Asian Journal of Atmospheric Environment
Vol. 10-1, pp. 22-31, March 2016
doi: http://dx.doi.org/10.5572/ajae.2016.10.1.022

ISSN (Online) 2287-1160
ISSN (Print) 1976-6912

Trend Analysis of Wildland Fires and Their Impacts on Atmospheric Environment over East Asia

Sung-Kyun Shin[1)] **and Kwon-Ho Lee**[1),2),*]

[1)]Research Institute for Radiation-Satellite (RIRS), Gangneung-Wonju National University (GWNU), Gangneung 25457, Korea
[2)]Department of Atmospheric and Environmental Sciences (DAES), Gangneung-Wonju National University (GWNU), Gangneung 25457, Korea

*Corresponding author. Tel: +82-33-640-2319, E-mail: kwonho.lee@gmail.com

ABSTRACT

Active fire products from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observation during the 16 years from 2000-2015 were analyzed to estimate spatial and temporal variations of wildland fires over East Asia (region of interest: 20°N-55°N, 100°E-150°E). GLOBCOVER 2009 land cover data were also used to investigate the trend in wildfire occurrence with respect to each land cover type. Statistical analysis showed that the highest number of wildland fires occurred in the evergreen and vegetation covered areas, and strong seasonal variations were found in these areas. Total numbers of fires were 283,683 and 202,543, respectively. In particular, the wildland fires in croplands occurred mainly during summer season and distinguishable increasing trends were found. The correlations between number of wildland fires and air pollutants, such as black carbon, organic matter, and carbon monoxide, were also calculated in order to investigate the intensity of the air pollution caused by the wildland fires. Positive correlation between total column carbon monoxide contents and the occurrence of wildland fire was found. In addition, this correlation was higher than the correlation between fire occurrence and black carbon or organic matter. These results indicate that a significant amount of carbon monoxide originated from the wildland fires and influenced the regional atmospheric environment in East Asia.

Key words: Wildland fire, MODIS, Seasonal/annual trend, Black carbon, Carbon monoxide

1. INTRODUCTION

The wildfire is a significant emission source of air pollutants and is considered to be a parameter for climate change (Ramanathan *et al.*, 2005; Crutzen and Andreae, 1990). For instance, biomass burning can increase the concentrations of carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_X) downwind of the fire (Cheng *et al.*, 1998). These substances are well known to affect Earth's temperature and climate systems by altering their radiative properties (Hauglustaine *et al.*, 1994). Wildfires also have significant effects on human health and regional visibility (Lightly *et al.*, 2000).

East Asia is one of the most substantial natural source regions of wildfire in the world because large forest, vegetation, and cropland regions exist. Monitoring active fires in this region is a challenging task due to the high temporal and spatial variability of the occurrence of wildland fires. However, satellite observation, with its unique features of global observation coverage, high spatial resolution, and continuous operation, is a powerful technique for monitoring wildland fire. It is able to provide detailed information about wildland fire occurrence, extent, and short-term variation, as well as long-term trends. The Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites generates a suite of global active fire products and burned area information (MODIS Level 2 Fire/Thermal data; code names are MOD14 for Terra and MYD14 for Aqua) (Roy *et al.*, 2008; Justice *et al.*, 2002).

In this study, statistical analysis was conducted with MODIS fire products aggregated to a $0.1° \times 0.1°$ grid for the time period from March 2000 to May 2015 in order to estimate the spatio-temporal variations in the occurrence of wildfire over East Asia. Because wildland fires are differently prone to occur in different land cover types, we attempted to determine trends in the occurrence of wildland fire under the different land cover types defined by the GLOBCOVER 2009 land cover data (Sophie *et al.*, 2010). Correlations of wildfire occurrence with air pollutants potentially emitted from the wildland fires were also analyzed to investigate the influence of fire on the atmospheric environment. The main objectives of this study were to investigate the trend of occurrence of wildland fire and the impact of wildland fire on the atmospheric environment through an interdisciplinary analysis using combined satellite and model results. This paper is organized as follows. Section 2 presents the methods used in this study, and section 3 presents the results of the statistical analysis. The conclusions of the study are discussed and finally summarized in section 4.

