

# Modelling and prediction of air pollutant transport during the 2014 biomass burning and forest fires in peninsular Southeast Asia

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Received: 4 March 2015 / Accepted: 12 January 2016 / Published online: 21 January 2016  
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**Abstract** During the dry season, from November to April, agricultural biomass burning and forest fires especially from March to late April in mainland Southeast Asian countries of Myanmar, Thailand, Laos and Vietnam frequently cause severe particulate pollution not only in the local areas but also across the whole region and beyond due to the prevailing meteorological conditions. Recently, the BASE-ASIA (Biomass-burning Aerosols in South East Asia: Smoke Impact Assessment) and 7-SEAS (7-South-East Asian Studies) studies have provided detailed analysis and important understandings of the transport of pollutants, in particular, the aerosols and their characteristics across the region due to biomass burning in Southeast Asia (SEA). Following these studies, in this paper, we study the transport of particulate air pollution across the peninsular region of SEA and beyond during the March 2014 burning period

using meteorological modelling approach and available ground-based and satellite measurements to ascertain the extent of the aerosol pollution and transport in the region of this particular event. The results show that the air pollutants from SEA biomass burning in March 2014 were transported at high altitude to southern China, Hong Kong, Taiwan and beyond as has been highlighted in the BASE-ASIA and 7-SEAS studies. There are strong evidences that the biomass burning in SEA especially in mid-March 2014 has not only caused widespread high particle pollution in Thailand (especially the northern region where most of the fires occurred) but also impacted on the air quality in Hong Kong as measured at the ground-based stations and in LulinC (Taiwan) where a remote background monitoring station is located.

**Keywords** Biomass burning · Southeast Asia · MODIS aerosol optical depth · CALIPSO aerosol types · Modelling · Weather research forecast (WRF) · Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT)

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## Introduction

In Asia, the three main sources of particulate and gaseous emission are located in northeast Asia, Southeast Asia (SEA) and the Indian sub-continent. Northeast Asia sources are mainly anthropogenic industrial sources located in China, Korea and Japan and wind-borne dust from Gobi desert. Biomass burning during the dry season is the dominant emission in

Southeast Asia and the Indian sub-continent. The pollutants from these emission sources are dispersed and transported over a wide region in peninsular SEA, South China, Taiwan, the South China Sea (SCS) and eastward to the Pacific. The outflow of aerosols from the Indian sub-continent and from SEA to the Indian Ocean was comprehensively reviewed by Lawrence and Lelieveld (2010).

Transport of pollutants from high emission of anthropogenic sources in Northeast Asia (NEA) especially from north coastal China also has an impact in Indochina under favourable meteorological condition due to the northeast monsoonal flow (Cheng et al. 2013). The northeast monsoon from mid-December to mid-April transports air pollutants from China to the South China Sea and then potentially continually flows on to peninsular SEA. Therefore, near the end of the cool and dry northeast monsoon before the onset of the wet southwest monsoon and during the peak of the annual agricultural biomass burning in SEA in March, a circulation loop of air flow bringing air pollutants from biomass burning in SEA to southern China and Taiwan could transport air pollutants from both sources in SEA and northeast China back to peninsular SEA with the aid of the northeast monsoon flow.

Recently, there is an increasing trend of using satellite measurements to study the transboundary transport of particulate air pollution across a regional area or from one continent to another such as the transport of elevated aerosol layers from Africa or Asia to America or from America to Europe (Kaufman et al. (2002)). In Asia, Park et al. (2013) used hourly multi-spectral aerosol optical data from a sensor onboard the Korean geostationary satellite COMS (Communication, Ocean, and Meteorology Satellite) to derive the aerosol optical depth (AOD) in their study of the transboundary particulate air pollution from China to Korea and Japan. Sukitpaneemit (April 2014) used carbon monoxide (CO) measurement from a Measurements of Pollution in the Troposphere (MOPITT) instrument on the Terra satellite and aerosol optical depth (AOD) from Moderate Resolution Imaging Spectroradiometer (MODIS) satellites (Terra and Aqua) to study the transboundary dispersion of air pollutants in northern Thailand due to forest fires. In addition to ground-based network of measurements such as the Aerosol Robotic network (AERONET) and NASA Micropulse Lidar Network (MPLN), many of the BASE-ASIA and 7-SEAS studies of transboundary transport of aerosols from biomass

burning in Southeast Asia also used satellite-based measurements such as MODIS Terra/Aqua and the CALIPSO (Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellites (Tsay et al. (2013)).

Southeast Asia biomass burning during the dry season contributes significantly to the global carbon dioxide emission and the inter-annual fluctuations in global atmospheric carbon dioxide (CO<sub>2</sub>) concentrations. Shi et al. (2014) used the MODIS burned area products, the Global Fire Emissions Database version 3 (GFED3) and the Biosphere model integrating Eco-physiological And Mechanistic approaches using Satellite data (BEAMS) to estimate the fire carbon emission. They estimated the carbon emission of 214.1 TgC annually based on BEAMS/MCD45A1-Peat. Based on the burned area data from the MODIS MCD64A1, MCD45A1 fire products and the Global Fire Emissions Database version 3 (GFED3) from 2001 to 2010, the average annual burned areas were estimated to be 68,104, 50,933 and 61,263 km<sup>2</sup>, respectively. In peninsular Southeast Asia, the burned areas were predominantly concentrated in Myanmar, northern Thailand, eastern Cambodia and northern Laos. While in Sumatra and Kalimantan of Indonesia, there are marked differences in the spatial pattern of burned areas (Shi et al. 2014).

The climate in the Indonesian archipelago is mostly influenced by the sea surface temperature anomalies in the Pacific Ocean, in which the El Niño–Southern Oscillation (ENSO) is the main driver. On the other hand, the Indian Ocean influences the climate of both maritime and peninsular Southeast Asia and is responsible for the dry season and the monsoon wet season in that part of the world. The El Niño, originating in the Pacific, exacerbates the drought condition during the dry season in Indonesia and therefore causes frequent forest and peat fires in islands such as Sumatra, Borneo. The biomass burning and the peat and forest fires in Indonesia, mainly from Sumatra, during the El Niño 1997 is the most severe case of transboundary air pollution which affected not only the Malaysian peninsular but also the other countries in mainland Southeast Asia. Particulate pollution episodes across the region, due to biomass-burning, cause adverse health effect and high economic cost. The episode in 1997 had raised the concerns in many countries in SE Asia and was the reason for the intergovernmental collaboration between ASEAN countries to monitor, forecast and study the transboundary particulate pollution during the dry season.

Biomass burning is a strong source of CO emission. CO has a lifetime in the troposphere from weeks to months and is a good trace species for studying the long-range transport. Cheng et al. (2013) studied the transport of CO to a station in a mountainous area of Taiwan during the biomass-burning season in SE Asia. Using cluster analysis on CO and modelled wind data from WRF model during the biomass-burning season (February to May) from 2007 to 2010, they have been able to identify the synoptic weather patterns (low pressure system over Indochina) and physical features (high terrain in north Indochina) that are conducive to the transport of pollutants from Thailand and Myanmar to Taiwan.

Huang et al. (2013) accessed the impact on air quality in SE Asia and East Asia for the period from March to May 2006 due to the 2006 annual agricultural biomass burning season using the Community Multiscale Air Quality Modelling System (CMAQ). The CMAQ model was driven by the Weather Research Forecast (WRF) meteorological model. Their model prediction was compared to the AOD measurements from MODIS and AERONET as well as the measured CO concentration at the monitoring sites in Thailand. They found the impact of biomass burning extends from peninsular SE Asia to the South China Sea, the Taiwan Strait and some provinces in southern China.

In this paper, we focus primarily on biomass burning in peninsular Southeast Asia (Myanmar, Thailand, Cambodia, Laos and Vietnam) and the transport of pollutants emitted from these fires across the region and beyond. The biomass burning during the dry season is concentrated mostly in Myanmar, northern Thailand, Cambodia, northern and central Laos and to a lesser extent in southern Vietnam. In particular, the particulate air pollution during the dry season of March 2014 will be studied in detail. The March 2014 period is at the peak of the 2014 annual agricultural burning.

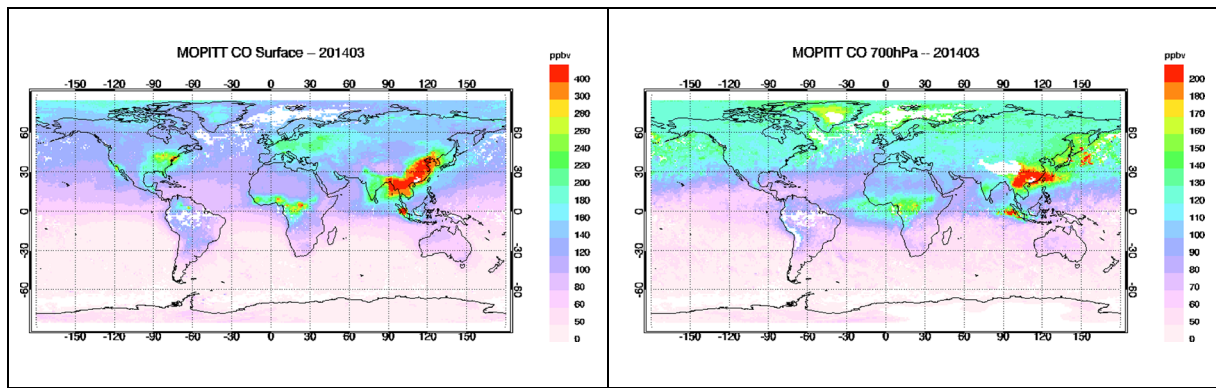
Both the Weather Research Forecast (WRF) Eulerian model and the Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT) model will be used to study the transport of pollutants across the region during the 2014 agricultural biomass-burning season. The prediction from the WRF/HYSPLIT models will be compared and corroborated with the MODIS AOD, CALIOP aerosol profiles and the ground-based station measurements of PM<sub>10</sub> and CO in Thailand, Hong Kong and Taiwan.

## Description of observed biomass burning and forest fires during March and April 2014

Agricultural biomass burning and forest fires in northern Thailand from the end of February 2014 to early April have caused high particulate pollution over the region, especially during the month of March 2014. Biomass burning always peaks in March as this month is mostly dry, and agricultural burning activities are in earnest before the wet monsoon started in late April. This agricultural practice of biomass burning to prepare the soil for the coming rainy season and a new rice planting season occurs annually throughout peninsular SEA: from Myanmar, Thailand, Cambodia and Laos to Vietnam.

Figure 1 shows the MOPITT satellite measurement of CO on the surface and at 700 mb (hPa) in March 2014 with thermal infrared (TIR)-only V6 levels 2 and 3 products. High surface CO concentrations are detected over SEA and eastern China. High CO concentration over SEA is from biomass-burning emission while mainly industrial emission causes high CO concentration over eastern China, especially along the coast. At 700 mb height, high concentrations of CO are mostly over northern SEA (Laos, northern Thailand, and northern Vietnam) and southern China. The source of the CO at high altitude is mainly from the biomass burning in SEA and then transported to southern China.

The biomass burning season of 2014 has caused high pollution episodes during the month of March throughout northern Thailand. Air quality monitoring stations in Chiang Mai, Chiang Rai and Mae Hong Son provinces have recorded numerous occurrences of particulate PM<sub>10</sub> concentration above standard. Chiang Mai, the largest city in northern Thailand and next to many biomass burning hotspots, has an excess of particle pollution to an unsafe level when the PM<sub>10</sub> concentration rose above 120 µg/m<sup>3</sup> on 11 March 2014 (Gebhart 2014). The high particle pollution persisted with particle concentration reaching 284.5 µg/m<sup>3</sup> on 22 March 2014 at 6 am at the Chiang Mai Town Hall monitoring station and at a very high hourly value of 324.4 µg/m<sup>3</sup> at Mae Hongson monitoring station located in the National Park near the Thailand–Myanmar border. The Chiang Mai airport was closed on 21 March, and flights were diverted due to poor visibility. Figure 2 shows the hourly PM<sub>10</sub> and CO concentration at the Chiang Mai Town Hall monitoring station and Mae Hongson and Chiang Rai monitoring stations run by



**Fig. 1** Global MOPITT measurement of CO on the surface (*left*) and at 700mb (hPa) height in March 2014. High levels of CO are detected over South East Asia and China on the surface and over

northern SEA and southern China at 700mb height (from [http://www.acd.ucar.edu/mopitt/MOPITT/data/plots6t/maps\\_mon.html](http://www.acd.ucar.edu/mopitt/MOPITT/data/plots6t/maps_mon.html))

Natural Resources and Environment Office in northern Thailand and at Ayuthaya (Witthayalai School) and Bangkok Thai Meteorological Department stations in central Thailand during the month of March 2014.

