A Case Study of Long-Range Transport of Smoke Aerosols Eastern Siberia to Northeast China in July 2014

Xiaojing Li1, Xiangao Xia2,3*, Jingjing Song2,3, Yufei Wu4, Xiaoling Zhang5, Renjian Zhang4
1 National Satellite Meteorological Center, Beijing, China
2 LAGEO, Institute of Atmospheric Physics, CAS, Beijing, China
3 University of Chinese Academy of Sciences, Beijing, China
4 RCE-TEA, Institute of Atmospheric Physics, CAS, Beijing, China
5 Beijing Meteorology Bureau, Beijing, China

ABSTRACT

Long-range transport of biomass burning aerosols from Eastern Siberia to Northeast China in July 2014 was studied by using ground-based ambient measurements and satellite products. Intensive active fires were revealed in Eastern Siberia during the late of July by the Moderate Resolution Imaging Spectroradiometer (MODIS) active fire products. Under the favorable synoptic pattern, the smoke layer was transported to Northeast China, which led to significant enhancement of surface PM$_{2.5}$ concentration. The peak PM$_{2.5}$ concentration exceeded 100 $\mu$g m$^{-3}$ that was 3–6 times larger than the background level. High aerosol optical depth at 550 nm with daily value exceeding 1.0 was observed at a background site in Northeast China. Smoke aerosols were characterized by fine-mode dominated particles with very weak absorption. Air quality in Northeast China was revealed to be potentially impacted by the long-range transport of smoke aerosols from Eastern Siberia during the biomass burning season, which probably impacted human health, weather and climate. Therefore, further study on this issue is urgently required for quantitatively evaluating potential contribution of long-range transport to regional air pollution in Northeast China.

Keywords: Smoke; Long-range transport; Eastern Siberia; Northeast China; Air pollution.

INTRODUCTION

Forest fires affect the carbon cycle, climate, and air quality. Particles emitted from forest fires and those formed in their plumes have major radiative effects on climate and contribute to dense continental-scale haze layers. Forest fires contribute 4–12% of the biomass annually burned on the planet (Warneck, 2000). The emissions of black carbon aerosols and organic aerosols as a result of forest fires may account for 9 and 20% of the global emissions, respectively (Conard and Ivanova, 1997). Much attention has been paid to fires in tropical forest and savanna, the main source of emissions of trace gases and particles on the planet. Since the 1990s, fires in the boreal forests in the Northern Hemisphere have been widely studied due to the rapid development in spatio-temporal coverage of fire events by satellite and reliable quantitative estimates of burned areas and combustion emissions. As a result of high combustion temperature of boreal forest fires, substantial combustion products can be transported into the free troposphere that favors their rapid transport over significant distances (Eck et al., 2003). The boreal forest fires were recognized significantly affect the atmospheric composition on both regional and planetary scales (Jaffe et al., 2004).

Two-thirds of the boreal forests are located in Russia. About 43 Mha forests and woodlands were burned in Russia in 2000–2008 and about 90% of which were burned in the Eastern Siberia and the Russian Far East (Vivchar, 2011). Significant spatial and seasonal variations in the large-scale fields of fire emissions were observed by satellite that were determined by the physical, geographic, and climatic features of individual regions (Vivchar et al., 2010). Large-scale biomass burning in boreal forests can contribute to regional and hemispheric air pollution. Seasonal and long-term variations in the chemical composition and radiative properties of the atmosphere on both regional and global scales are affected by the emissions from forest fires in Siberia, for example, significant enhancement in the concentrations of carbon monoxide (CO) and ozone (O$_3$) were episodically observed in western North America as a result of long-range transport of Siberian fire combustion products (Jaffe et al., 2004). Transport of these airmasses
to North America from Siberia was confirmed by aircraft and surface observations, which showed effects of biomass burning on downwind regional air quality and human health.

The objective of this study is to quantify the significant effect of the Siberian forest fires on air quality and column-integrated aerosol optical properties over Northeast China in July 2014. This is the first study, as far as we know, to investigate the impacts of long-range transport of biomass burning aerosols in Eastern Siberia on air quality in Northeast China. Satellite and ground-based data are used to achieve this goal. The paper is organized as follows. The data and method is presented in following section. Section 3 presents major results. Discussion and conclusions are presented in Section 4.