2. METHODOLOGY

2.1 Data Processing

The annual and seasonal trends in the occurrence of wildland fire and the impacts of air pollutants were analyzed with an interdisciplinary combination of satellite and model data. Fig. 1 shows the overall processes of data analysis used in this study, including satellite data processing, land cover classification, and estimation of the compositions and the amounts of air pollutants. The analytical approach comprised the following steps:

1. Occurrences of wildland fire were counted geospatially from the MODIS data. The accumulated numbers of fire counts were then arranged statistically in order to estimate short-term and long-term trend patterns.
2. The land cover types in East Asia were classified based on the GLOBCOVER 2009 data. The trends of wildland fire occurrence were also determined according to the land cover type.
3. The amounts and compositions of air pollutants caused by wildland fire were estimated by using the Monitoring Atmospheric Composition and Climate (MACC) global air quality service of the European Centre for Medium-Range Weather Forecast (ECMWF) re-analysis data.
4. Finally, a correlation analysis between the wildland fire occurrences and the amount of air pollutants was conducted to investigate the impacts of wildland fire on the regional atmospheric environment. Additional description of each dataset and the processes used follow.

2.2 Satellite Data

Global and regional frequencies of fire occurrence were investigated by using the MODIS satellite dataset. The study area of this research (20°N-55°N, 100°E-150°E), which was selected as the domain for investigation of regional variation in the occurrence of wildfire, is shown in Fig. 2. The daily MOD14 fire and thermal anomaly data for March 2000 to May 2015 were collected from the MODIS web interface of Level 1 and the Atmosphere Archive and Distribution System (LAADS) (available at https://ladsweb.nascom.

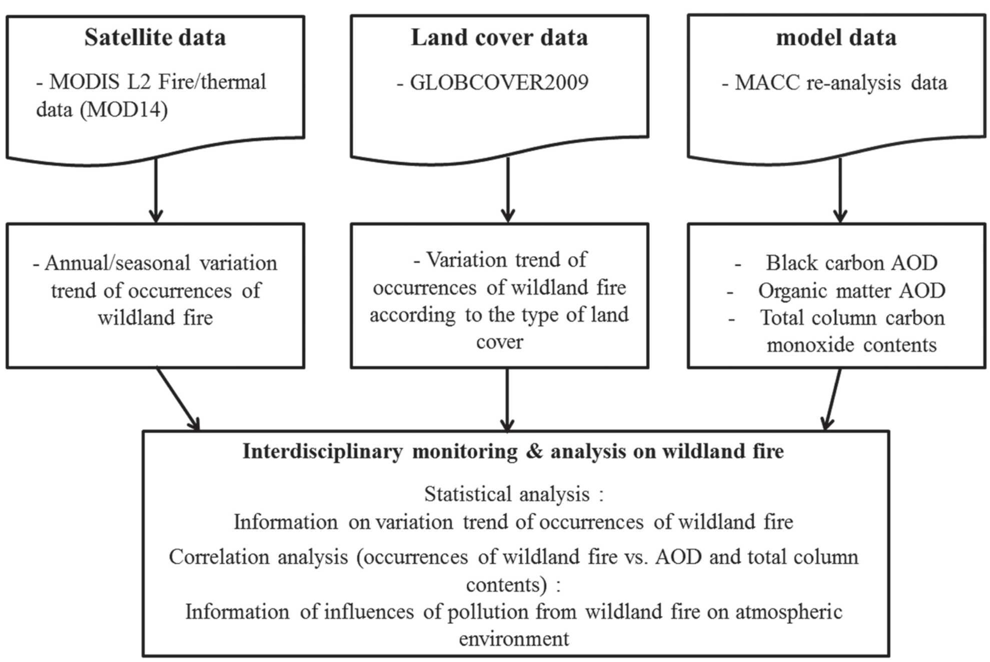

Fig. 1. Schematic workflow diagram for the interdisciplinary analysis on the variation trend and impact of wildland fire on the atmospheric environment.