The 24-h  $PM_{10}$  standard of  $120 \mu\text{g}/\text{m}^3$  in Thailand was exceeded at Mae Hongson station every day from 14 March 2014 to 31 March 2014. At Chiang Mai and Chiang Rai stations, the standard was exceeded on most days from 11 March 2014 to 31 March 2014 except on the days where the data are missing (22 to 26 March 2014) and on 30 to 31 March 2014 at Chiang Mai where the 24-h  $PM_{10}$  concentrations were  $117.9$  and  $113.5 \mu\text{g}/\text{m}^3$ , respectively. The high  $PM_{10}$  concentrations measured at Mae Hongson station in the remote area were due to forest fires while at Chiang Mai and Chiang Rai, the high values were mostly due to agricultural biomass burning. The forest fires near Mae Hongson occurred approximately on 14 March 2014, a few days after the beginning of the intense biomass burning around Chiang Mai and Chiang Rai on the 10 or 11 March 2014.

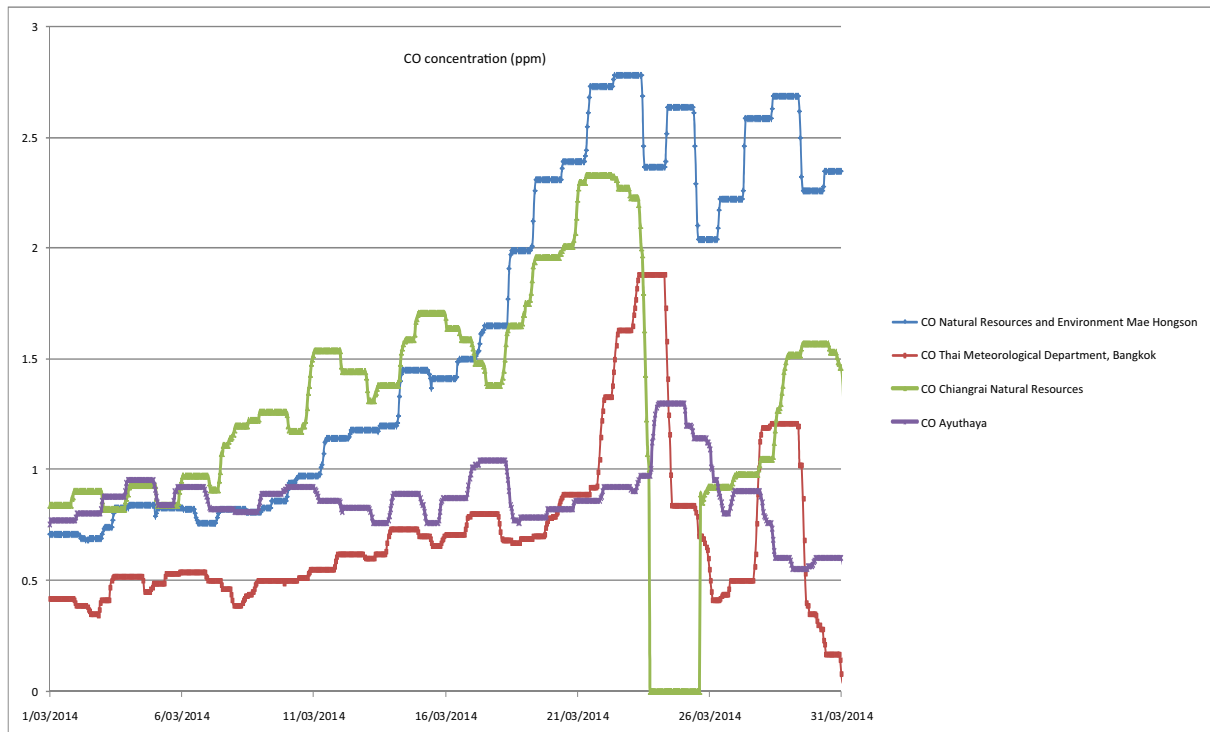
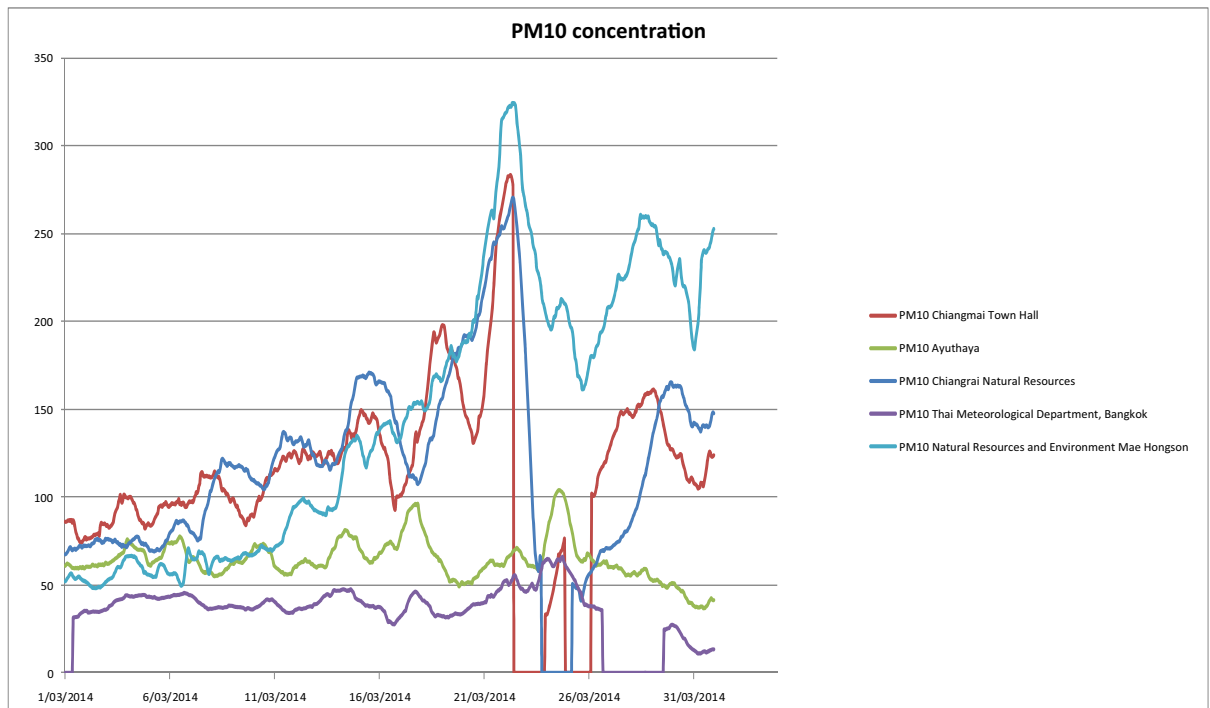
Tsai et al. (2013), in their study of source indicators of biomass burning in Chiang Mai basin during the dry season burning from 2 February to 2 April 2010, have found that the average mass ratio of levoglucosan/mannosan of 14.1–14.9 during biomass-burning period at two sites was higher than the ratio of 5.73–7.69 during the normal period of the year. This indicates more hardwood burning during the dry season burning period. Forest fires during this period are also important sources of smoke haze. They also found higher concentrations of glycerol and erythritol which indicate soil biota from forest and farmland soils were released during the biomass burning.

The patterns of CO concentrations are similar to those of  $PM_{10}$  in Mae Hongson and Chiang Rai where

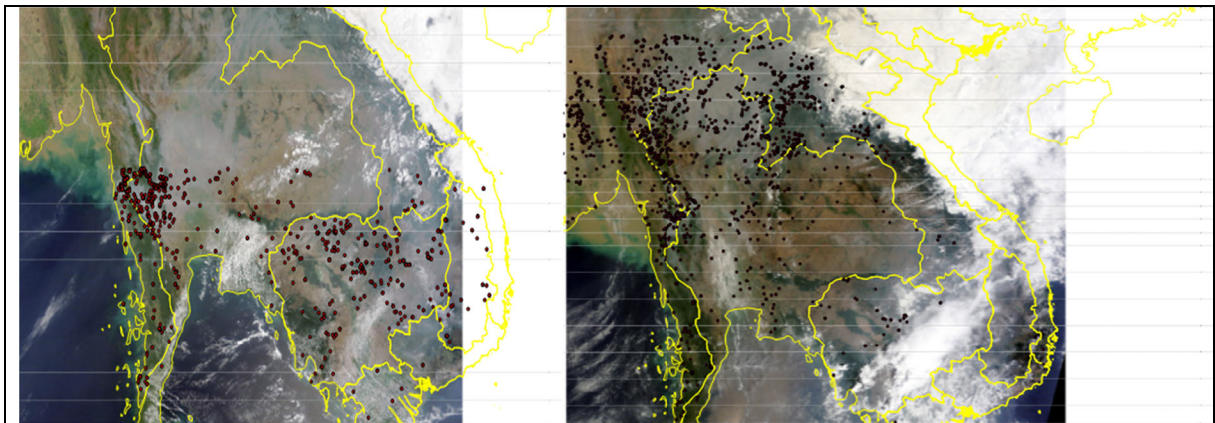
intense biomass burning occurred in the vicinities. In central Thailand, high concentration levels of CO were detected in Ayuthaya and in Bangkok at the Thai Meteorological Department monitoring station with the peak levels detected 1 or 2 days after the peak levels as measured at the northern stations on 22 March.

The  $PM_{10}$  concentration at monitoring stations in the central part of Thailand, Ayuthaya and Bangkok has peak levels on 24 March 2014, 2 days later than those stations in the north. Air pollutant concentration as measured at a site depends on the local meteorology and emission. In unstable atmospheric conditions, such as high wind speed or convection, air pollutants will be dispersed and hence, concentration will be low. Low wind speed or mixing down from above can cause high pollution concentration from local emission and transported emission in the troposphere and the stratosphere. The transported emission from northeast Thailand is the main cause for the high particle concentration as measured in central Thailand. The extent of the agricultural biomass burning and forest fires can be seen from the images and hotspots of the region as captured and processed from the MODIS Terra/Aqua satellites. Figures 3 and 4 show the images and the number of hotspots from MODIS fire products.

During March 2014, the largest number of hotspots detected by MODIS satellites in Thailand and in Myanmar is in the period from 18 to 21 of March 2014. Subsequently, between 27 and 28 of March 2014 is another high number of hotspots occurred in these countries. These peaks correspond to the high  $PM_{10}$  concentration as measured at the monitoring stations in northern Thailand (Chiang Mai, Mae Hongson and Chiang Rai) on the 21–22 and 28 of March (Fig. 2). Northern



**Fig. 2** Hourly PM<sub>10</sub> ( $\mu\text{g}/\text{m}^3$ ) and CO (ppm) concentration in northern Thailand (Chiang Mai, Mae Hongson and Chiang Rai) and central Thailand (Ayuthaya and Bangkok) from 1 March 2014 to 31/3/2014



**Fig. 3** Fire hotspots from MODIS Fire Information for Resource Management System (FIRMS) and satellite image of haze above Myanmar, Thailand, Cambodia and Vietnam on 7 March 2014 (left) and on 21 March 2014 (right) show clearly that northern

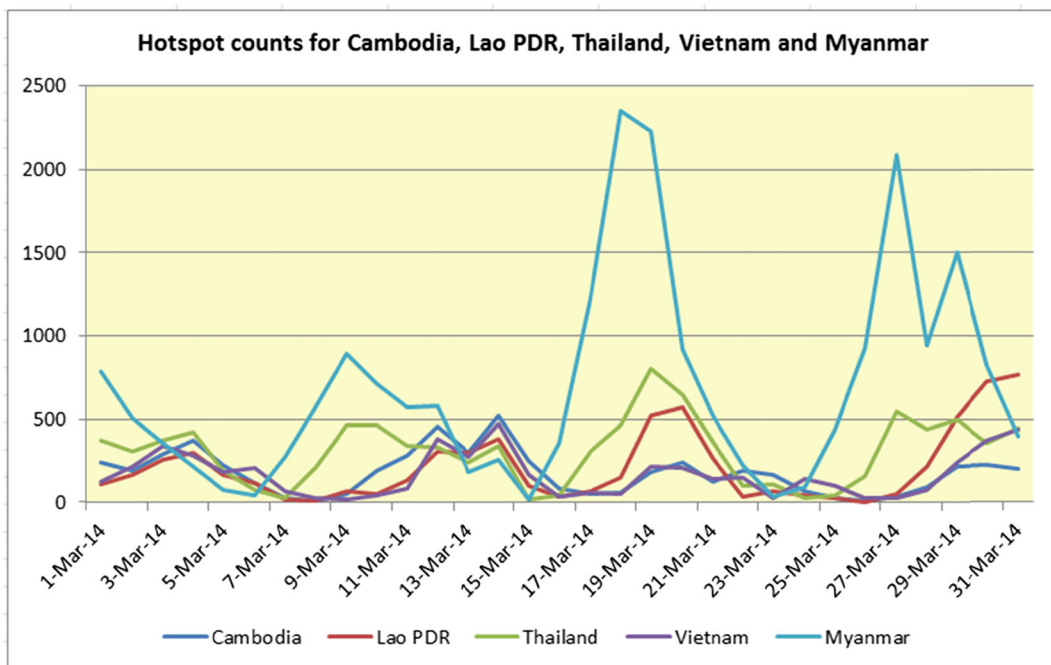
Thailand and the area near the border of Thailand and Myanmar were covered with smoke from biomass burning. Note that smoke hazes are thin and in greyish colour while clouds are dense, thick and in white colour

Laos has the third largest number of hotspots in the region with a peak in 31 March 2014. On the following month, April 2014, the pattern is similar with Myanmar and Thailand still dominant but the number of hotspots is reduced with peaks of about 800 hotspots for Myanmar and 200 for Thailand (Meteorological Service Singapore (2014)).

