Analysis of the origin of peak aerosol optical depth in springtime over the Gulf of Tonkin

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Abstract

By aggregating MODIS (moderate-resolution imaging spectroradiometer) AOD (aerosol optical depth) and OMI (ozone monitoring instrument) UVAI (ultra violet aerosol index) datasets over 2010-2014, it was found that peak aerosol loading in seasonal variation occurred annually in spring over the Gulf of Tonkin (17-23°N, 105-110°E). The vertical structure of the aerosol extinction coefficient retrieved from the spaceborne lidar CALIOP (cloud-aerosol lidar with orthogonal polarization) showed that the springtime peak AOD could be attributed to an abrupt increase in aerosol loading between altitudes of 2 and 5 km. In contrast, aerosol loading in the low atmosphere (below 1 km) was only half of that in winter. Wind fields in the low and high atmosphere exhibited opposite transportation patterns in spring over the Gulf of Tonkin,

implying different sources for each level. By comparing the emission inventory of anthropogenic sources with biomass burning, and analyzing the seasonal variation of the vertical structure of aerosols over the Northern Indo-China Peninsula (NIC), it was concluded that biomass burning emissions contributed to high aerosol loading in spring. The relatively high topography and the high surface temperature in spring made planetary boundary layer height greater than 3 km over NIC. In addition, small-scale cumulus convection frequently occurred, facilitating pollutant rising to over 3 km, which was a height favoring long-range transport. Thus, pollutants emitted from biomass burning over NIC in spring were raised to the high atmosphere, then experienced long-range transport, leading to the increase in aerosol loading at high altitudes over the Gulf of Tonkin during spring.

Keywords

Gulf of Tonkin

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Transportation

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Introduction

The region of Southeast Asia (SEA), which neighbors Southern China, is considered one of the hotpots for the global atmospheric brown cloud study (Ramanathan et al., 2008). As a result of vigorous economic growth for the last three decades, especially the rapid expansion of process and manufacturing industries, anthropogenic emissions have experienced rapid increases in SEA (Ohara et al., 2007). After adding in emissions from seasonal biomass burning (Reid et al., 2009), these emissions may affect other countries or regions through long-range transport, in addition to deteriorating local air quality.

Compared with long-range transport issues in Northeast Asia (Carmichael et al., 2002;

Kim et al., 2011), transport of Indo-China Peninsula (IC) emissions to surrounding countries or areas has raised relatively less concern. Even in the international joint project 7SEAS (7-Southeast Asian Studies), which is focused on the SEA region, few research works related to transport of IC emission have been carried out (Reid et al., 2013). This could be partly due to its complicated transport pattern driven by monsoon climate (Chang et al., 2011), low latitude synoptic systems and topographic effects (Lin et al., 2009a). Additionally, the transport between IC and the surrounding regions would probably be mutual. In terms of the effects of transport of pollutants from IC, there have been studies attributing episodic decreasing of air quality over the Pearl River Delta region (Deng et al., 2008) and the enhancement of tropospheric ozone over Hong Kong (Chan et al., 2000) to transport of pollutants from IC in spring. By analyzing aerosol measurements in spring at Mountain Lulin in Taiwan Province, Chuang et al. (2014) attributed high level carbonaceous aerosols to the air masses originating from IC biomass burning.

The Gulf of Tonkin (shown in **Fig. 1**), which is bordered by IC and South China, is much closer to IC compared with the receptors mentioned above. Additionally, it is mostly covered by ocean. Local emissions are significantly low, making this region an ideal receptor area to study regional transport. However, there have been few studies reported in the literature pertaining to the study of aerosol characteristics at the regional scale over the Gulf of Tonkin, and even the status in terms of the long-term average is relatively unknown.