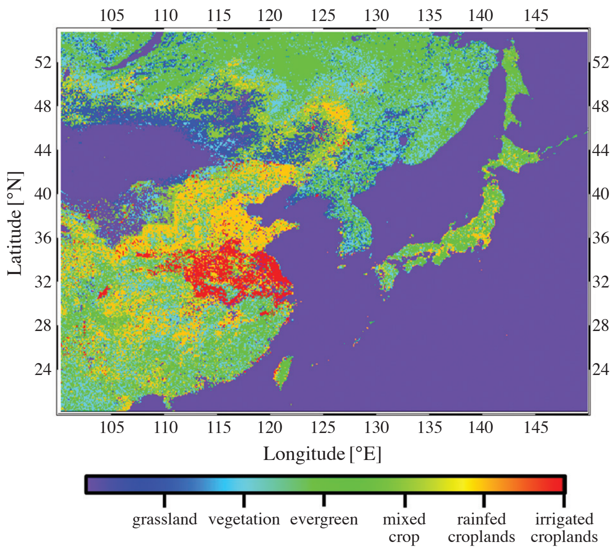

Fig. 2. The six land cover types derived from GLOBCOVER 2009.

nasa.gov/). The fire detection algorithm for MODIS is similar to the algorithm developed for the AVHRR and TRMM VIRS. The brightness temperatures derived from two infrared channels (for instance, the 11 μm and 4 μm channels) are mainly used for this algorithm. There are two types of strategies for fire detections of MODIS: (a) absolute detection, if the fire is strong enough, and (b) relative detection, if the thermal emission is relatively weak. A pixel is rejected if the MODIS channel has a reflectance of more than 30% and it lies within 40 degrees of the specular reflection position for daytime, when sunlight may cause detection error. A detailed description of the algorithm of the MODIS fire product is given in Justice *et al.* (2002).

2.3 Land Cover Data

GLOBCOVER 2009 data (available from http://due.esrin.esa.int/files/Globcover2009_V2.3_Global_.zip) (Sophie *et al.*, 2010) were used to identify the land cover types in East Asia in order to investigate the difference in trend of wildland fire occurrence according to different land cover types. The GLOBCOVER 2009 data were constructed and coordinated by the European Space Agency (ESA). Thirteen multispectral input data with 300 m spatial resolution were recorded by the Medium Resolution Imaging Spectrometer (MERIS) instrument aboard the European Environmental Satellite (ENVISAT). It provided information on global land cover with 22 informational classes (Di Gregorio *et al.*, 2000).

In this study, we simplified the land cover types in East Asia into six classes (e.g., grassland, vegetation, evergreen, mixed crop, rain-fed cropland, and irrigated cropland). The trend of wildland fire occurrence was investigated according to each of these classes. The land cover map that was used in this study is shown in Fig. 2.

2.4 Air Quality Model Data

The MACC data provide reanalysis data for global atmospheric composition, including the major air pollutants. The MACC model can be downloaded at the web page of the ECMWF (http://apps.ecmwf.int/datasets/data/macc-reanlysis/). These reanalysis model data based on an assimilation of satellite-observed air pollutants are operationally corrected by a global model departed from integrated observation data (Bellouin *et al.*, 2013; Inness *et al.*, 2013). At present, MACC reanalysis data are available only from 2003-2012. The reanalysis data provide aerosol optical depth (AOD) of various aerosols such as mineral dust, black carbon, and organic and total columnar trace gases contents. Total AOD (τ_{Tot}), black carbon AOD (τ_{BC}), organic matter AOD (τ_{OM}), and total column carbon monoxide content (CO) from the MACC reanalysis data were used to determine the variation of air pollutants. These parameters could be emitted from wildland fire, and the correlations between these parameters and the variations of wildland fire were investigated in order to estimate the influences of wildland fire events on the atmospheric environment.