DATA AND METHODS

Satellite Products

The Moderate Resolution Imaging Spectroradiometer (MODIS) is the first spaceborne radiometer developed especially for active fire detection from space. The MODIS active fire products are the result of detection of the temperature and reflectance anomalies of the surface (Kaufman et al., 2007). The MODIS detects fires in 1 km pixels that are burning at the time of overpass under relatively cloud-free conditions using a contextual algorithm (Giglio et al., 2006). The global monthly fire location product (MCD14ML) with confidence of 100% are avaliable online (ftp://fuoco.geog.umd.edu), which are used to reveal spatio-temporal variation of active fires in northeast Asia.

MODIS Collection 6 aerosol optical depth at 550 nm (AOD) product was used to show the spatio-temporal variation of aerosol loading in fire source and downwind regions during a biomass burning episode in July 2014. AOD over land is seperately retrieved by using the dark target regions during a biomass burning episode in July 2014. AOD was calculated from direct spectral irradiance measurement based on the Beer-Lambert Law. The uncertainty of AOD was estimated to be 0.01–0.02 (Eck et al., 1999). Angstrom exponent (AE), an indicator of aerosol size, was calculated from AOD at 440 and 870 nm. Aerosol size distribution and absorption were retrieved from almucantar diffuse spectral sky radiance measurement and AOD at four wavelengths by using a optimized inversion algorithm (Dubovik et al., 2006). The uncertainty of aerosol single scattering albedo was estimated to be within 0.03 for AOD at 440 nm larger than 0.4 (Dubovik and King, 2000).

Black carbon (BC) concentration at Tongyu was made with a model AE-31 aethalometer (Mage Scientific, USA). The aethalometer measured optical attenuation at seven wavelengths (370, 470, 520, 590, 660, 880, and 950 nm) for particles deposited on the quartz-filter. The measurement at 880 nm was used to determine BC concentration as light absorption can be considered to be solely induced by BC at this wavelength. The shadowing effect of increased aerosol loading on the filter was corrected according to Virkkuola et al. (2007). Multi-scattering effect of quartz-filter and deposited aerosols was suggested to be wavelength independent (Weingartner et al., 2003). Thus, the absorption Angstrom exponent (AAE), which defined as the slope of linear regression of absorption coefficients against wavelengths at logarithm scale, was directly derived from the loading corrected BC data at the seven wavelengths of aethalometer.

Hourly PM$_{2.5}$ (particles with aerodynamic diameter less than 2.5 μm) mass concentration (μg m$^{-3}$) at 10 stations in Northeast China from June to August 2014 are available from the data archive of Ministry of Environmental Protection of China (http://datacenter.mep.gov.cn/) (Fig. 1).

RESULTS

The spatio-temporal variation of MODIS active fires during June, July and August in Northeast Asia was presented in Fig. 2. Active fires mainly occurred in Eastern Sebirea, more specific, the first and most important source region during summer is located in 116°–128°E and 60°–65°N. Sporadic active fires are also observed in region # 2 (95°–115°E and 55°–60°N). Very few active fires occurred in Northeast China, region # 3 (120°–130°E and 42°–50°N). Burning of crop residues in Northeast China was frequently detected in early spring and late fall, the harvest season of crops (Xia et al., 2013; Zha et al., 2013). In June, a few active fire points were only observed in late June and most of fires occured in region #2 (the maximum active fire count of 185 occurring on June 28). In August, sporadic fires were observed in Northeast Asia. The most interesting feature in July was that a strong biomass burning episode occurred in region # 1 from middle to late July. The peak active fire counts occurred on July 18 (940 counts) and July 22 (780 counts) in region # 1. Smoke plume during this biomass burning episode (from 22 July to 30 July) was captured by
Fig. 1. Spatial distribution of 10 PM$_{2.5}$ monitoring stations (asterisk) in Northeast China and 2 sunphotometer stations involved in this study (solid dot). The color indicates topography.

Fig. 2. Monthly active fire points detected by the MODIS onboard Terra in June (a), July (b) and August (c) in Northeast Asia as well as daily fire counts in selected regions in summer 2014 (d), including the first region (116°–128°E and 60°–65°N), the second region (95°–115°E and 55°–60°N) and the third region (120°–130°E and 42°–50°N).

