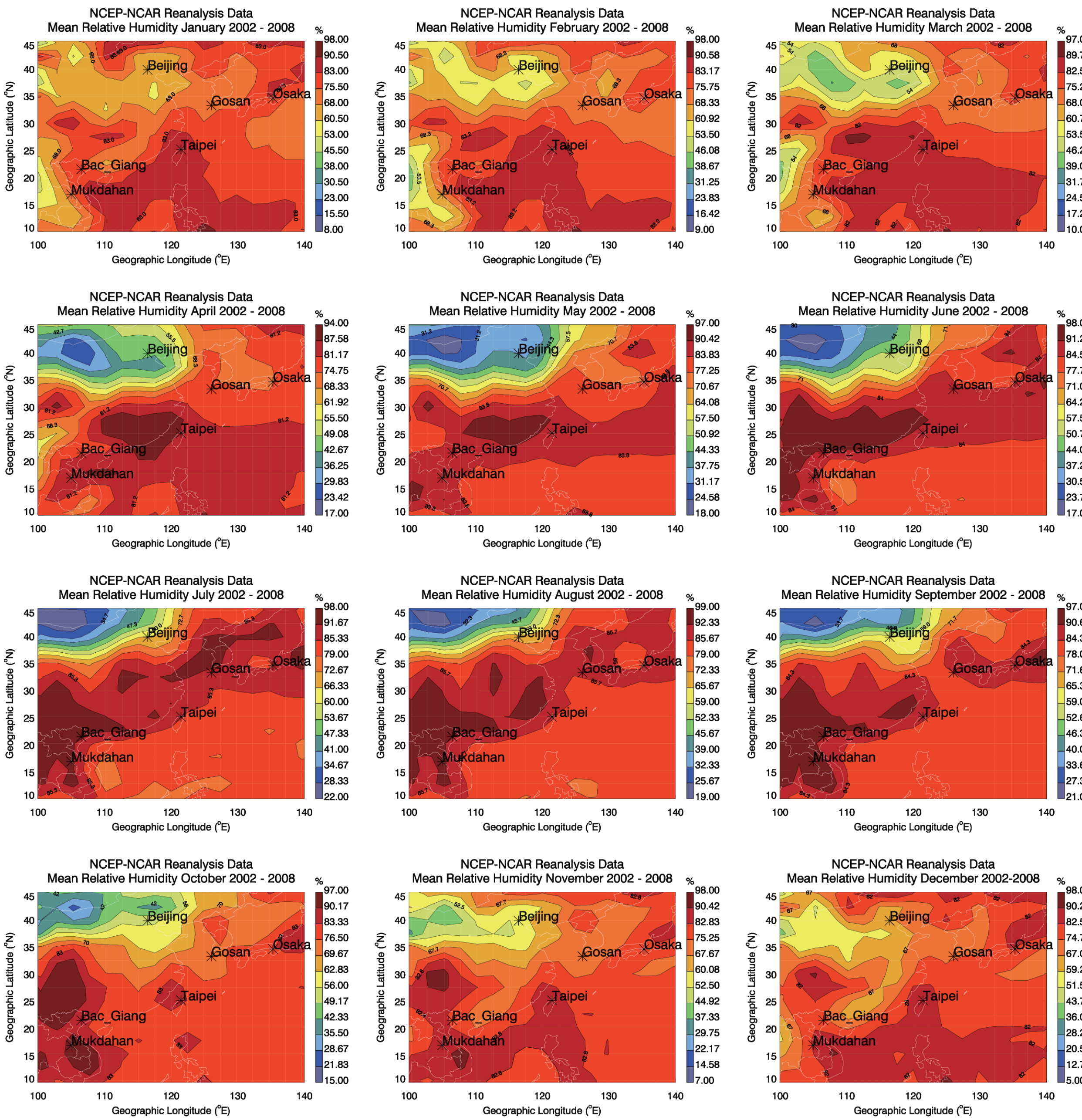

Fig. 9. Monthly mean NCEP-NCAR reanalysis relative humidity data during 2002 - 2008 over the study area.