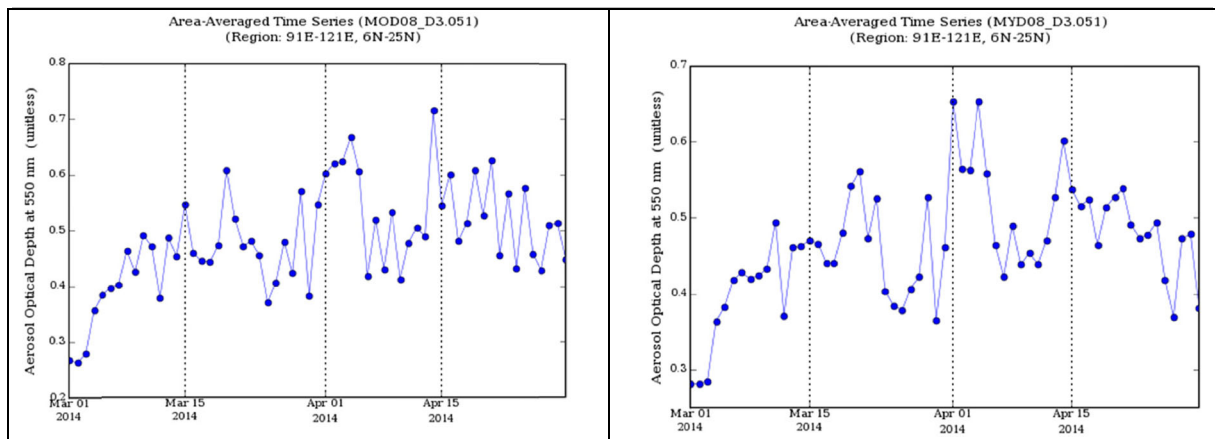
550-nm wavelength. The AOD is a measure of radiation extinction due to aerosol scattering and absorption by aerosol particles in the atmosphere. The Terra orbit has local equatorial crossing time at approximately 10:30 a.m. in a descending node while the Aqua orbit has local equatorial crossing time at approximately 1:30 p.m. in ascending node.

The effect of biomass fires can be seen on the AOD as measured by MODIS Terra and Aqua satellites at

The MODIS AOD Terra and Aqua daily level-3 data 1° by 1° resolution products (MOD08 for Terra and



**Fig. 4** Hotspots counts for the month of March 2014 in Cambodia, Laos, Thailand, Vietnam and Myanmar (source: Meteorological Service Singapore, [http://www.weather.gov.sg/wip/c/portal/layout?p\\_1\\_id=PUB.1003.639](http://www.weather.gov.sg/wip/c/portal/layout?p_1_id=PUB.1003.639))



**Fig. 5** Time series of AOD averaged over the Southeast Asia region from 1 March to 30 April as measured by Terra (*left*) and Aqua (*right*) satellites (from Giovanni online data system [http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance\\_id=MODIS\\_DAILY\\_L3](http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_DAILY_L3))

MYD08 for Aqua) shows that for the period of 1 March to 30 April 2014, the AOD time series averaged over the Southeast Asia region (W 91.2, E 121.2, N 25.8 and S6) has a peak AOD on 20 and 21 March 2014, as shown in Fig. 5. Figure 6 shows the spatial distribution of AOD over the same region for the months of February, March and April 2014.

The burning of biomass started at the beginning of March and persisted to early April. From Fig. 6, it can be seen that northern Vietnam and southern China were also severely affected. Even though central and southern Vietnam was not affected to the same level as those above but on some days (such as the 20 and 21 of March) high AOD were also measured above these regions.

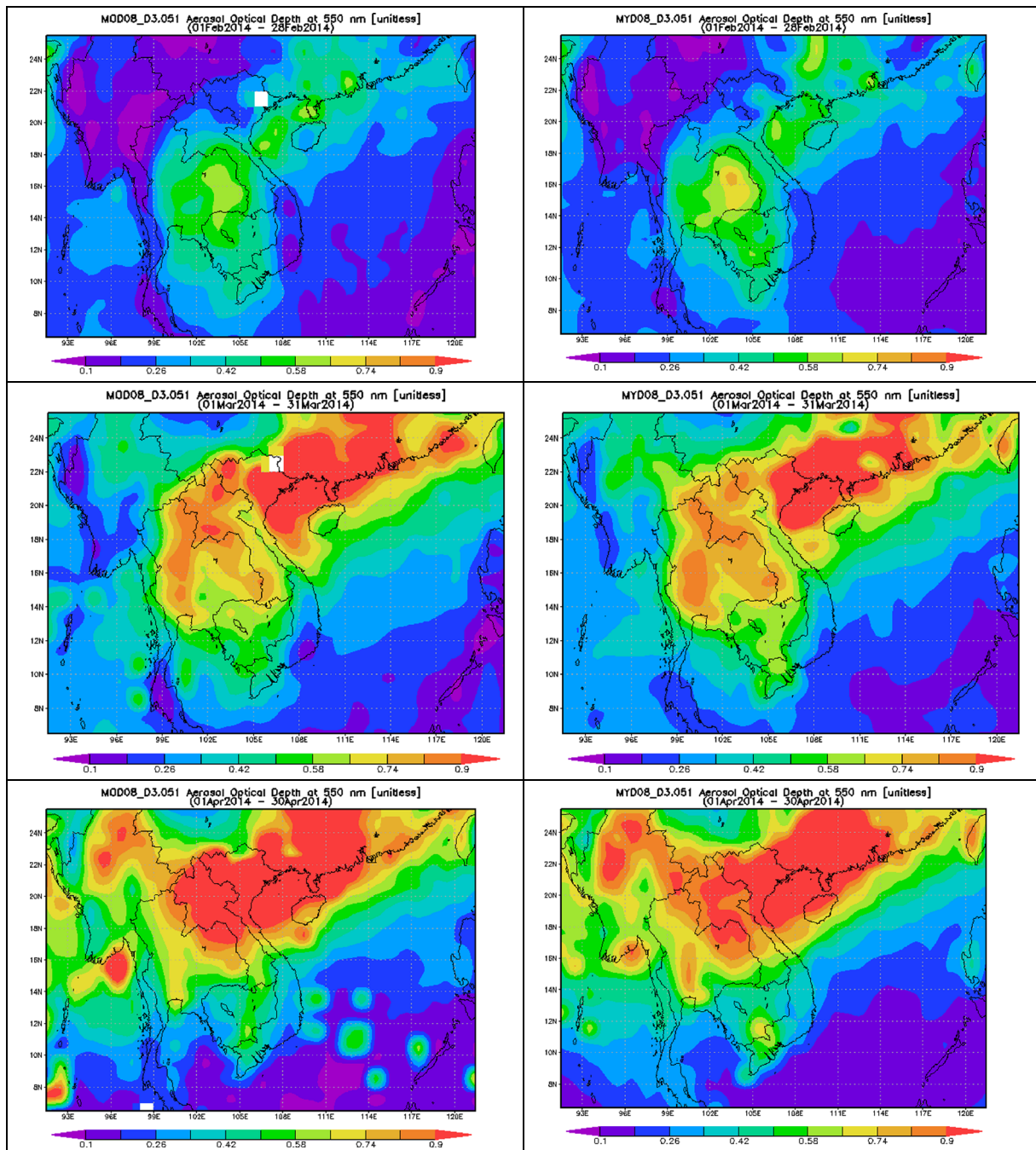
It should be noted that the northeast monsoon flow which transports air pollutants from northeast Asia, anthropogenic sources of emission in northeast and southern China could also contribute to the aerosol loading in addition to the local emission. In their studies of marine aerosols between Taiwan and Dongsha Island, Stohl et al. (2007) suggested that air pollutants from China are transported to the South China Sea during the northeast monsoon period.

By measuring pollutants including aerosols, CO, SO<sub>2</sub>, ozone and the aerosol optical characteristics as well as aerosol vertical profiling using EZ-Lidar on the remote island of Dongsha in northern SCS, Wang et al. (2013) suggested that emissions from both China and Southeast Asia contribute to the aerosol loading over the SCS and the transport from China to SCS is confined to the marine boundary layer (0–0.5 km) while the aerosols from biomass burning in SEA are transported at a much higher layer (3–4 km).

Ou-Yang et al. (2013) analysed surface ozone measurement on the remote Dongsha Island which is considered as a background ozone monitoring station. During the Asian boreal winter monsoon period (northeast monsoon), elevated ozone levels of approximately 60 ppbv were measured when strong northeasterly winds prevail in contrast with low levels of ozone of about 30 ppbv during the northeast monsoon subsided. They suggested that the northeasterly monsoon winds transport the pollutants from northern China to as far south as Dongsha Island in the SCS.

**Meteorological and particle trajectory modelling during the March 2014 biomass burning**

The determination of particle concentration and tracing of dispersed emitted particles due to biomass burning from many locations happening at various times in a region is a complex task. From the hotspots images as detected by MODIS satellite products at particular dates and times, the burning sites can be determined. But the duration of the biomass burning at the site is more difficult to estimate, and the uncertainty is higher in cloudy conditions when the MODIS satellite detection of hotspot is limited. In this paper, we use the Lagrange particle dispersion model, Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT) with global archived GDAS meteorology data to determine the dispersion and transport of particle air parcels. An overview of HYSPLIT was described by Draxler and Hess (1998). A Lagrangian approach is chosen here as it is suitable to study the transboundary transport of particles



**Fig. 6** AOD as measured at 550 nm wavelength by Terra and Aqua satellite for the months of February (*top*), March (*middle*) and April 2014 (*bottom*) (from Giovanni online data system <http://>

[gdatal.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance\\_id=MODIS\\_DAILY\\_L3](http://gdatal.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_DAILY_L3))

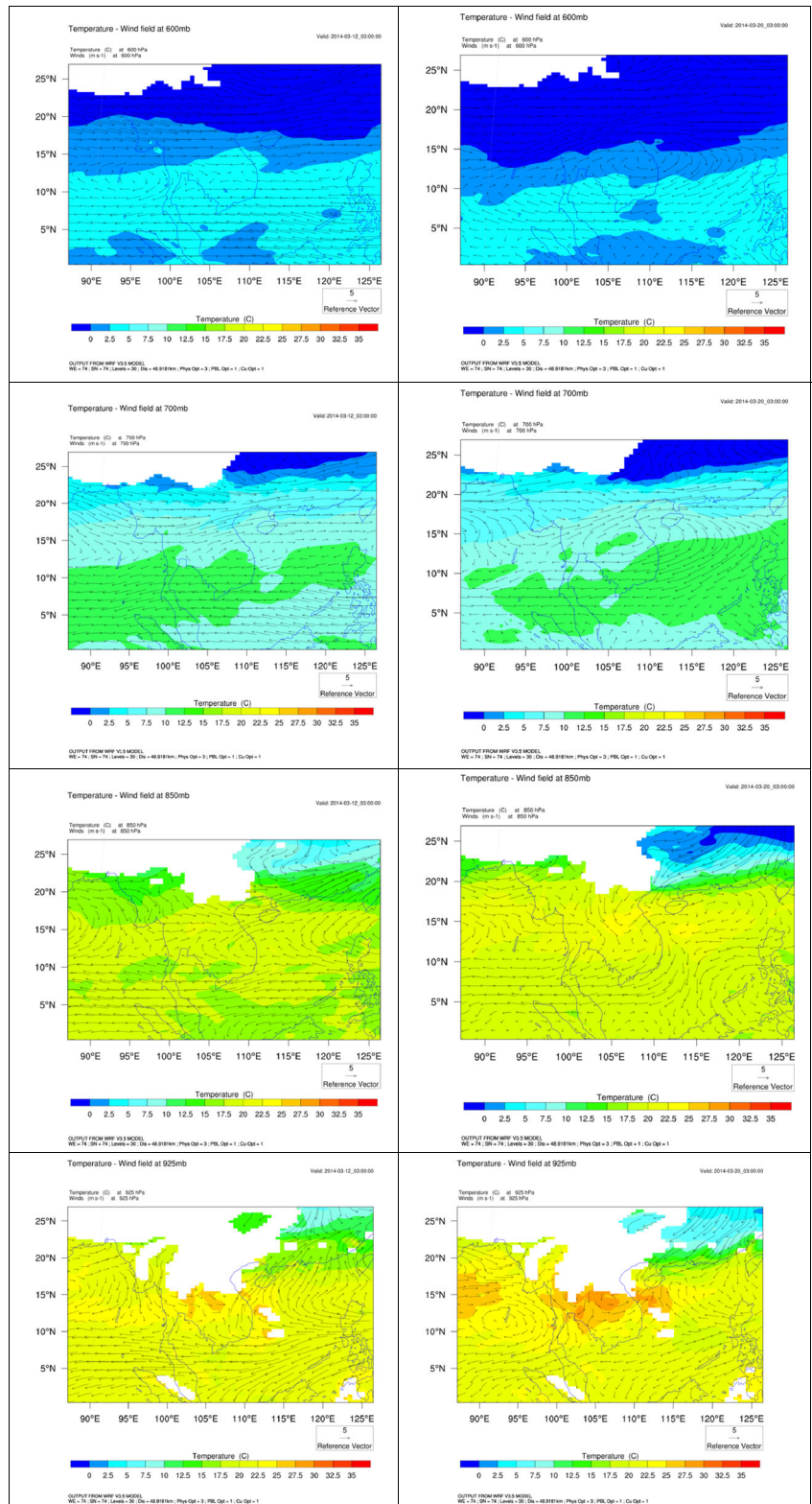
with backward and forward trajectories of air parcels across the Southeast Asian region due to biomass burning during the dry season.