The daily MODIS RGB images (produced by using the red, green and blue spectral bands of the MODIS) (Fig. 3). A combination of Geopotential Height and wind speed at 850 hPa (all from the National Center for Environmental Prediction reanalysis) as well as MODIS image clearly suggested the transport of smoke from fire source region to the downwind region. On July 22 and 23, active fires were mainly observed in Eastern Siberia that produced a large smoke layer in the fire source region. The active fire region and Northeast China were mainly located in the west side of a temperate Low (identified by “L” in Fig. 3) in Eastern Siberia. The prevailing wind from the active fire region to Northeast China was northwesterly at 850 hPa, with the wind speed of 8–14 m s$^{-1}$. Convergence and upward airflow in the fire source region was obviously favorable for the transport of smoke aerosols into the free troposphere that thereby favors their rapid transport over significant distances by the prevailing wind in the free troposphere. The smoke layer reached the boundary of Northeast China on July 23. The Low weakened and moved slowly along the south direction from July 22 to July 24. Northwesterly winds prevailed over Northeast China on July 24, which resulted in the extension of the smoke layer to the north of Northeast China. In following two days, Northeast China was controlled by a weak High that was located in the rear of the low mentioned above. The downdraft and weak horizontal winds with velocity of 2–6 m s$^{-1}$ at 850 hPa led to the accumulation of smoke aerosols over Northeast China and
Fig. 3. MODIS RGB images overlapped the geopotential height and wind field at 850 hPa at 6:00GMT during the biomass burning episode (from 22 July to 30 July).

Fig. 4. MODIS RGB images overlapped the geopotential height and wind field at 850 hPa at 6:00GMT during the biomass burning episode (from 22 July to 30 July).

the formation of haze near the ground. Meanwhile, on July 26, the landfall typhoon Matmo moved northward to the north part of Huanghai Sea and turned into a temperate low. Along with the turning of the Low to the northeastern direction and the High sustaining in Northeast China until July 27, the smoke layer in the north of Northeast China slowly extended to the south as a result of northeasterly and easterly winds. After July 27, following another Low moving from Mongolia to Northeast China, southwesterly winds dominated over Northeast China that drove the smoke left completely on 30 July from this area. Although active fires were still observed on 29 July in Eastern Siberia, transport of smoke layer was cut off by the invasion of the temperate Low. The haze over Northeast China dissipated gradually owing to lack of persistent long-range transport of smoke aerosols. Long-range transport of the smoke layer to Northeast China was clearly shown by the back-trajectory analysis. The 5-day backward trajectories at 500 m AGL on 24 July at station # 1 and on 26 at station # 8 were calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) (Stein et al., 2015). Air masses reaching these two stations were mainly from region # 1 where active fires occurred (Fig. 4), indicating that the maximum values of surface PM$_{2.5}$ concentrations were closely related to the long-transport of the smoke layer from Eastern Siberia.

The extension of the smoke layer has be evidenced by the spatial distribution of the MODIS AOD product (Fig. 5), although occasional occurrence of clouds made AOD retrievals not available. The atmosphere was clear (AOD < 0.2) in regions that were not impacted by the smoke, however, AOD in regions impacted by the smoke frequently exceeded 2.0 when the smoke layer moved from north to south. More specific, the north part of Northeast China was nearly completely covered by the smoke layer with AOD values even reaching 3.0 on 24 July. The transport of the smoke layer was also reflected by the spatial-temporal variation of CO (Fig. 6). The peak CO concentration exceeded 5.0 × 10$^{18}$ molec cm$^{-2}$, which was one order of magnitude larger than that observed during an episode of crop residue burning in mid-eastern China (Xia et al., 2013). Trasnport of the smoke plume from north to south was clearly shown by the daily spatial distribution of CO over Northeast Asia. Enhancement of CO on 29 July in Eastern Siberia was consistent with variation of MODIS active fires and AODs, but the synoptic circulation did not favor the long-range transport of smoke layers to Northeast China.