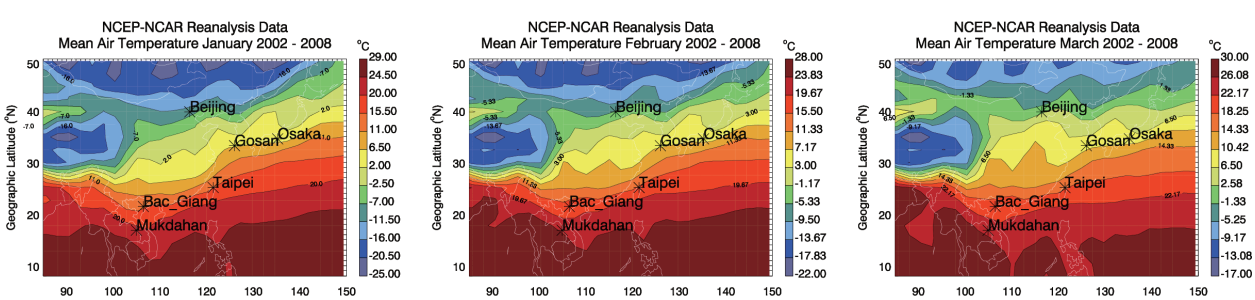

Fig. 10. Monthly mean NCEP-NCAR reanalysis temperature data during 2002 - 2008 over the study area.

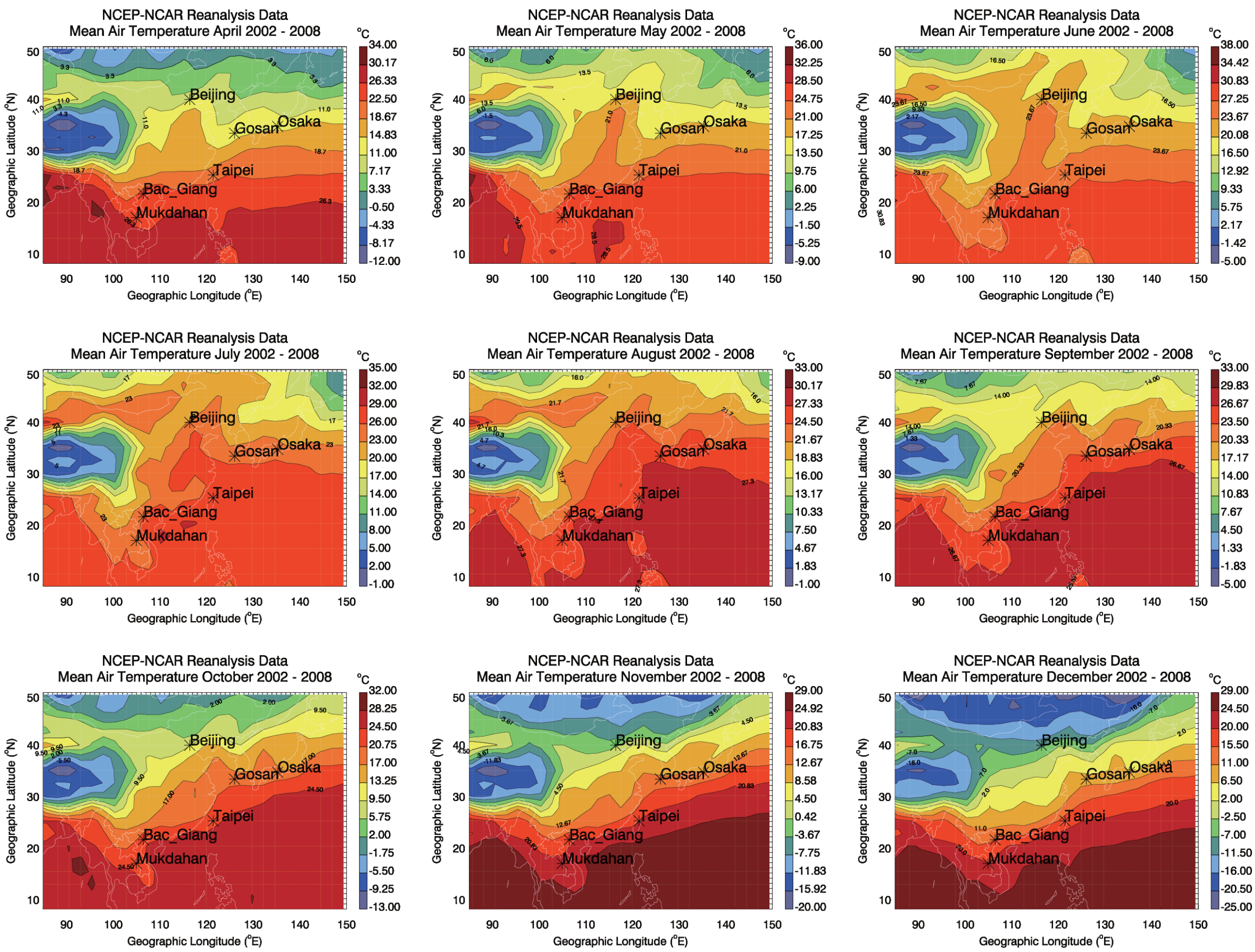

Fig. 10. (Continued)