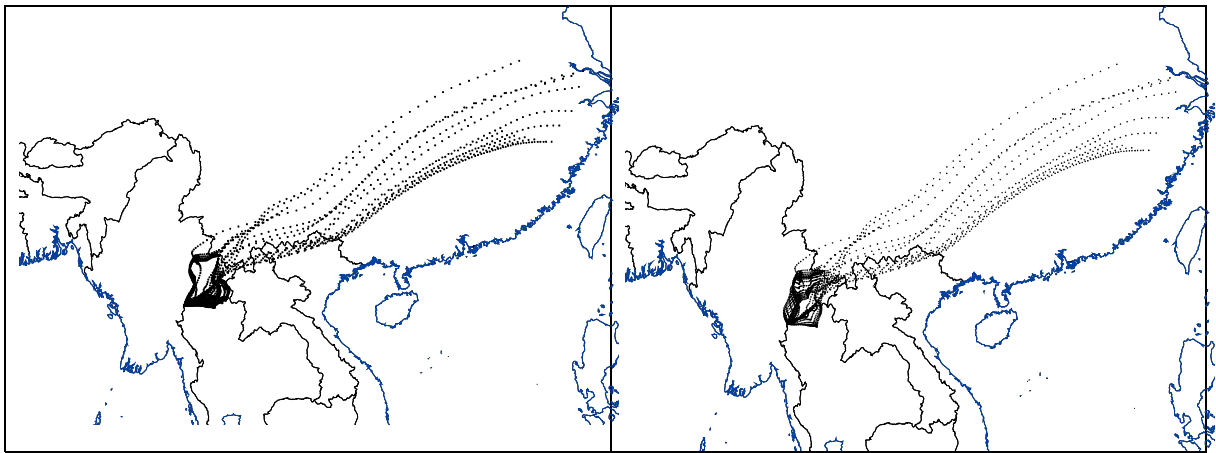
As Lagrange particle dispersion model (LPDM), such as HYSPLIT or flexible particle dispersion model

(FLEXPART), computes trajectories of a large number of particles or air parcels in the atmosphere, does not involve numerical diffusion calculation and is relatively fast in computing time compared to the Eulerian models, they have been widely used in the study of transport and



**Fig. 7** Temperature and wind field at 600, 700, 850 and 925 mb on 12 March 2014 03:00 UTC (left) and 20/3/2014 03:00 UTC (right)





**Fig. 8** HYSPLIT forward trajectories of released particle tracers every 1 h at a site near Mae Hongson in the border area on 19 March 2014 00:00 to 23:00 UTC (*left*) and on 20 March 2014 00:00 to 23:00 UTC (*right*)

trajectories of pollutants released from point sources. For long-range transport of pollutants, there are various applications of LPDMs to study the transport of pollutants from biomass burning (Rolph et al. 2009; Forster et al. 2001; Stohl et al. (2007), Fiebig et al. 2009) and ozone transport in the stratosphere and troposphere (Stohl and Trickl 1999).

In addition to the Lagrangian HYSPLIT model, the Weather Research Forecast (WRF) Eulerian model is also used. WRF was developed by National Center for Atmospheric Research (NCAR) in the USA. The WRF model is widely used in universities and research institutes including national weather bureau in some countries for real-time forecasting. In this paper, we will use the WRF model (version 3.5) for modelling the 3-D meteorological condition during the March 2014 biomass burning in Southeast Asia.

WRF is a mesoscale 3-D weather model prediction system with dynamic advection, physics including various convection, radiation, boundary layer and cloud microphysics options. The WRF is a very useful and suitable tool used to downscale the coarse global forecasting model (GFS) output such as NCEP GFS, the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim or Global Climate Model (GCM) prediction to a finer resolution applicable to a region (e.g. Southeast Asia).

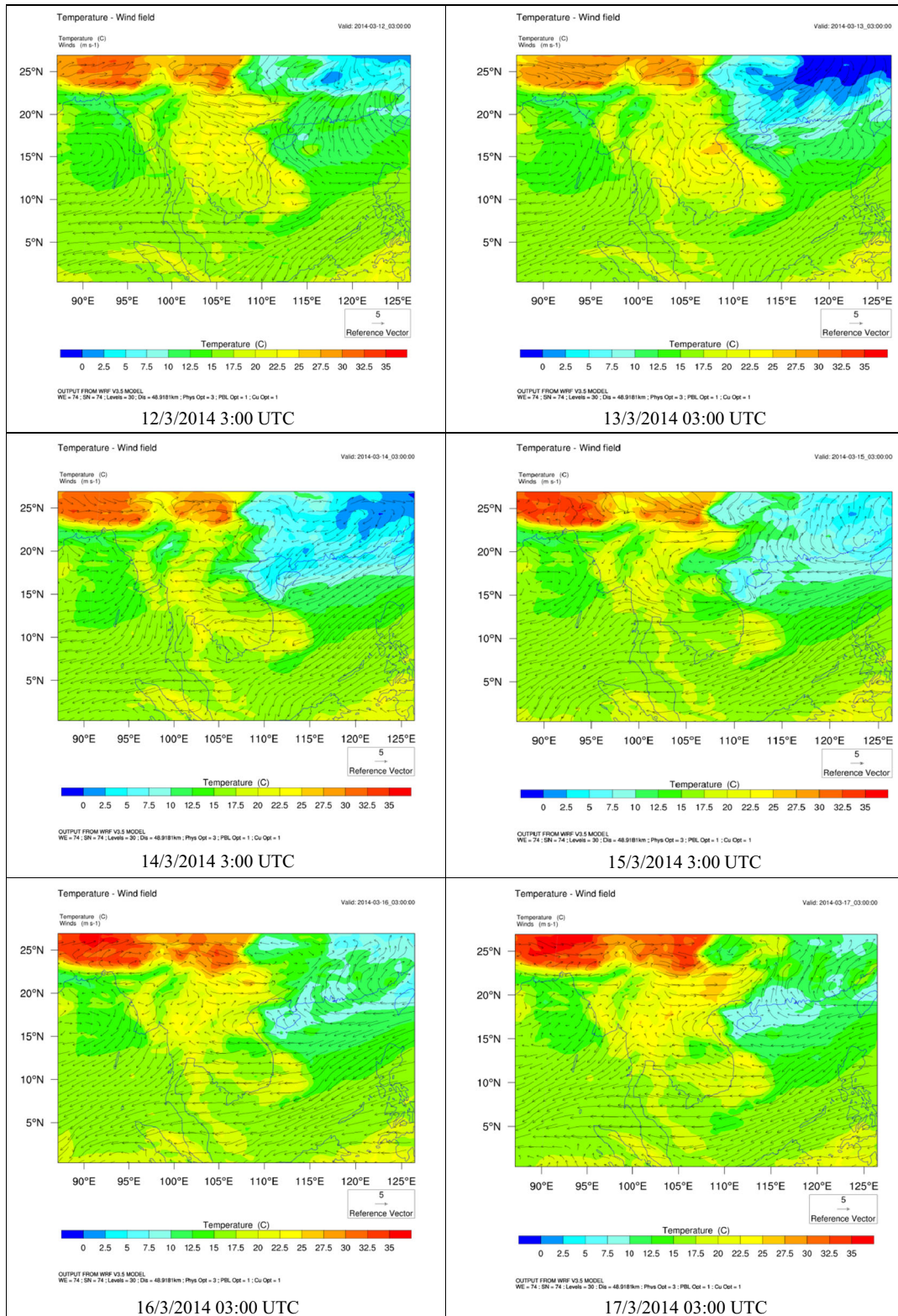
We used the WRF with the defined options for the forecasting of meteorological variables. The defined options are single-moment (WSM) 3-class simple ice scheme for microphysics, rapid radiative transfer model (RRTM) scheme for longwave radiation, Dudhia scheme

for shortwave radiation, Monin–Obukhov similarity scheme for surface layer physics, Noah land-surface model for land surface, YSU scheme for boundary layer, Kain–Fritsch (new Eta) scheme for cumulus cloud physics and four soil layers in land surface model.

The WRF configuration is based on two nested domains. The outer domain is 74 by 74 grids with grid size at 50 km in x and y direction. The inner nested domain is of 10 km × 10 km grid size. Both domains have 30 vertical levels with pressure on top at 5000 Pa. The centre reference latitude and longitude is 16.8° and 102.36° (pol\_lat = 73.2°, pol\_lon = -77.64°) with lat-lon map projection. The initial and boundary conditions and coarse data are the NCEP GFS global analysis data downloaded from NCEP GFS to drive the WRF model run.

The meteorological pattern for the month of March 2014 in SEA and southern China can be better understood by analysing the vertical structure of the wind flow as provided by the WRF modelling results. Low pressure in the Himalaya and northern Indochina and relative high temperature during daytime persist for most of the period from 11 to 24 March 2014. The temperature and wind field at 600, 700, 850 and 925 mb (hPa) levels in the lower troposphere on 12 March 2014 and 20 March 2014 at 10 a.m. LST is shown in Fig. 7. The westerly flow from the Bay of Bengal and northern SE Asia to southern China and Taiwan is clearly evident at 600, 700 and even at 850 mb.

This wind pattern is typical for March as shown by Lin et al. (2013). The westerly wind at 600 and 700 mb high altitudes is the result of the dominating SE Asia high over the region of northern SE Asia, South China Sea and



**Fig. 9** The surface temperature and wind field at 10 am LST from 12 (top left) to 21 (right bottom) of March 2014. From 14 to 18 March 2014, offshore wind from the South China Sea flows inland across the southern Indochina peninsular to the Bay of Bengal