3. RESULTS

3.1 Temporal Variation of Wildland Fires

During the 16 years of MODIS observation, wildland fire occurrences were counted over the study area shown in Fig. 2. These wildland fires were detected on the basis of MODIS satellite observation with the fire detection algorithm, as described in section 2.1. Fig. 3 shows time series of fire counts by monthly occurrence for wildland fires in the world and in East Asia during 2000-2015 (May). The proportion of wildland fire count in East Asia to the count in the world is also presented in Fig. 3. At the global scale, the wildfire occurrence series shows two distinct peaks, the first occurring in 2002 and the second occurring in 2003. The occurrences of wildfire in 2004, 2009, and 2010 are lower than those of 2002 and 2003, although the trend in occurrence of wildland fire varies with respect to each corresponding time series.

At the regional scale, the wildland fire occurrences in East Asia differ slightly from the trend of occurrence around the world. In general, the occurrences of wildland fire in East Asia were lower than the global occur-

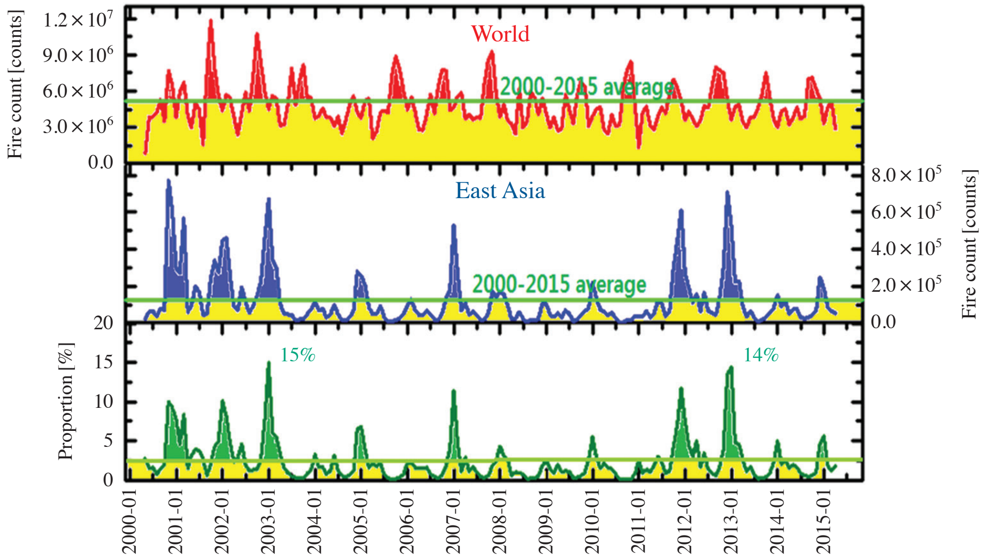

Fig. 3. Time series of the occurrence of wildland fire around the world (red), in East Asia (20°N-55°N, 110°E-150°E) (blue), and proportion of the occurrence of wildland fire in East Asia to that for the world (olive) during 2000-current (May 2015). The green solid lines indicate the average values, respectively, during 2000-2015.