a decrease in AE over Mukdahan and Bac-Giang, indicating an increase in the particle size. It can be seen that over Mukdahan and Bac-Giang most of the rainfall is concentrated in the summer months, while there is some sort of even distribution in all months over Taipei, Osaka, and Gosan. The sudden and heavy rainfall above Mukdahan and Bac-Gaing increases the relative humidity to about 95% in June and July (Table 3 and Figs. 8 and 9). These conditions might be favorable for hygroscopic growth of particles over these stations, causing AE to decrease.

Note that the AOT peak in June over Osaka and Gosan coincide with that over Beijing. Eck et al. (2005) also found a similar tendency using AERONET data over Beijing, Anmyon, and Shirahama. Kim et al. (2007) reported a similar pattern using MODIS data over a region covering the three stations as well as AERONET measurements over Beijing, Gosan, and Shirahama. They concluded that the June peak is characteristic of the column-integrated optical properties over East Asia resulting from stagnant synoptic meteorological system and the local as well as surrounding emissions in the season. Bao et al. (2008) suggested that increased biomass burning activity in summer could be the reason for the June peak over Beijing. Our results reveal that the AOT over Taipei differs from this general behavior. Moreover, the tendency over Taipei, Mukdahan, and Bac-Giang appears to be similar. Note that the seasonal wind over Taipei (as well as for Mukdahan and Bac-Giang) differs from that for Beijing, Osaka, and Gosan (Fig. 7). In spring, Beijing, Osaka, and Gosan are influenced mostly by wind blowing over the desert regions of central and northern China, whereas Taipei appears to be less affected. Wind coming from South Asian regions appears to be responsible for transporting aerosols to Mukdahan, Bac-Giang, and probably Taipei. In the summer months it can be seen that while Beijing, Osaka, and Gosan receive air blowing over the polluted regions of Eastern China, Mukdahan, Bac-Giang, and Taipei continue to receive the South Asian air mass. A similar tendency could also be noted in autumn and winter. Thus, the local aerosol characteristics and the possible transport from South Asian regions contribute to the seasonal AOT behavior over Mukdahan, Bac-Giang and to a certain extent over Taipei, while transport from mainland China influences the AOT over Beijing, Osaka, and Gosan, giving a similar seasonal pattern with a characteristic June maxima. Apparently, most of the observed loading in June over these stations is through transport from the eastern parts of China where industrial emissions, bio-mass burning and forest fires could be the sources. The AE and FMF values further suggest that small particles dominate.

6. CONCLUDING REMARKS

Mukdahan and Bac-Giang show an AOT pattern that peaks in spring and autumn. The relatively larger AE in these seasons suggest that smoke and pollution due to bio-mass burning and/or forest fire could be the major source. Transport from the Indian sub-continent, Indonesia and the Philippines affect the AOT pattern in spring. Forest fires could also contribute in the dry winter season. Over Bac-Giang there are indications of larger particles in spring, probably due to dust transport from desert regions over India. In summer, unlike other stations, both AOT and AE decrease over these stations, probably caused by the combined effect of washout by heavy rainfall and hygroscopic growth with the increase in moisture content. Although Bac-Giang and Mukdahan are neighboring stations the differences in sources as well as the seasonal circulation strength over these stations play a role in the observed differences in AOT and AE, especially in spring and autumn.

Over Beijing dust particles dominate in the spring season, while industrial pollution and smoke contribute in the summer season. These particles could be transported to Osaka and Gosan in the corresponding seasons and give rise to increased aerosol loading over these stations. Over Taipei the aerosol loading caused by transport events seems to have much less influence on the average aerosol concentration. Similar to Mukdahan and Bac-Giang the AOT over Taipei also shows a slight decrease in summer, while there seems to be no change in the corresponding AE values.

The spring dust events affect Beijing, Osaka, and Gosan significantly, while the effect is not pronounced over Taipei. The dust transport from China seems to not affect Mukdahan and Bac-Giang, although the possibility exists for dust being carried from the desert regions of India to these locations.

The June peak in AOT, which is characteristic of Beijing, Gosan, and Osaka is absent over Taipei, Mukdahan, and Bac-Giang, suggesting that pollutants contributing to the peak are transported mainly from the eastern parts of China.

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