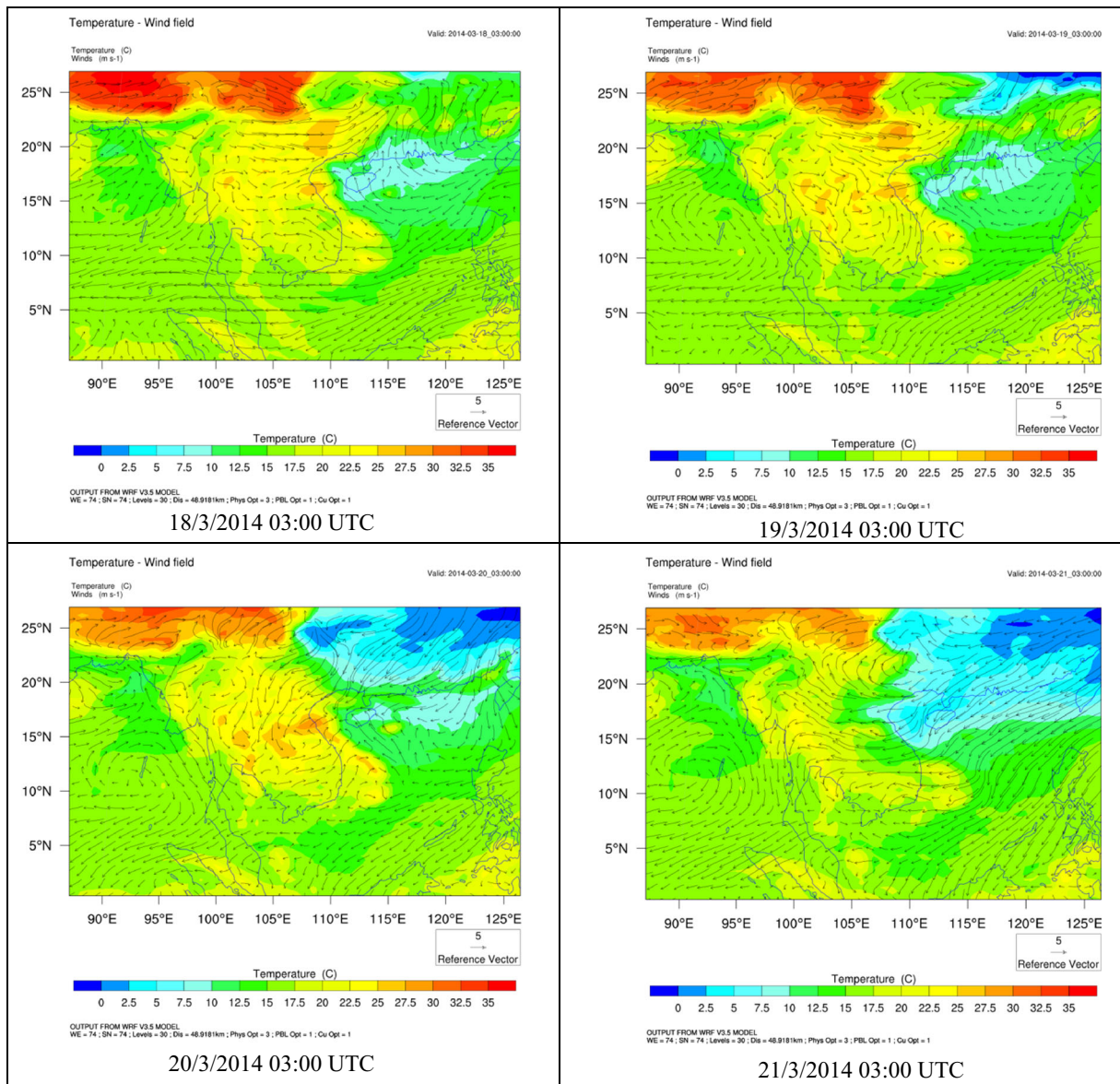
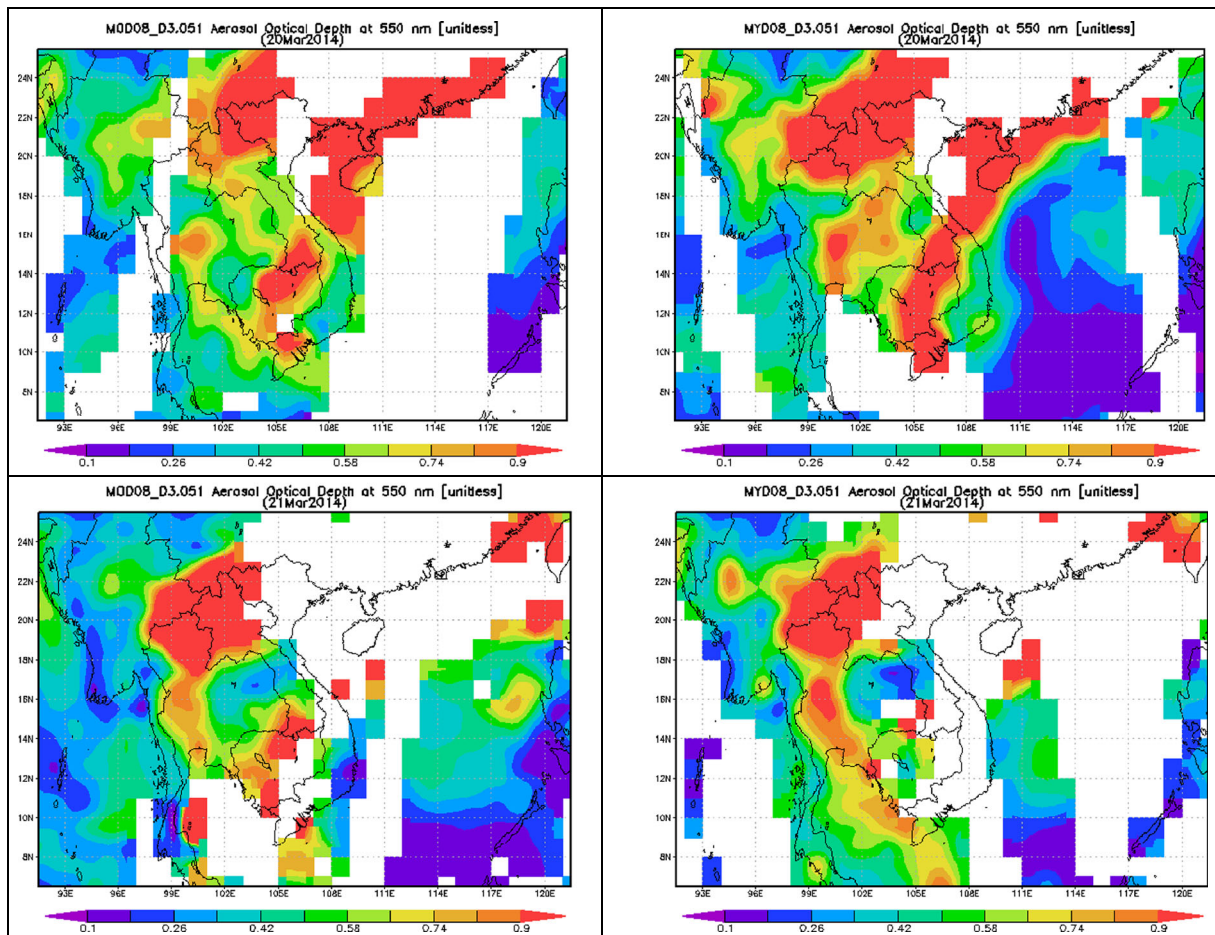


Fig. 9 (continued)

East Sea of Taiwan (Lin et al. 2013; Chen et al. 2002) and weakens in April at the onset of the southwest monsoon.

The dominating easterly flow at 600, 700 and 850 mb from the South China Sea over the southern part of SE Asia to the Bay of Bengal is due to the dry and cool northeast monsoon which starts from mid-December to mid-April. The March southerly wind at 850 and 925 mb from the centre of SE Asia (Laos, central Thailand and northern Vietnam) converges to the southern part of China near the border between China with these Southeast Asian countries.

From the study of climatology during March and April for the period of 1979 to 2010, Lin et al. (2013) suggested that during March, an upward branch of the East–west cell/circulation lifts pollutants from biomass fires to approximately 700 mb. This lifting is enhanced by the above-mentioned southerly convergent flow. The combination of westerly flow at 700 mb and the lifting biomass pollutants of the southerly flow to the north facilitates the transport of pollutants from biomass fires originating in north Thailand, Myanmar and Laos to southern China, East Asia and even eastward across



**Fig. 10** AOD as measured at 550 nm on Terra and Aqua satellites for 20 (*top*) and 21 (*bottom*) March 2014 (from Giovanni online data system [http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance\\_id=MODIS\\_DAILY\\_L3](http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_DAILY_L3))

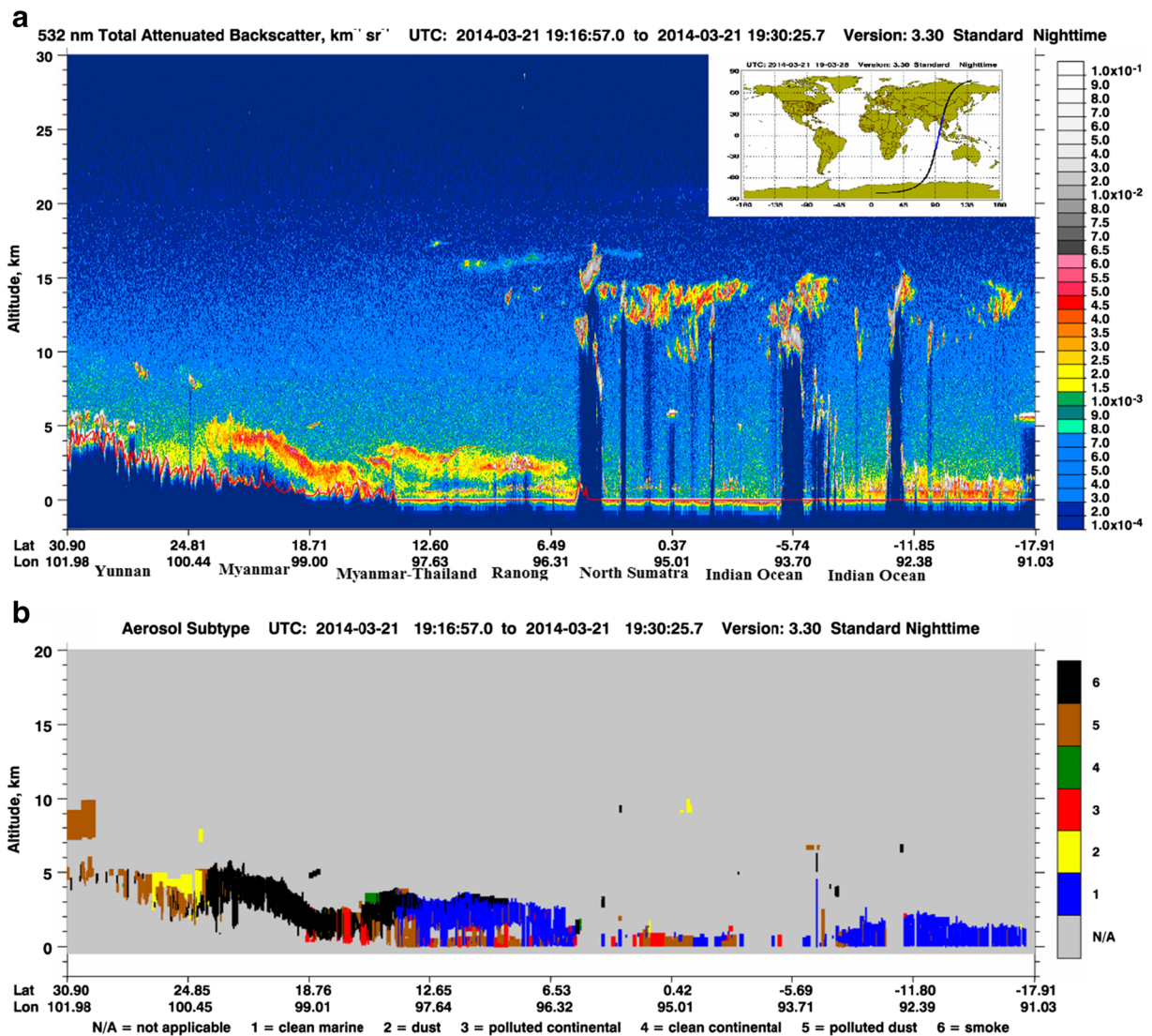
the Pacific. This is indicated by the AOD as measured by Terra and Aqua satellite for the month of March (Fig. 6), showing high aerosol concentration above the southern and part of central China.

Previous studies showed that pollutants and trace gases from biomass burning in SEA and South Asia during the dry season were also transported and detected in the Tibetan Plateau, especially in the southeastern section of the plateau. The wind patterns at 600 and 700 mb as shown in Fig. 7 suggest favourable condition for the transport of air pollutants from biomass burning in northern SEA and north India to southeast of the Tibetan Plateau. Engling et al. (2011) have shown that observed elevated levels of aerosols and black carbon (BC) in the Tibetan Plateau were due to transport of smokes from biomass burning in SEA and in the north of the Indian Peninsular during the fire season. By analysing of PM<sub>2.5</sub>, organic carbon (OC) and element

carbon (EC) as well as levoglucosan and mannosan measurements at sites in Yunnan Province of the southeastern Tibetan Plateau, Sang et al. (2013) have identified source categories (crop residues and soft- and hardwood) and contribution of biomass smoke from both local and SEA sources.

Forward trajectories from HYSPLIT simulations from a release of particle tracers at 10 m height above-ground from a northern Thailand site near Mae Hongson in the border area of Thailand and Myanmar, where forest fires occurred during the March 2014 biomass burning period, show transport of particles at high altitude to central China and East Asia as shown in Fig. 8.