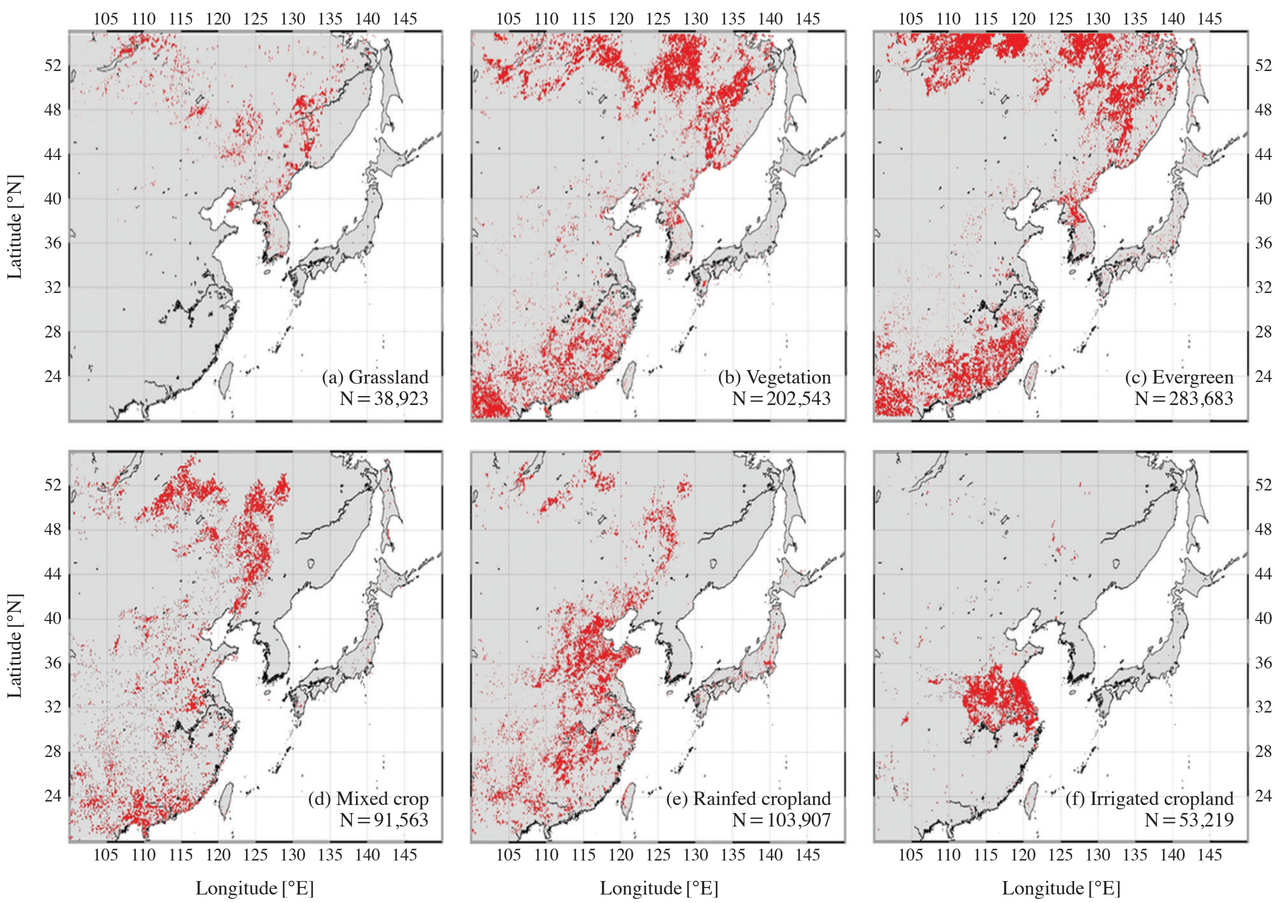

Fig. 4. Occurrence of wildfire in each classified land cover type during 2000-current (May 2015). (a) grassland, (b) vegetation, (c) evergreen, (d) mixed cropland, (e) rain-fed cropland, and (f) irrigated cropland.

rences. However, East Asian wildland fires occurred remarkably in the middle of 2000-2003, 2007, and 2012-2013. The number of wildland fires in East Asia in these years accounts for more than 10% of the contribution to the global occurrence record. It is clear that the occurrences of wildfire were varied with respect to time and space. Nevertheless, it is difficult to identify a distinguishable long-term trend in wildland fire occurrence.

3.2 Variation of Wildland Fire According to Land Cover Type

We analyzed the occurrence of wildfire in East Asia separately according to each land cover type. Fig. 4 shows the distribution of wildfire occurrences for each land cover type in East Asia during 2000-May 2005. The wildfire occurrences corresponding to each individual land cover type are also summarized in Table 1.