The development of satellite remote sensing enables the understanding of global or regional distribution, origin and transportation of pollutants (Huang et al., 2008; Ma et al., 2013; Ramanathan and Feng, 2009; Warner et al., 2014; Yu et al., 2010). For SEA, satellite images are often susceptible to clouds and underlying surface conditions (Reid et al., 2013). This restricts the effective utilization of short-term satellite data for studying pollution episodes. However, from a long-term perspective, data averaged for certain regions has found extensive application. This is especially true of the emergence of synergistic earth observations based on application of multiple platforms, sensors, detecting bands and publicly available datasets, such as the “A-Train” (Stephens et al., 2002). The datasets could complement and be verified

by each other. Thus, making use of long-term averaged datasets in research is more reliable.

In this study, the characteristics of seasonal variations of aerosol loading in terms of multi-year averages over the Gulf of Tonkin are analyzed, and its origins are also explored. First, the seasonal variation characteristics of aerosol loading are described, followed by analyzing aerosol vertical structure detected by CALIOP (cloud-aerosol lidar with orthogonal polarization). Then, the origins of aerosol loading over the Gulf of Tonkin are analyzed by comparing climatology wind fields at different layers, investigating emissions from different source over IC, and exploring aerosol vertical structure over the source region. Finally, the uplift mechanism of pollutants at low atmosphere is discussed. All of the above was mainly achieved using multiple remote sensing datasets from satellite, long-term meteorology data and emission inventory data over IC and the surrounding areas.

1 Data and methods

1.1 Satellite data

A total of 5 years (2010-2014) of satellite datasets from sensors such as moderate-resolution imaging spectroradiometer (MODIS), ozone monitoring instrument (OMI), CALIOP and atmospheric infrared sounder (AIRS) were used in the study. Given the long time series and global coverage, MODIS aerosol optical depth (AOD) has been widely used to investigate the characteristics of regional distributions of aerosols as long-term averages. The level 3 daily product with horizontal resolution of 1×1 degree was used here.

The OMI ultra violet aerosol index (UVAI) is retrieved from OMI detections of two channels in ultraviolet spectra (Torres et al., 1998). It has excellent ability to identify absorbing aerosols, especially aloft aerosol layers such as smoke. In this paper, the level 3 monthly product of UVAI with horizontal resolution of 1×1 degree was used.

CALIOP is a primary payload onboard the cloud-aerosol lidar and infrared pathfinder satellite observations (CALIPSO) satellite, which provides detailed detection of vertical structure and distribution of aerosols and clouds along the orbit track. A 532 nm aerosol extinction coefficient (AEC) contained in the CALIOP level 3 product was mainly used in this

study, and datasets under all sky condition were selected. Strict quality control criteria were implemented to screen CALIOP level 2 datasets to form level 3 products, including a strict filter on CAD (cloud-aerosol discrimination) score to define aerosols, aerosol extinction QC (quality control), aerosol extinction uncertainty, discrimination of thin aerosol layer, avoiding misclassified cirrus in the high atmosphere, etc. Details regarding screen strategies could be obtained from the CALIOP level 3 product documentation and the study by Winker et al. (2013).

AIRS is a member of the AIRS/AMSU (advanced microwave sounding unit)/HSB (humidity sounder for Brazil) suite of instruments flying onboard the Aqua satellite. The accuracy of the temperature and humidity profiles is recognized as being able to improve forecasts from meteorological prediction models. Pressure at the top of the planetary boundary layer (PBL) is reported in the level 2 Support Product. This height is reported in units of pressure (hPa). The top of the boundary layer corresponds to the pressure of the largest absolute value of the gradient of the relative humidity (relative to the liquid phase of water) layer profile calculated on the support pressure layer grid.