Figure 9 shows the temperature and surface wind fields at 10:00 a.m. local time (3:00 UTC) as predicted from the WRF model for the period from 11 to 24 March 2014. From the 12 to 13 March 2014, the wind is flowing down from northern Thailand and Burma,



**Fig. 11** Widespread thick smoke aerosols on 21 March 2014 at nighttime above the Myanmar and Thailand border area from biomass burning as measured by CALIOP, **a** 532 nm total attenuated backscatter in the night time transect (*inset*) from Yunnan (China) to Myanmar–Thailand border and Indian Ocean. **b** Types

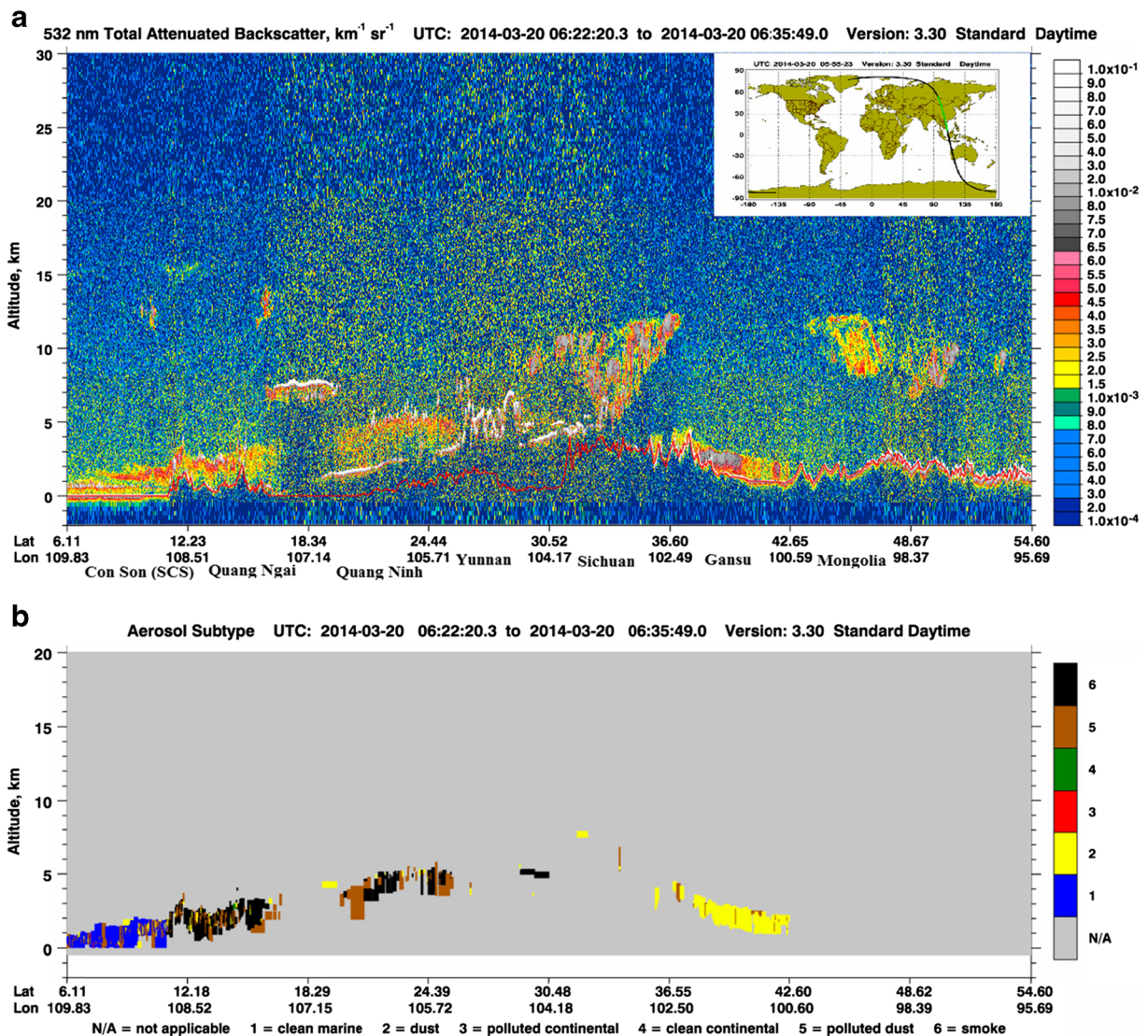
of aerosols above the stratocumulus cloud: dust and polluted dust above Yunnan, smoke above Myanmar–Thailand border, mostly marine aerosols above the Bay of Bengal near Ranong and clean marine aerosols above the Indian Ocean

where most of the biomass fires were concentrated, to southern Thailand, the gulf of Thailand and across to Laos and central Vietnam. This caused increasing level of pollutant concentrations mostly in central Thailand soon later before the wind changed direction on the 14th.

However, from 14 to 17 March 2014, offshore wind from the South China Sea flows inland across the southern part of Indochina peninsular to the Bay of Bengal. Wind in central, northern Thailand and east of Myanmar is mostly confined and circulated within those areas while westerly wind is more prominent in northern

Laos facilitating the transport of pollutants to northern Vietnam and southern China. This is in line with what Lin et al. (2013) have observed and found in their study.

The AOD data as measured from MODIS Terra/Aqua satellites for the days of intensive fires and high concentration of air pollutants in northern Thailand (20 and 21 March) show the extent of the effect of biomass fires in the region. In addition to the high AOD over northern Thailand and Myanmar, the AOD as detected by MODIS Terra/Aqua on the 20 and 21 of March as depicted in Fig. 10 also shows significantly high AOD



**Fig. 12** Smoke aerosols and polluted dust on 20 March 2014 at daytime from 2 to 3 km above central Quang Ngai (central Vietnam) and at about 5 km above Quang Ninh (North Vietnam). **a** 532 nm total attenuated backscatter in the daytime transect (*inset*) from Con Son island (SCS) to Central, northern Vietnam

and China, Mongolia. **b.** Types of aerosols above the stratocumulus cloud: mostly marine aerosols above SCS near Con Son Islands, smoke and polluted dust above Quang Ngai, Quang Ninh and dust above northern China near Mongolia

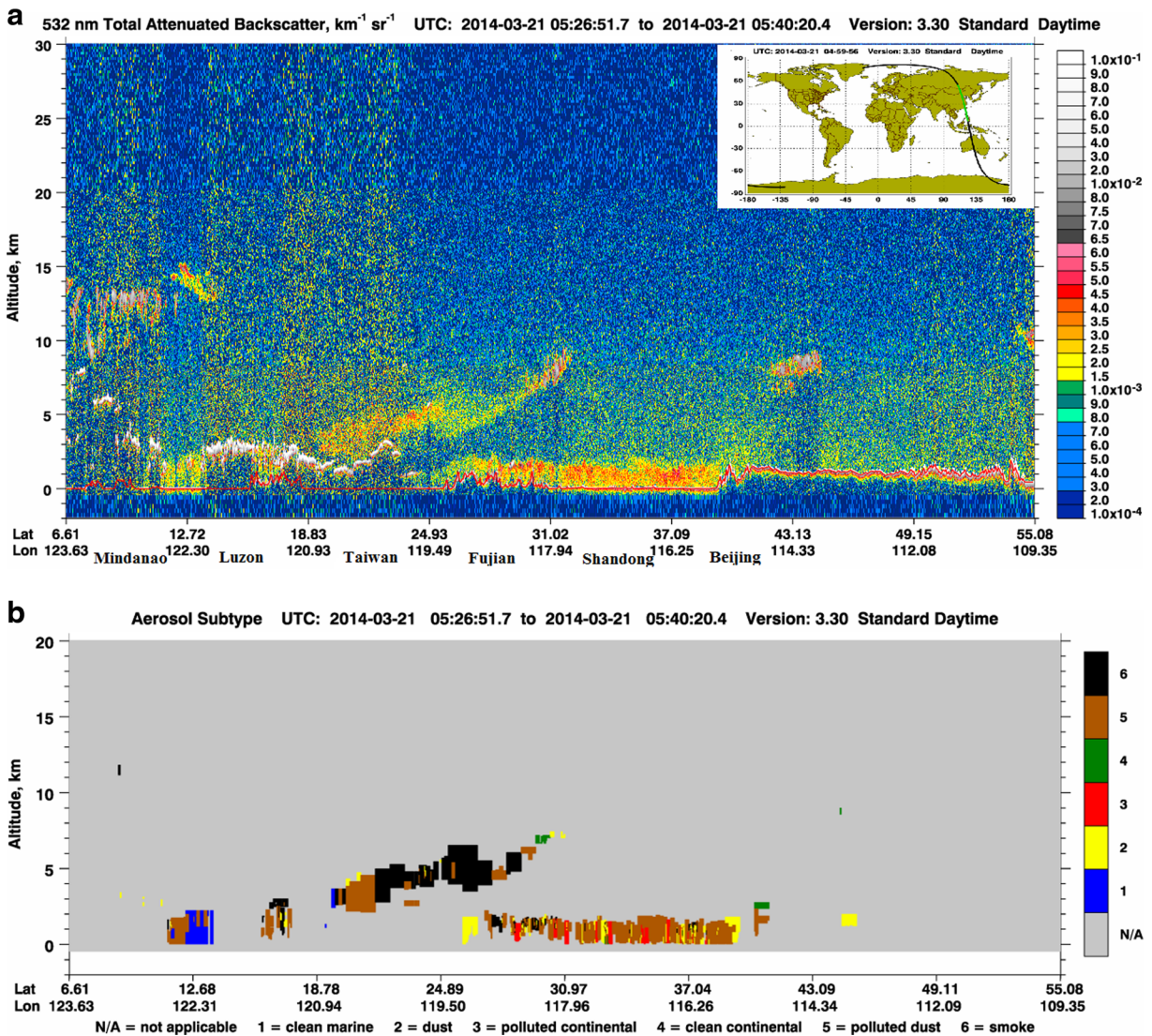
over southern Laos, Cambodia and southern Vietnam in the Mekong delta where agricultural biomass-burning activities also occurred.

The AOD maps show that the aerosol concentration for 20 and 21 March 2014 were mostly confined to the burning areas in SEA and to southern China, the Gulf of Tonkin, Hong Kong and Taiwan. Most of eastern Myanmar, the Bay of Bengal, the Andaman Sea and the South China Sea have low aerosol concentration. This corresponds to the results from HYSPLIT and WRF

simulation as described above during these days as the meteorological conditions favoured the transport of aerosols toward the northeast.

**Aerosol profiles and SEA biomass burning**

Vertical distribution of aerosols and their interaction with clouds as measured from the CALIOP (Cloud–Aerosol Lidar with Orthogonal Polarization) Lidar



**Fig. 13** Smoke aerosols and polluted dust on 21 March 2014 at daytime from 4 to 6 km above Taiwan and Fujian (China). **a** 532 nm total attenuated backscatter in the daytime transect (*inset*) from Mindanao, Luzon (the Philippines) to Taiwan, Fujian,

Shandong and Beijing. **b** Types of aerosols above the stratocumulus cloud: marine and polluted dust aerosols above Mindanao and Luzon, smoke, polluted dust and continental aerosols just above Fujian, Shandong and Beijing

on-board the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite is valuable to understand the extent and structure of smoke plumes. The CALIPSO satellite launched in April 2006 provides nearly continuous measurements of the vertical structure and optical properties of clouds and aerosols. It has a two-wavelength polarization-sensitive Lidar, an imaging infrared radiometer (IIR) and a high-resolution wide field camera (WFC).

Gautam et al. (2013) have used CALIOP level 2 (version 3.01) profile product measurements such as

aerosol extinction coefficient and volume depolarization ratio (VDR) over Indochina peninsular domain ( $5^{\circ}$ – $25^{\circ}$  N and  $90^{\circ}$ – $100^{\circ}$  E, which are similar in size to our WRF SEA domain) to study the aerosol vertical distribution and aerosol composition from February to April 2007. The VDR, as defined as the ratio of the perpendicular and parallel components of the backscatter polarized signals, is an indicative of the aerosol type. From the zonal mean profiles along satellite tracks, they derive the average zonal profiles of extinction coefficient and VDR ratio and found that over the oceanic regions



(Bay of Bengal and SCS) are clean marine aerosols and over the northern land areas (15°–25° N) are thick layer of aerosols extending up to ~4 km compared with the low aerosol loading over the equatorial regions.

We use vertical feature mask (VFM) of the CALIOP level 2 data products (version 3.30), with 5 km horizontal resolution and temporal coverage from 01 March 2013 to the present, to examine the vertical aerosol profiles over SEA and surrounding regions during the March 2014 biomass burning in SEA. The identification of aerosol types as provided in the VFM CALIOP level 2 data products is based on the CALIPSO aerosol models which use six aerosol types as identified by the cluster analysis of a multiyear (1993–2002) AERONET data set. The six types are dust, polluted continental, polluted dust, smoke (biomass burning), clean continental and clean marine aerosols. The smoke aerosol model in CALIPSO uses the extinction-to-backscatter ratios  $S_a$  values of 70 sr at 532 nm and 40 sr at 1064 nm wavelength for smoke aerosols from biomass burning (Omar et al. 2009).

Figure 11 shows, on 21 March 2014 at nighttime, above the stratocumulus cloud layer, the thick extensive smoke aerosol layer along the Myanmar–Thailand border area (east and northeast of Thailand) at an altitude of between 2.5 and 5 km. Even near Ranong in the Bay of Bengal, the smoke layer is evident above the clean marine aerosol layer.