The number of wildland fire occurrences differed according to land cover type. The most frequent occurrences were recorded for the land cover types of evergreen and vegetation because the total areas of evergreen and vegetation are widely distributed in East Asia. The number of wildland fire occurrences in evergreen and vegetation areas was 283,683 and 202,543, respectively. The higher occurrences of wildland fire in these areas are caused by the large amount of fuel. There are sufficient sources of burnable materials, including trees, plants, bushes, etc. Although the occurrences of wildfire in cropland areas were lower than those in the evergreen/vegetation areas, the number of occurrences of wildland fire in cropland areas was distinguishably higher than the number of occurrences in grassland areas. Field burning of crop straw after harvest in rural agricultural regions and pre-urban areas of China could be responsible for this result.

Fig. 5 shows the annual wildland fire count in East

Table 1. Number of fire occurrences by land cover type during 2000-current (May 2015) over East Asia.

Land cover type	Number of fire occurrences
Grassland	38,923
Vegetation	202,543
Evergreen	283,683
Mixed crop	91,563
Rainfed cropland	103,907
Irrigated cropland	53,219

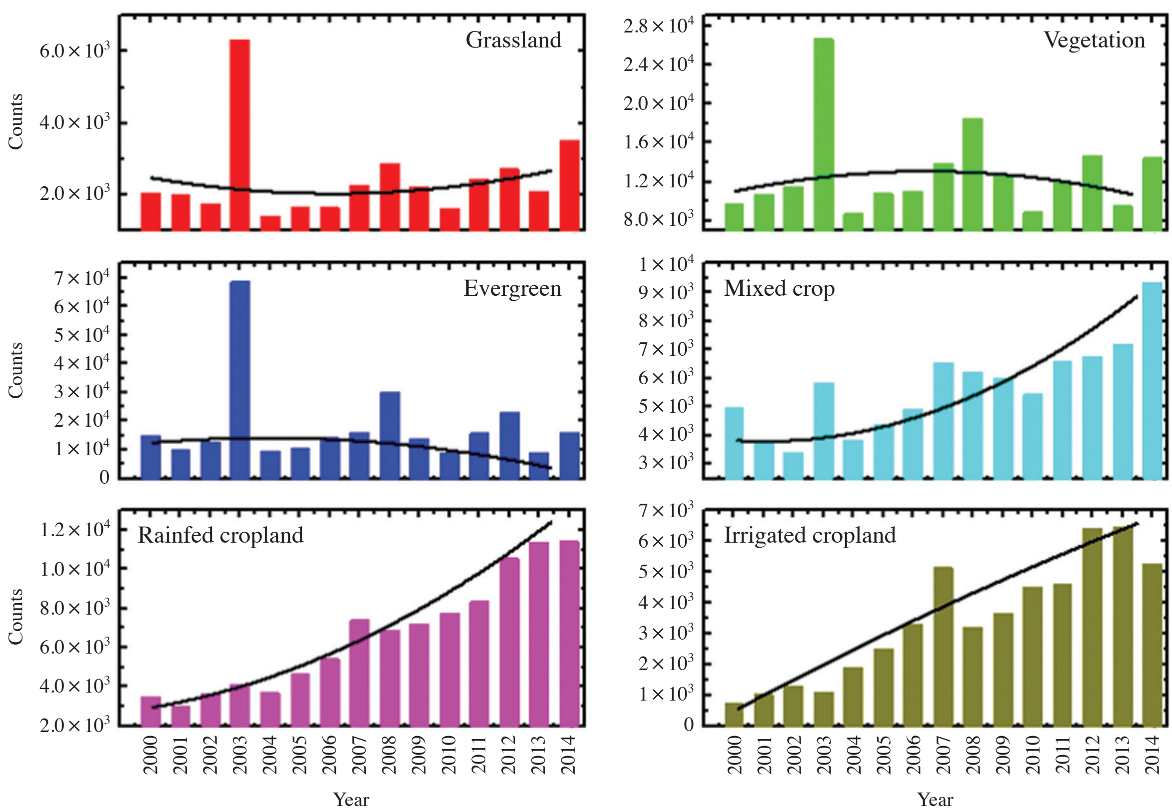

Fig. 5. Annual variation of wildland fire in each classified land cover type in East Asia during 2000 to current (May 2015). The polynomial fitted line is also shown as the black solid line.