The long-range transport of the smoke layer and its impact on column-integrated aerosol loading and surface aerosol concentration was evidenced by ground-based remote sensing and ambient measurements. AOD at Yakutsk before the biomass burning episode ranged from 0.03 to 0.33 with the mean value of 0.12 ± 0.09 (Fig. 7). This is indicative of a very low background level of AOD in Eastern Siberia.
likely as a result of limited local anthropogenic emissions. AOD dramatically increased to 2.58 ± 0.91 on 24 July and 1.75 ± 0.64 on 26 July when the smoke plume impacted this station. The corresponding daily mean AE was 1.51 and 1.74, respectively, indicating dominant contribution of fine particles to aerosol loading during this biomass burning period. AOD decreased dramatically to the background level (0.06) on 27 July after the smoke air mass moved away from the station. AOD at Tongyu during 1–23 July was generally less than 0.20 except on 15 July, however, an episode of persistently high AOD values occurred in following 10 days, during which daily AOD ranged from 0.55 ± 0.07 on 31 July to 1.99 ± 0.23 on 29 July. The AE values during this period ranged from 1.03 to 1.45, which suggested that high AOD was mainly attributable to fine particles. Significant increase of fine particles during the burning period was clearly shown by size distribution retrievals at two stations (Fig. 8). The volume concentration of fine particles for AOD of 2.3 (radius < 0.6 μm) at both stations reached 0.25 μm³ μm⁻², which accounted for 93% of total concentration. Smoke fine mode particle radius (r_f) at Yakutsk increased from 0.18 μm for AOD of 1.04 to 0.23μm for AOD of 2.22, which was likely indicative of aged smoke and subsequent hygroscopic growth. r_f remained to be ~2.2 μm at Tongyu,
which was close to retrievals at Yakutsk when the maximum AOD was observed. High aerosol loading at Tongyu lagged behind that at Yakutsk. This was likely indication of long-transport of the aged smoke aerosols to Tongyu. Absorption of smoke aerosols was very weak. Single scattering albedo ($\omega$) was ~0.95 and showed little wavelength dependence at both stations. More specific, $\omega$ at Tongyu for AOD of 2.32 reached 0.97. The value is much larger than the climatological mean value of 0.91 at Tongyu (Wu et al., 2015; Xia et al., 2016) and 0.90 at Liaozhong (41.5°N,
120.7°E (Xia, et al., 2007), but close to retrievals of long range transport of boreal forest smoke aerosols (Eck et al., 2003). The surface measurement of BC concentration and AAE at Tongyu, Northeast China, evidenced the long-range transport of the smoke layer from active fire sources (Fig. 9). BC concentration was lower than 0.4 μg m⁻³ on 22 and 23 July, it increased dramatically when the station was covered by the smoke layer on July 24, which was accompanied by an increase of AAE. Both factors indicated that Tongyu was impacted by smoke aerosols. The peak value of BC of 3.5 μg m⁻³ was observed on 26 July, afterwards, BC decreased gradually and reached the background level on 3 August. It should be noted that daily variation of surface BC concentration did not agree with that of column integrated AOD very well. AOD at Tongyu remained to be larger than 1.0 until 30 July when surface BC concentration decreased to 1.0 μg m⁻³. This likely indicated that smoke aerosols were likely in existence at the upper level of the atmosphere, which needs verification by more measurements, for example, aerosol profile measurement by lidar. Significant effect of long-range transport of biomass burning aerosols on air quality in Northeast China was shown in Fig. 10, daily PM₂.₅ concentration during June–August at 10 stations located in Northeast China. At 6 stations located in north of 43°N, most of daily PM₂.₅ concentrations from June 1 to July 23 was less than 75 μg m⁻³, the threshold value for the Grade II level according to the National Ambient Air Quality Standard (NAAQS) of China (GB3095-2012). The mean values ranged from 16 to 32 μg m⁻³, indicating that the background level of surface aerosols in this region was low. However, PM₂.₅ concentrations increased dramatically and exceeded this threshold in following 4–5 days as a result of long-range transport of smoke aerosols from the Eastern Siberia. The peak value ranged from 123 to 190 μg m⁻³ that occurred on 25 or 26 July when the smoke layer swept slowly over this region (Fig. 4). The mean value during this episode side (July 24–July 31) was 3–6 times larger than that from July 1 to 22. PM₂.₅ concentrations dropped to the background level (18–40 μg m⁻³) on August 1–2 when the smoke layer left this region and PM₂.₅ remained relatively stable until to the end of August. Significant impact of long-range transport of smoke aerosols was also evidenced at 4 stations located at about 42°N, although this feature was not outstanding as compared with those stations in north of 43°N. Daily PM₂.₅ concentration on 26 and 27 July exceeded 100 μg m⁻³ at stations located in east of 122°E and south of 42°N, the maximum values observed in this summer, which was closely related to the long-range transport of the smoke layer as suggested by the back trajectory analysis (Fig. 4).