1.2 Emission inventory

The regional emission inventory in Asia (REAS) (Kurokawa et al., 2013) was used to represent anthropogenic emissions over the domain of research. This dataset contained monthly emissions by sector from 2000 to 2008 over Asia. The anthropogenic sources considered in REAS included fuel combustion from power plants, industry, transport and domestic sectors, industrial processes, agricultural activities, solvent use and etc. The REAS emission inventory included most air pollutants, such as SO₂, NO_x, VOCs (volatile organic compounds), CO and primary PM_{2.5} (particulate matter with diameter smaller than 2.5 μm) components, and greenhouse gases as well. It has the horizontal resolution of 0.25 × 0.25 degree. Here, REAS emission data in 2008 were used to represent anthropogenic emissions over IC.

The global fire emissions database (GFED) (van der Werf et al., 2010) was used to characterize biomass burning emissions. The emission amounts of air pollutants were

calculated based on burned dry matter, which was estimated based on the burned area retrieved by satellite data, vegetation type, combustion completeness, etc. Emission factors were then used to translate dry matter burned to trace gaseous and aerosol emissions. The air pollutants considered in GFED included trace gases, like CH₄, CO, SO₂, and other aerosol emissions. GFED has global monthly data from 1997 till now. A total of 5 years (2010-2014) of GFED data was used to characterize the current status of biomass burning emissions over IC.

1.3 Meteorological data

Monthly mean reanalysis data from the National Centers for Environmental Prediction (NCEP) (Kalnay et al., 1996) was used to characterize regional transportation patterns for each season. The wind field was selected at 1000 and 700 hPa to represent the status of the surface and high atmosphere (about 3 km high), respectively.

1.4 Weather research and forecasting simulation

The mesoscale meteorology model weather research and forecasting (WRF) was used to predict PBL height in the biomass burning season over IC. The model domain covered all of East Asia, with a horizontal resolution of 36 km. A total of 35 layers were unevenly distributed vertically up to 50 hPa. One year simulation was conducted for the year of 2010, with four-dimensional assimilation nudged by NCEP grid data. The simulated wind field characterized the observation at the surface and 700 hPa level very well during March to April. The physics options in the simulation are listed in **Table 1**.

1.5 Research area

The Gulf of Tonkin is located northwest of the South China Sea. It is bordered by Guangxi Province to the north, Hainan Island to the east and Vietnam to the west, with an area of about 130,000 km². In order to facilitate satellite data utilization in this study, a rectangular area with coordinates of 17-23°N and 105-110°E was defined to represent the region of the Gulf of Tonkin, shown as domain A in **Fig. 1**.

Another rectangular area with coordinates of 17-21°N, 95-105°E was defined and is shown as domain B in **Fig. 1**, which is located in the Northern IC (NIC). This is the region

where a high occurrence of fires has been observed by MODIS compared with other areas of IC. The delimited region covers the southeast part of Myanmar, Northern Thailand and Northern Laos, characterizing an area with intensive biomass burning over the entire IC.

2 Characteristics of aerosol loading over the Gulf of Tonkin

2.1 Seasonal variation

A significant seasonal variation of AOD over the Gulf of Tonkin could be seen from the monthly variation of MODIS AOD (**Fig. 2**) over a span of 5 years (2010-2014). Maximum values of AOD appeared every March to April, with low values appearing every June to August. The monthly variation of OMI UVAI (**Fig. 2**) showed a very similar pattern during the same period.

The AOD distribution (**Fig. 3**) averaged from March to April over the past 5 years indicated a belt region with high aerosol loading, which extended from NIC to Guangxi Province. During the same period, a more discernable belt region with high OMI UVAI (**Fig. 3**) stretched from west to east, starting from Myanmar, then propagating eastwards and consecutively passing through Northern Thailand, Northern Laos and Northern Vietnam, and finally reaching the Gulf of Tonkin and Guangxi Province of China.