Asia during 2000-May 2015 for each land cover type. For the grassland, vegetation, and evergreen land cover types, wildland fires were maximum in 2003. Then, the frequency of wildfire occurrence decreased from 2004 but increased again in 2008 as a second peak. The frequency of wildland fire occurrence also increased from 2012. The figure clearly shows an increasing trend of wildland fire occurrence for cropland. The occurrence of wildfire in cropland areas increased continuously since 2004, although the values varied slightly with respect to the different time series. It is believed that cropland areas have increased with the growth of the agricultural industry in China. Wildfires in cropland following harvest were directly linked to this increasing trend of wildfire occurrence. For instance, Streets *et al.* (2003) reported that approximately 122 Tg of crop residues are burned annually in China and this amount has increased steadily.

We also investigated the seasonal variation of wildland fire according the classification of land cover type. Fig. 6 shows the variation of wildland fire occurrence with respect to season for each land cover type. For the grassland, vegetation, and evergreen land cover types, wildland fire occurred most frequently in the spring season. It is well known that brush fires are much more common in spring because of the combination of high wind and low humidity. The higher numbers of occurrences of wildfire in the regions classified as grassland, vegetation, and evergreen are in good agreement with this climatic circumstance. However, the occurrence of wildland fire in cropland areas showed a different seasonal trend. In the case of wildland fire in the rain-fed cropland and irrigated cropland areas, wildland fire occurred most frequently in the summer season. We initially assumed that the occurrence of wildland fire would be less in the summer season because of meteorological condition such as summer monsoon and high humidity during the summer season. Wheat is the most widely cultivated crop in East China (e.g., Hebei, Henan, Shandong, and Anhui provinces), and the wheat is sown around mid-October and reaped at the end of May or the beginning of June. In June, after the harvest, the straw of the wheat is burned (Huang *et al*., 2012). This opposite trend may be attributable to the crop residue fires set in June in East China.