Aerosol profile, as measured by CALIOP on 20 March 2014 at daytime and shown in Fig. 12, indicates smoke plume layers high above central and northern Vietnam but not above southern Vietnam and central and western China. Above Gansu (central China) and

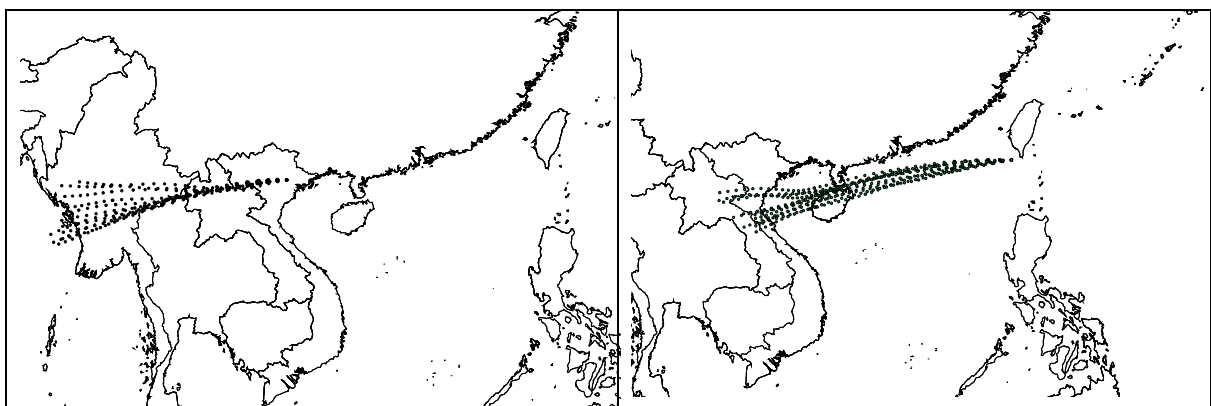
northern China near Mongolia, there was a thick extensive layer of dust.

HYSPLIT back trajectory analysis on 20 March 2013 6UTC at a site in Quang Ngai (central Vietnam) 1000 m aboveground and at a site in Quang Ninh (North Vietnam) 5000 m aboveground where smoke plume layers were detected by CALIOP Lidar indicate that the smoke aerosol layer above Quang Ngai originated from the local biomass fires but the high altitude layer above Quang Ninh came from biomass fires in northern Thailand, Myanmar and Laos.

Figure 13 shows on 21 March 2013 at daytime, smoke plume layer at high altitude (from 4 to 6 km) above Taiwan and Fujian in the coastal area of southern China. HYSPLIT back trajectory analysis on this date 5000 m above a site near Taiwan shows that the aerosol layer was transported from central and northern Laos as shown in Fig. 14.

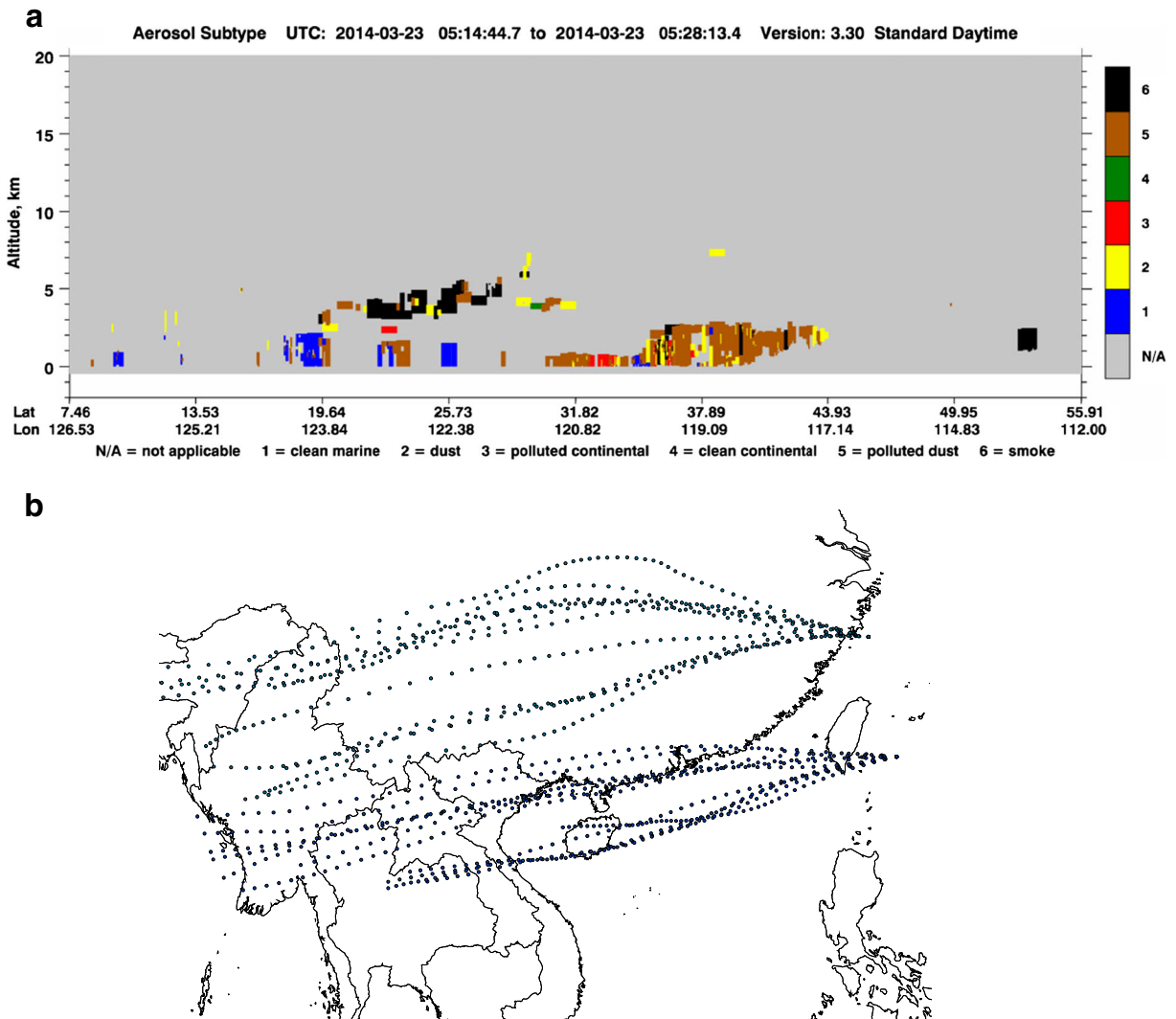
Figure 14—HYSPLIT 24-h back trajectories (released every 2 h) of air masses arriving 5000 m above Quang Ninh (North Vietnam) on 20 March 2014 06:00 UTC (left) and 36-h trajectories (released every 3 h) air mass arriving near Taiwan at 5000 m on 21 March 2014 05:00 UTC (right).

On 23 March 2014 at daytime, above northern SEA in Thailand and Myanmar, less extensive smoke aerosol layer than in the previous 2 days indicates the subsidising of the biomass fires (figure not shown). But on this day at daytime high above the Pacific Ocean just off the east coast of Taiwan to Zhejiang on the east coast of China, a large extensive smoke layer from biomass fires in the previous days was present at high altitude from 4 to 5 km as shown in Figs. 15a and 16. HYSPLIT back trajectories on 23 March 2014 at 5 UTC



**Fig. 14** HYSPLIT 24 h back trajectories (released every 2 h) of air masses arriving 5000 m above Quang Ninh (north Vietnam) on 20 March 2014 06:00 UTC (left) and 36 h trajectories (released

every 3 h) air mass arriving near Taiwan at 5000 m on 21 March 2014 05:00 UTC (right)



**Fig. 15** **a** Aerosol profile on 23 March 2014 at daytime from CALIOP Lidar. **b** HYSPLIT 48 h back trajectories (released every 4 h) of air mass arriving 5000 m above two sites, one ( $22.64^{\circ}$  N,  $123.14^{\circ}$  E) near Taiwan and the other ( $27.93^{\circ}$  N,  $98.61^{\circ}$  E) near Zhejiang

and 5000 m above the two sites which define the limit of the extent of the smoke aerosol layer below the satellite path show that the arrived air masses came from Myanmar, northern Thailand, northern Laos and northern Vietnam.

The CALIPSO satellite data, as described in details above, shows that the smoke aerosols due to the agricultural biomass burning and forest fires in northern Thailand, Myanmar and Laos with intense burning period from 15 to 21 March were transported at altitude above the stratocumulus cloud across the region to northern and central Vietnam, Taiwan, southern China, the east coast of China and beyond. The smoke aerosol layer on 23 March 2014 at daytime (5 UTC) of about

1 km thick (from 4 to 5 km) stretched from the Pacific Ocean just off east of Taiwan to Zhejiang on the east coast of China as shown in Fig. 13a. This smoke layer profile is only one cross-section of the aerosol plume between 5:14 and 5:28 UTC. Wang et al. (2013), using comprehensive measurements of mass concentration, optical properties, hygroscopicity and vertical distribution of aerosols during the boreal spring of 2010 on Dongsha Island north of SCS near Taiwan, has found that the aerosols from biomass burning in SEA were transported at a higher layer (3–4 km) while aerosols mainly from north China arrived in a confined marine boundary layer (0–0.5 km). Our results are consistent with their findings.

The high AOD over southern Laos, Cambodia and the Mekong delta in southern Vietnam on 20 and 21 March as depicted in Fig. 10 is mostly due to the local emission from the agricultural biomass burning in these areas. On these 2 days, the number of hotspots as detected by MODIS in Laos, Cambodia and Vietnam peaks at approximately 550 counts for Laos and 200 counts for both Cambodia and Vietnam (Fig. 4). The WRF modelling results show that surface easterly wind from the SCS prevails over southern Vietnam and Cambodia. Back trajectories using HYSPLIT with Ho Chi Minh City (HCMC) as a release point at 10 m above-ground on 16 and 22 March at every 6 h for 72 h show air masses arriving from the SCS.

There is no indication of aerosol transport from other regions to southern Vietnam. The air quality data (PM<sub>2.5</sub> and PM<sub>10</sub>) from ground monitoring stations in HCMC does not indicate unusual high concentration at these days. Comparison of the concentration data of PM<sub>2.5</sub> and PM<sub>10</sub> for the month of March 2014 to the data of the same month from other years (2012) did not show any difference in the concentration pattern. Except, as expected, the PM<sub>2.5</sub> and PM<sub>10</sub> concentrations in March toward the end of the dry season are higher than those from the wet months of May to October.

**Ground-based air quality measurements and SEA biomass burning**

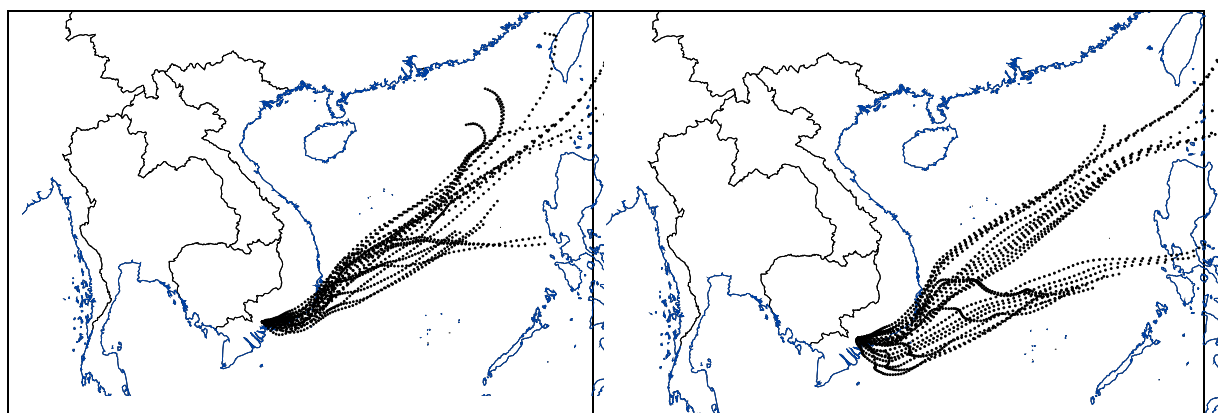
Depending on the local meteorological condition, mixing down of air mass aloft or deposition of air pollutants can happen. For this reason, air quality data from ground

monitoring stations at sites in South China or Taiwan can be used to detect or verify the transport of air pollutant from biomass burning in SEA to southern China. Ground air monitoring stations such as those in Hong Kong and a background station in the remote mountain at Mt. Lulin (23.47° N, 120.87° E at 2682 m above sea level) in central Taiwan are analysed to ascertain the presence of transboundary air pollutants as detected at these sites.