DISCUSSION AND CONCLUSIONS

China suffers from serious air pollution problem in recent tens of years. Regional air pollution events frequently occur in three fast-developing regions, i.e., North China Plain, the Yangtze delta region and the Pearl delta region. Much attention has been paid to air quality and measures have been taken to tackle heavy air pollution in these regions. Regional air pollution events were also reported in Northeast China in recent years. Annual mean AOD at urban regions was larger than 0.4 as a result of a mixture of anthropogenic and natural aerosols (Che et al., 2015; Zhao et al., 2015). Events with BC concentrations > 7 μg m⁻³ were often observed at Tongyu in four seasons, which was suggested to be related to long-range transport of anthropogenic emissions and biomass burning aerosols (Wang et al., 2010; Cheng et al., 2010). Little is still known about the causes...
Fig. 9. Variation of hourly BC mass concentration (red) and absorption angstrom exponent (AAE, black) during the period of 22 July to 10 August 2014. The daily moving average values of BC concentration and AAE are overlapped as the bold lines.

Fig. 10. Daily mean PM$_{2.5}$ concentrations at 10 stations in Northeast China. The biomass burning episode was represented by the grey box.

for the regional air pollution there because research is still very limited. Long-range transport of air pollution should be carefully accounted for before measures are taken to fight regional air pollution in Northeast China. To achieve this goal, surface measurements of aerosol physical, optical and chemical properties in Northeast China should be enhanced, especially, the chemical properties of smoke aerosols should be studied in detail, which can not only provide direct evidence to the long-range transport but also be used to validate model simulations. Satellite-based assessment of long-range transport of anthropogenic and natural aerosols should also be enhanced since it can provide a good spatial coverage.

In this paper, long-range transport of biomass burning aerosols from Eastern Siberia to Northeast China was studied in detail based on satellite remote sensing products, which was enhanced by surface observations. This is to our best knowledge the first time to assess the effect of the long-range transport of smoke aerosols on air quality in Northeast China at a regional scale. Major conclusions are as follows.

Biomass burning in Eastern Siberia emitted huge amounts of aerosols into the atmosphere in the source region. AOD > 2.0 was observed during the peak burning period. Biomass burning aerosols were mainly composed of fine particles and showed very weak absorption. The peak tropospheric CO concentration exceeded $5.0 \times 10^{18}$ molec cm$^{-2}$ during the burning period that was one order of magnitude larger than that observed during an episode of crop residue burning in Mid-eastern China.

Smoke aerosol layer can be transported to Northeast China from Eastern Siberia in a few days under favorable synoptic patterns. The smoke aerosol layer over Northeast
China showed following features: AOD frequently exceeding 1.0, 93% of volume concentration accounted for by fine mode particles, fine mode radius remaining to be 0.23 μm, very weak absorption. Surface PM$_{2.5}$ at stations in Northeast China increased to more than 100 μg m$^{-3}$, which was 3–6 times larger than the background level. As shown in this study, air quality in Northeast China was significantly impacted by the smoke layer from Eastern Siberia, but a few issues still need further study, for example, how often does this effect occur? how to quantitatively assess contribution of long-range transport to air quality in Northeast China? A combination of measurement and model simulation is urgently required. More specific, chemical properties of smoke aerosols, especially chemical tracer to the biomass burning should be measured. Furthermore, vertical profile of smoke is required for the recording of transport processes. Simulations by using weather model coupled with Chemistry, for example, WRF-Chem model, is essential for understanding of potential effects of long-range transport of biomass burning on environment and climate.

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