Although the distribution patterns observed by MODIS AOD and OMI UVAI were not exactly the same, both showed high values over NIC to the Gulf of Tonkin. This implied that high aerosol loadings expanded regionally in the area. However, OMI UVAI is known to be more sensitive to elevated aerosol layers (Torres et al., 1998). As a result, it is often used to identify transport of dust and smoke from biomass burning (Torres et al., 2007). Some reports have revealed that UVAI is good at identifying aerosols even above bright surfaces such as clouds (Torres et al., 2012). The high value belt detected by OMI UVAI mentioned in the preceding discussion implies that aerosols over the Gulf of Tonkin should be affected by the transportation from NIC in the high atmosphere in spring.

2.2 Vertical structure

A total of 5 years of statistics on the vertical distribution of AEC were made over the Gulf of

Tonkin by CALIOP data in 2010-2014. Dates from December to January, March to April, and July to August were selected to represent winter, spring and summer, respectively. Although AEC is an optical property of aerosols, it could still be used to characterize the level of aerosol concentration.

Significant seasonal variation was shown in the vertical structure of aerosols over the Gulf of Tonkin (**Fig. 4a**). In summer, the aerosol level was relatively low for all altitudes compared with other seasons. In winter, most aerosols remained below 2 km, and high level aerosol was concentrated below 1 km. In spring, aerosols kept to rather high levels from the surface layer up to 5 km high. Especially above 2 km, aerosols reached a much higher level than in other seasons, and a peak occurred at about 3 km high.

CALIOP AOD was obtained by integrating AEC vertically for each season. Seasonal variation was found to be maximal in spring, followed by winter, and minimal in summer. This trend was the same as with the seasonal variation of MODIS AOD, although they showed differences in magnitude.

CALIOP AOD (**Fig. 4b**) for 3 typical layers (< 1, 1-2, and > 2 km) in each season was also obtained by integrating AEC vertically. In winter, about 60% of aerosols concentrated below 1 km, whereas the aerosol layer was rather thin above 2 km. In spring, more than 50% of aerosols occurred above 2 km, while relatively low aerosol loading appeared below 1 km, only accounting for 24.4% of the total loading. It could be obviously seen that high AOD in spring was mainly caused by an abrupt increase of aloft aerosol loading. However, the opposite status occurred in winter. In summer, the aerosol level was rather low at all layers.

In the low atmosphere (<1 km height), seasonal variation of AOD was found to be maximum in winter, followed by lower values in spring and the least in summer. This trend was consistent with the measured monthly mean variation of PM₁₀ (particulate matter with a diameter smaller than 10 µm) (**Fig. 4c**) in recent years at 2 ground sites at Beihai, Guangxi Province, located near the tip of a cape entering the Gulf of Tonkin. This can be used to characterize the regional status, and meant that ground measurements verified seasonal variations retrieved from CALIOP at low atmosphere.

3 Sources analysis

3.1 Regional transportation pattern

The Gulf of Tonkin is located in the region controlled by the East Asia monsoon. March to April is the monsoon transition period from winter to summer (Chang et al., 2011). The wind field aggregated by 5-year (2010-2014) NCEP data (**Fig. 5**) showed that during March to April, the prevailing wind at the surface was quite different from that at high atmosphere over the Gulf of Tonkin and adjacent areas. This implied different origins for the surface and high layer transport. Easterly wind prevailed at the surface layer over the Gulf of Tonkin, implying that pollutants in the low atmosphere were affected primarily by transport from China.

However, westerly wind prevailed at the 700 hPa (about 3 km high) over a region (100-110°E, 17-22°N) covering the Gulf of Tonkin and extending westwards to NIC, which favored transport of pollutants from NIC. The Gulf of Tonkin is located in the downwind area of NIC. As shown in the vertical distribution of AEC over the Gulf of Tonkin (**Fig. 4a**) in spring, high aerosol loading aloft corresponds to the transport at high atmosphere, and the peak in the AEC vertical profile occurred just about 3 km high. In terms of the aloft wind field over the entire IC, westerly winds prevailed north of 17°N, while easterly wind prevailed south of 15°N. This implied that pollution transport from southern IC would have no significant effect on the Gulf of Tonkin.