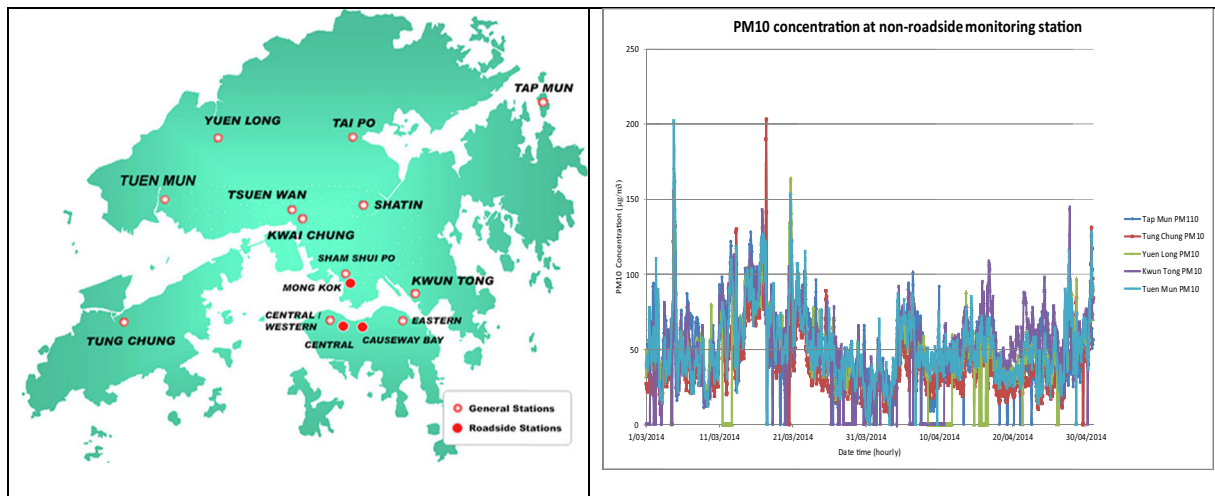
Data analysis of PM<sub>10</sub>, PM<sub>2.5</sub> and CO measurements from spatially scattered non-roadside ground monitoring stations in Hong Kong shows a consistent high concentration of these pollutants from 15 March 2014 to 22 March 2014. Figures 17, 18 and 19 show the temporal pattern of PM<sub>10</sub> concentrations at Tap Mun, Tung Chung, Yuen Long, Kwun Tong and Tuen Mun stations from 1 March 2014 to 30 April 2014. The stations are scattered across Hong Kong (Kowloon and islands) as shown.

The nearly identical temporal pattern of PM<sub>10</sub> concentrations at these spatially disperse monitoring stations suggests that the regional emission rather than the local emission is responsible for the inter-daily variation in PM<sub>10</sub> concentrations at these sites. At Lulin Atmospheric Background Station (LABS) in central Taiwan, a similar temporal pattern of PM<sub>10</sub> concentration from 15 March 2014 to 22 March 2014 to those at the Hong Kong sites for the same period.

As Lulin background station in central Taiwan is very far away from monitoring stations in Hong Kong, and their local characteristics such as terrain are very different, we expect very little correlation between the particle concentrations at these sites. However, the correlation of PM<sub>10</sub> at Lulin and PM<sub>10</sub> at Tuen Mun station for the



**Fig. 16** HYSPLIT 72 h back trajectories (released every 6 h) of air masses arriving at HCMC on 16 March 2014 00:00 UTC (left) and on 22 March 2014 00:00 UTC (right)

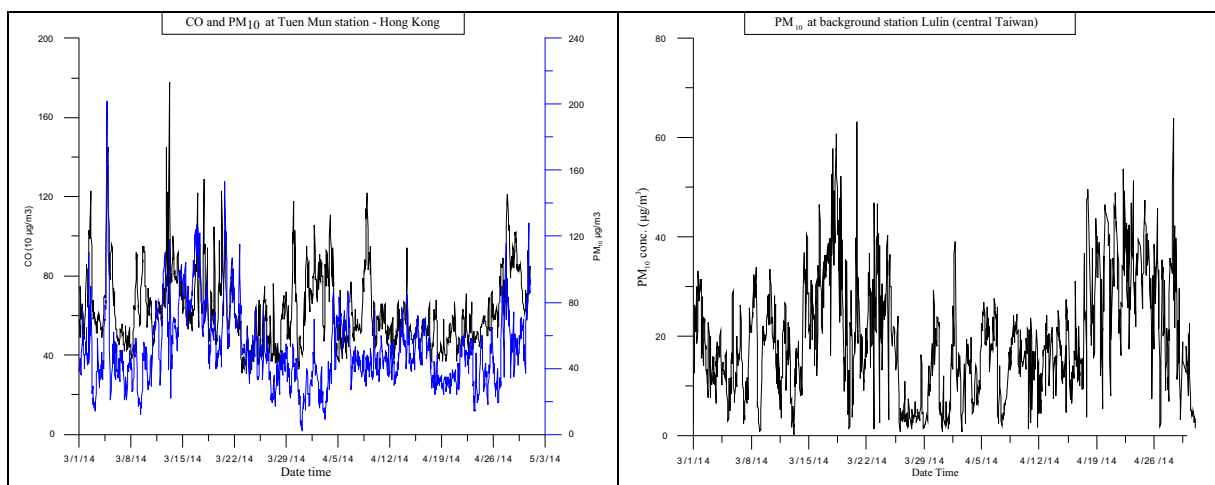


**Fig. 17** Air quality monitoring stations in Hong Kong (*left*) and PM<sub>10</sub> concentrations from the period of 1 March 2014 to 30 April 2014 at five non-roadside monitoring stations (Tap Mun, Tung Chung, Yuen Long, Kwun Tung and TuenMun)

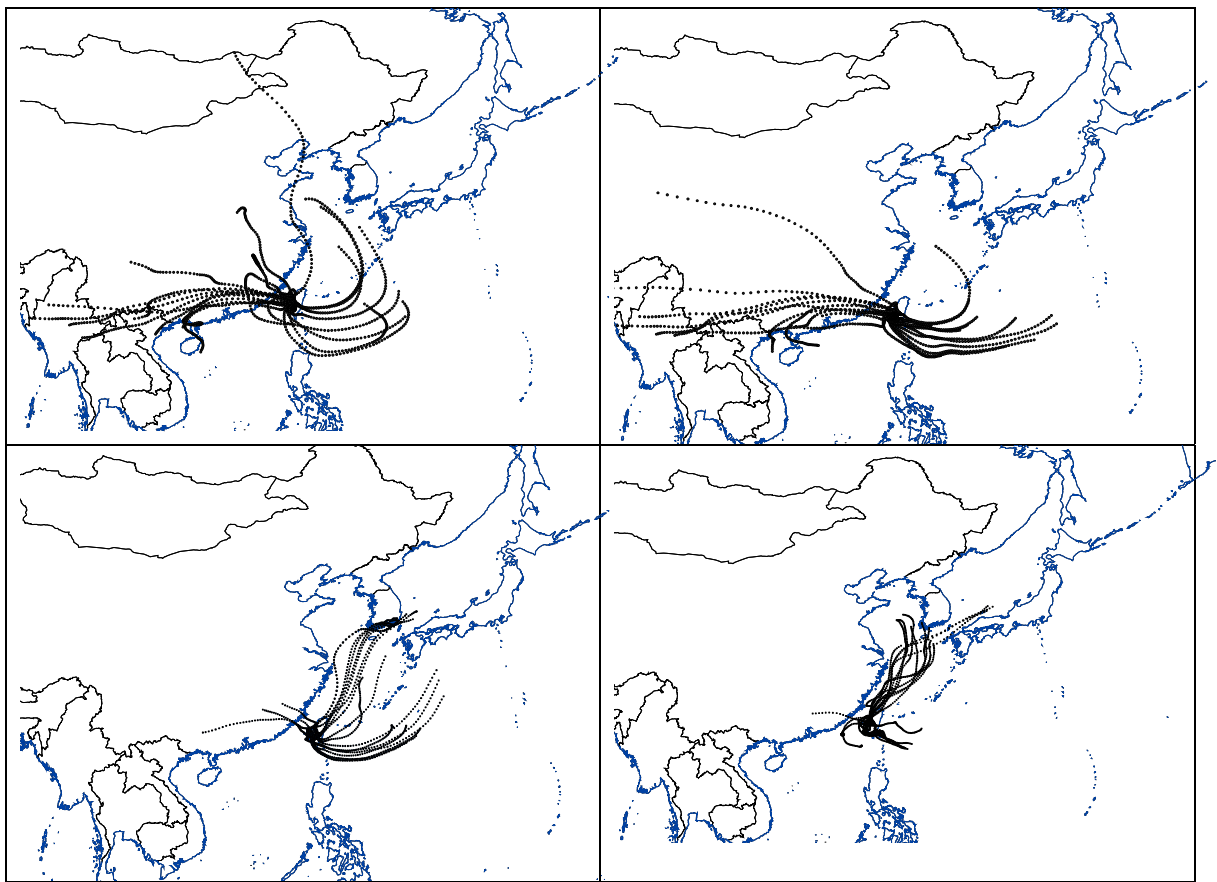
period of 15 March 2014 to 30 March 2014 is shown to be higher than those for different periods. The correlation is about 0.5 compared with practically nearly 0 for other periods (such as for the March period or the April period).

From the results of the WRF meteorological model simulation and the observed temporal particle concentration pattern at Lulin and Hong Kong monitoring sites, it is suggested that the high concentrations of PM<sub>10</sub> for the period of 15 March 2014 to 22 March 2014 as detected at the above sites are most likely due to air pollutant transport from biomass burning in SEA. The MODIS AOD across the SEA and south China as shown in Fig. 10 confirms that the high aerosol column concentrations occurred above the region for these days.

It is very likely that for the period of 15 March 2014 to 22 March 2014, the elevated concentration of PM<sub>10</sub> at Lulin (an increase of about 15 µg/m<sup>3</sup> compared to previous period) and Hong Kong non-roadside stations (an increase of about 20 µg/m<sup>3</sup> compared to the previous period) is mainly due to the transboundary air pollutants from SEA rather than from northeast China. Back trajectory analysis using HYSPLIT based on archived GDAS global meteorological data at Mt. Lulin background station for the days in March (15 March 2014 to 22 March 2014) when high concentrations of PM<sub>10</sub> were detected shows that the air parcels came mainly from SEA (north of Thailand, Laos and Vietnam).



**Fig. 18** a CO and PM<sub>10</sub> concentrations as measured at TuenMun station in Hong Kong and b PM<sub>10</sub> concentration as measured at Lulin background station in central Taiwan from 1 March 2014 to 30 April 2014



**Fig. 19** HYSPLIT back trajectories of air masses arriving at Lulin station on 17 March 2014 14:00 UTC and 20 March 2014 13:00 UTC (*above*), on 17 April 2014 15:00 UTC and 26 April 2014 00:00 UTC (*below*)

But for the period in late April 2014, as the pattern at Lulin is different from those at Hong Kong sites, the source of elevated concentration at Lulin can be ascertained using meteorological model simulation such as HYSPLIT back trajectory. The back trajectory is performed for those days in late April 2014 (17 April to 28 April 2014), and the results show that the source of the high particle concentration is from the north of Taiwan, i.e. northeast Asia.

**Conclusion**

Similar to the situation in the Malaysian peninsular and the Indonesian archipelago during the dry season from June to October when biomass burning and peat and forest fires, especially in Sumatra and Kalimantan (Borneo), cause widespread transboundary haze in Singapore and Malaysia, the biomass burning from agricultural

activities in peninsular SEA, especially in Thailand and Myanmar, during March and early April results not only in the widespread particle pollution in these countries but also in the long-range transport of smoke aerosols in the troposphere to southern China, Taiwan and far beyond. Using CALIOP Lidar measurements and WRF/HYSPLIT modelling, we have shown the long-range transport of smoke aerosols at high altitude (approximately from 3 to 5 km) during March 2014 biomass burning in SEA due to the prevailing meteorological conditions to southern China, Taiwan and East Asia but not to southern Vietnam. This is in line with the previous results from the BASE-ASIA and 7-SEAS studies.

Using the results from WRF and HYSPLIT models as well as analysing and comparing AOD and particles measurements from monitoring stations in the Thailand, Hong Kong and Taiwan, we have shown that during March 2014, intensive agricultural biomass burning in SEA, especially in northern Thailand and Myanmar, and

forest fires in northern Thailand has caused not only high pollution in Thailand but also elevated concentration in Hong Kong and Taiwan. The period from 15 March 2014 to 22 March 2014 is when meteorological condition is most favourable for the transport of air pollutants from northern Thailand, Myanmar, northern Laos and northern Vietnam to southern China and Taiwan.

The peak of the fire and smoke coverage from biomass burning is from 20 to 21 March when the highest particle concentrations are measured in Thailand and high AOD were detected over SEA and southern China. But after those days and thereafter, from 23 March 2014, when the biomass fires are subsiding, there is little evidence that these fires in SEA have caused air pollutants to be detected at high levels on the ground in southern China and Taiwan due to transported smoke aerosols to southern China, Taiwan and beyond. The high particle concentration and AOD for the period after 22 March 2014 in northern SEA, southern China (Hong Kong) and Taiwan (Lulin) are mainly due to local sources (biomass burning in SEA, industrial pollution in southern China) or transport of pollutants from northern China or East Asia rather than from biomass burning in northern part of SEA.

**Acknowledgments** The provision of air quality data from the Pollution Control Department (PCD) of Thailand, the Environmental Protection Department of Hong Kong SAR, Professor N. Lin of National Central University (Chung-Li, Taiwan) and the Environmental Protection Administration (EPA) of Taiwan is gratefully acknowledged.

Analyses and visualizations, where they are indicated in the paper, were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC, and CALIPSO satellite products from NASA Langley Research Center. We also acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (<http://www.ready.noaa.gov>) used in this publication.

#### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no competing interests.

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