3.2 Biomass burning

IC is one of the key biomass burning areas in SEA (Reid et al., 2013). NIC was found to be the region with the strongest biomass burning based on MODIS fire counts and density (**Fig. 1**). Monthly MODIS fire counts over NIC (**Fig. 6a**) during 2010-2014 exhibit significant seasonal variation. Substantially high numbers of fire counts occurred during March to April, and rather low numbers occurred for the remaining months. Here, emission amounts from both GFED and REAS were aggregated over the entire IC and NIC, respectively. Four species concerned with biomass burning emission were selected to compare the contribution from different origins as listed in **Table 2**.

When comparing species emitted from anthropogenic sources and biomass burning during March to April (**Table 2**), it was found that the latter made a significant contribution to local emissions over IC. Apart from NO_x emissions (31% of the anthropogenic emission), BC (black carbon) reached 79% of the amount of anthropogenic emissions, and both CO and OC (organic carbon) emissions exceeded that of anthropogenic emissions. Over NIC, where MODIS fire counts were mostly concentrated, the emission amounts for most species exceeded those of anthropogenic ones, i.e., the emissions of OC, CO and BC were 5.22, 3.11, and 2.49 times the amount of anthropogenic emissions, respectively. NIC is less developed in comparison with Southern IC, and has low population density. The relatively low anthropogenic emissions made biomass burning become the major emission source in spring.

3.3 Vertical distribution of aerosols over the Northern IC

AEC vertical structure aggregated by 5 years of CALIOP retrieval over NIC (**Fig. 7**) exhibited significant seasonal variation. Aerosols remained at relatively low level from the surface to the high atmosphere in both summer and winter. However, AEC was substantially higher in spring compared with the other two seasons at all altitudes. At an altitude of 1 km, AEC was double in magnitude in comparison with the value in winter, and was triple in magnitude in comparison with the value in summer. At 2 km, AEC was three times the value for both winter and summer. The ratio was much higher at an altitude of 3 km. It could be seen how great the effects of biomass burning were on local aerosol loading in spring.

Based on AEC values in the vertical profile (**Fig. 7**), it was clear that aerosol loading was maintained at a high level from the surface up to 3 km high in spring. AEC values were 0.28, 0.2 and 0.08 km⁻¹ at 2, 3 and 4 km, respectively. However, some studies attempted to reconstruct AEC based on measured aerosol components (Watson, 2002) or develop a regression between PM_{2.5} concentration and AEC (Tao et al., 2014). This relationship would vary with time and location. Thus, it was difficult to obtain a unified formula or definite expression between the two. This can also be attributed to the differences in aerosol shape, size, component, mixture state, and hygroscopicity. There have been some ground measurements having both results: one example is a heavy pollution case in Los Angeles, where AEC reached

0.5 km⁻¹ with the corresponding PM_{2.5} mass concentration of 102 µg/m³ (Seinfeld and Pandis, 2006); another case was in summer in Beijing, where Bergin (2001) reported a mean aerosol scatter coefficient of 0.488 km⁻¹ and an absorption coefficient of 0.083 km⁻¹, corresponding to a daily mean PM_{2.5} mass concentration of 136 µg/m³. Compared with this study, it could be implied that the aerosol concentration characterized by AEC had reached a rather high level in the high atmosphere over NIC in spring, and it should be noted that the AEC shown here was a monthly averaged result. Thus, it could be concluded that the pollutants emitted at the surface had risen up to more than 3 km high only near the source region.

3.4 Pollutant uplift

NIC, the region corresponding to the densest fire counts in SEA, is dominantly a mountain region. The topography is higher than in southern IC. In many places, the elevation is above 1 km. Due to the low latitude location, the effects of radiative heating are strong. It was also indicated by routine measurement over Northern Thailand (www.tmd.go.th/em/climate.php?FileID=1) that surface air temperature was usually above 30°C in March or April, which facilitated building high PBL height.

The mesoscale meteorology model WRF was used to simulate the meteorological field in March to April over East Asia. An average of daily maximum PBL height over IC (**Fig. 8a**) suggested that the highest PBL was over NIC, which had strong biomass burning activities. Additionally, the PBL height was above 3 km high in most areas in NIC.

AIRS, a sensor equipped on Aqua, which is similar to MODIS, passed over the ground track at approximately 13:30 local time. Thus, the retrieved PBL height could be used to estimate the maximum PBL height in approximately one day. The averaged PBL height from March to April (**Fig. 8b**) showed that the height distribution generally followed the topography, i.e., a mountain range or plateau with high elevation corresponded to a high PBL height. The plain area surrounding Hanoi, Vietnam, and adjacent to the Gulf of Tonkin corresponded to a shallow PBL height. However, the mountain range just west of Hanoi showed a rather high PBL height. Meanwhile, the region with the highest PBL height occurred at about 25°N north of NIC, where the Yun-Gui Plateau is located. Compared with the land area, a rather low PBL

height occurred over the ocean. These comparisons indicated that the PBL height over IC retrieved from AIRS was reasonable. In terms of regional distribution, the PBL height over IC was generally higher than over the surrounding area. Over NIC, PBL height was heterogeneously distributed. However, PBL height could be above 800 hPa (2 km high) for most areas in the region. In some areas, PBL height reached above 750 hPa (2.5 km high).

Since different methods were used to characterize PBL height over NIC, certain differences did exist in magnitude and spatial distribution. The PBL height detected by AIRS may not be the daily maximum. The simulated peak of PBL height in the WRF prediction occurred during 15:00 to 18:00 local time on most days. The long duration of sunshine in low latitude regions each day may be the reason. Although both methods have inherent uncertainties in predicting PBL height, the height predicted by both methods reached as high as 2.5 to 3 km over NIC. This implied that the vertical diffusion by diurnal PBL development could be the primary reason why pollutants were raised up to a height of approximately 3 km.

Moreover, clear sky was seen frequently from March to April over NIC, which could be the reason why a high number of fire spots could be detected by MODIS. In addition, high humidity in the air, as well as small scale cumulus convection, occurred frequently over NIC. This was observed clearly in the daily MODIS true color map. This enhanced the capability to lift pollutants from the surface to the high atmosphere.

Pollutants emitted from biomass burning at the surface were easily lifted up to 3 km in the source region during March to April over NIC. This was verified by the high aerosol loading at the same height in the aerosol vertical structure retrieved from CALIOP (**Fig. 7**). Westerly wind prevailed at high atmosphere in the region from NIC to the Gulf of Tonkin, which facilitated long-range transport of pollutants and became the major reason for annual peak AOD occurring in spring over the Gulf of Tonkin.

Although westerly wind could extend westwards to the Indian peninsula, substantial meridional components occurred starting from western IC and extending westwards to the Indian peninsula. Due to the long distance from Northern India to the Gulf of Tonkin, transport originating from India would experience a rather complicated passage. Additionally, it would

most likely be affected by other synoptic processes. In these cases, if transport arrived at the Gulf of Tonkin, effects could not be compared with NIC.

4 Summary

Synergetic analysis of multiple satellite datasets, especially the seasonal variation of aerosol vertical structure retrieved from CALIOP over the Gulf of Tonkin and NIC, was carried out over a span of 5 years (2010-2014), along with analysis of the emission inventory of both anthropogenic and biomass burning and long-term wind fields at high and low atmosphere. Major findings are summarized as follows:

(1) Peak aerosol loading appeared annually in spring (March to April) over the Gulf of Tonkin, whereas the lowest value occurred in summer (July to August).

(2) The aerosol vertical structure explored by the spaceborne lidar CALIOP indicated that an abrupt increase of aerosol at heights ranging between 2 and 5 km led to a maximum AOD in spring over the Gulf of Tonkin.

(3) The prevailing winds were opposite at high and low atmosphere over the Gulf of Tonkin from March to April, implying that the origins of pollutants were different for high and low atmosphere. Easterly wind prevailed at low atmosphere, implying transport from mainland China. Westerly wind prevailed at high atmosphere and stretched westward to the entire NIC, implying transport from NIC.

(4) From March to April, when emissions from biomass burning overwhelmed anthropogenic sources over NIC, AEC was significantly larger in comparison to other seasons from the surface layer to high atmosphere. This indicated the significant impacts on local aerosol loading from biomass burning in spring.

(5) Over NIC, relatively high topography and strong radiative heating, along with convection by small-scale cumulus, facilitated lifting pollutants to heights over 3 km, where westerly winds prevailed and enabled the long-range transport downwind, increasing aerosol loading at high atmosphere and leading to a AOD maximum in spring over the Gulf of Tonkin.

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List of figures

Fig. 1 Research domain and major region of CALIOP (cloud-aerosol lidar with orthogonal polarization) data analysis, including the Gulf of Tonkin delimited as rectangle A and the Northern Indo-China Peninsula (NIC) delimited as B. Ground monitoring sites were located at Beihai, Guangxi Province, over the Gulf of Tonkin for validation of retrieved results. MODIS (moderate-resolution imaging spectroradiometer) fire counts during March to April in 2010-2014 are overlapped.

Fig. 2 Monthly variation of MODIS AOD (aerosol optical depth) and OMI (ozone monitoring instrument) UVAI (ultra violet aerosol index) over the Gulf of Tonkin from 2010 to 2014.

Fig. 3 Regional distribution of MODIS AOD and OMI UVAI averaged from March to April, 2010 to 2014.

Fig. 4 (a) Seasonal variation of vertical structure of aerosol extinction coefficient (AEC) retrieved from CALIOP averaged for 2010-2014; (b) vertical integral of AEC in **Fig. 4a** in each layer along with mean MODIS AOD for each season; (c) monthly variation of PM₁₀ (particulate matter with a diameter smaller than 10 μm) concentration at two ground sites shown in **Fig. 1**.

Fig. 5 Mean wind field at 1000 and 700 hPa levels in 2010-2014.

Fig. 6 Monthly variation of MODIS fire counts over NIC (domain B in **Fig. 1**) from 2010 to

2014.

Fig. 7 Seasonal variation of AEC vertical structure during 2010-2014 over NIC delimited as domain B in **Fig. 1**.

Fig. 8 (a) Mean of daily maximum PBL (planetary boundary layer) height by WRF (weather research and forecasting) simulation during March to April in 2010 and (b) mean of daily PBL height by AIRS (atmospheric infrared sounder) retrieval at 13:30 local time during March to April in 2010–2014 over IC.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

CALIPSO level 3 allsky 532 nm_Ext_Coef
Northern Indo-China 2010-2014

Fig. 8

Table 1 Physic options in the WRF (weather research and forecasting) simulation.

Physical process	Option
Microphysics	WSM3
Longwave radiation	RRTM
Shortwave radiation	Dudhia
PBL	YSU
Land surface	RUC
Surface layer	Monin-Obukhov
Cumulus parameterization	Grell

WSM3: WRF single-moment 3-class microphysics scheme; RRTM: a rapid radiative transfer model; YSU: Yonsei University; RUC: rapid update cycle; PBL: planetary boundary layer.

Table 2 Ratio of emissions from biomass burning to anthropogenic sources (global fire emissions database/regional emission inventory in Asia) for major species during March to April over Indo-China Peninsula (IC) and Northern IC.

	Black carbon	CO	Organic carbon	NO _x
Entire IC	0.79	1.11	1.65	0.31
Northern IC	2.49	3.11	5.22	0.65