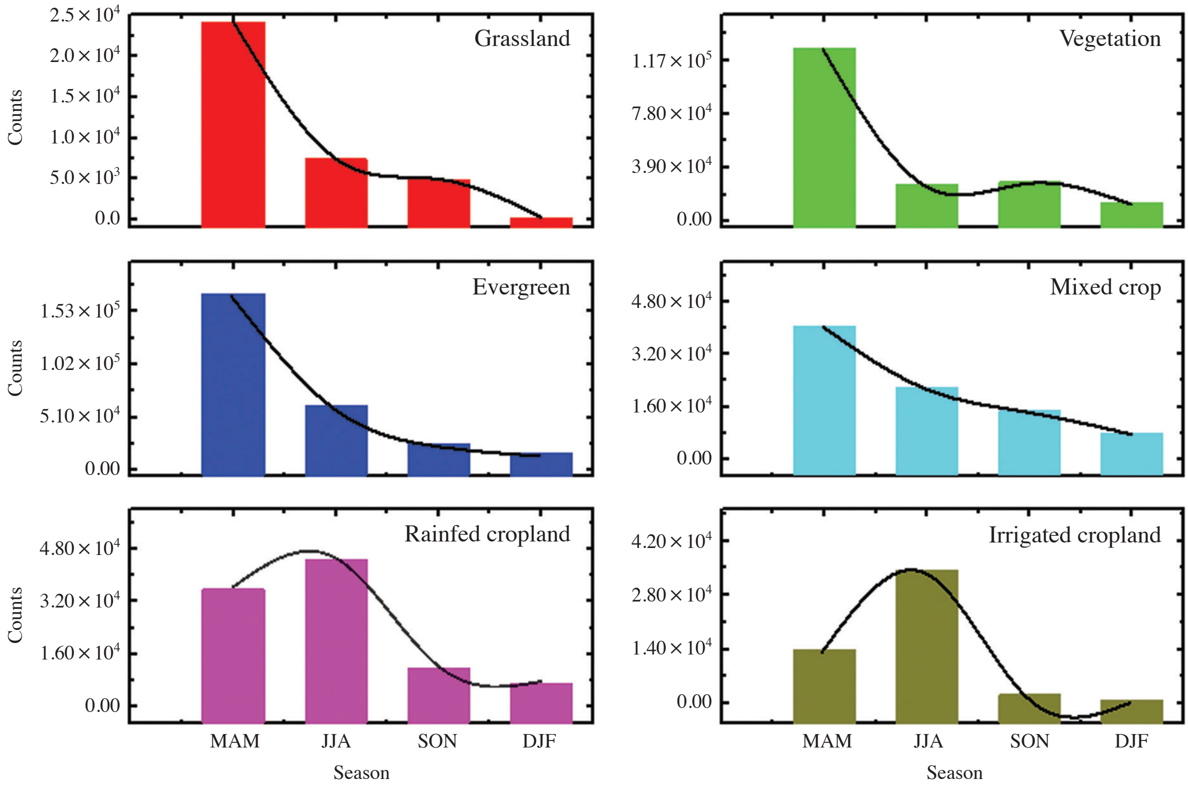

Fig. 6. Seasonal variation of wildland fire in each classified land cover type in East Asia during 2000 to current (May 2015). MAM (March to May), JJA (July to August), SON (September to November), and DJF (December to February) indicate the spring, summer, fall, and winter season, respectively.

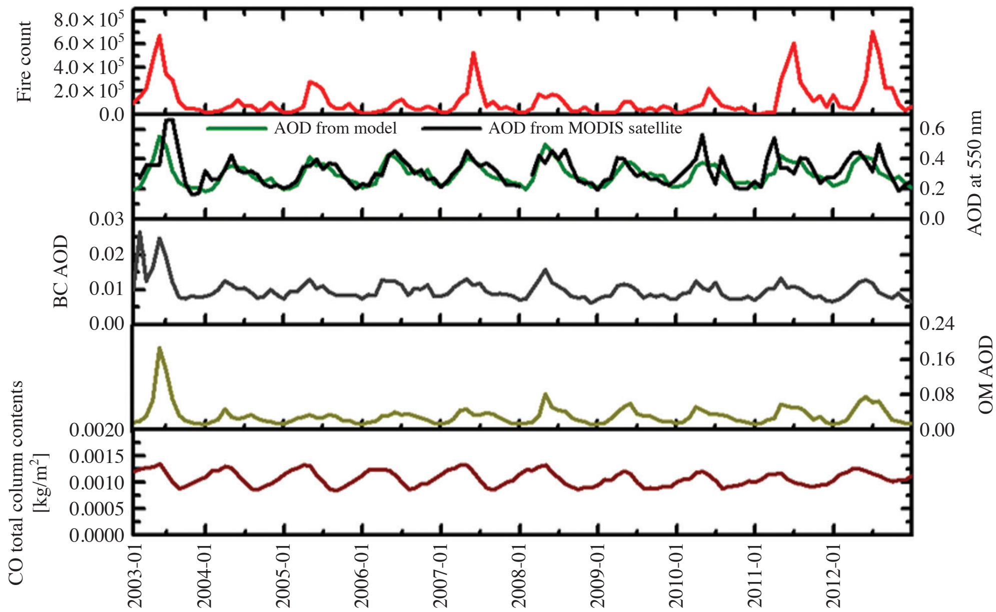

Fig. 7. Annual variation of the occurrence of wildland fire along with total, black carbon, and organic matter AOD at 550 nm and total columnar carbon monoxide content.

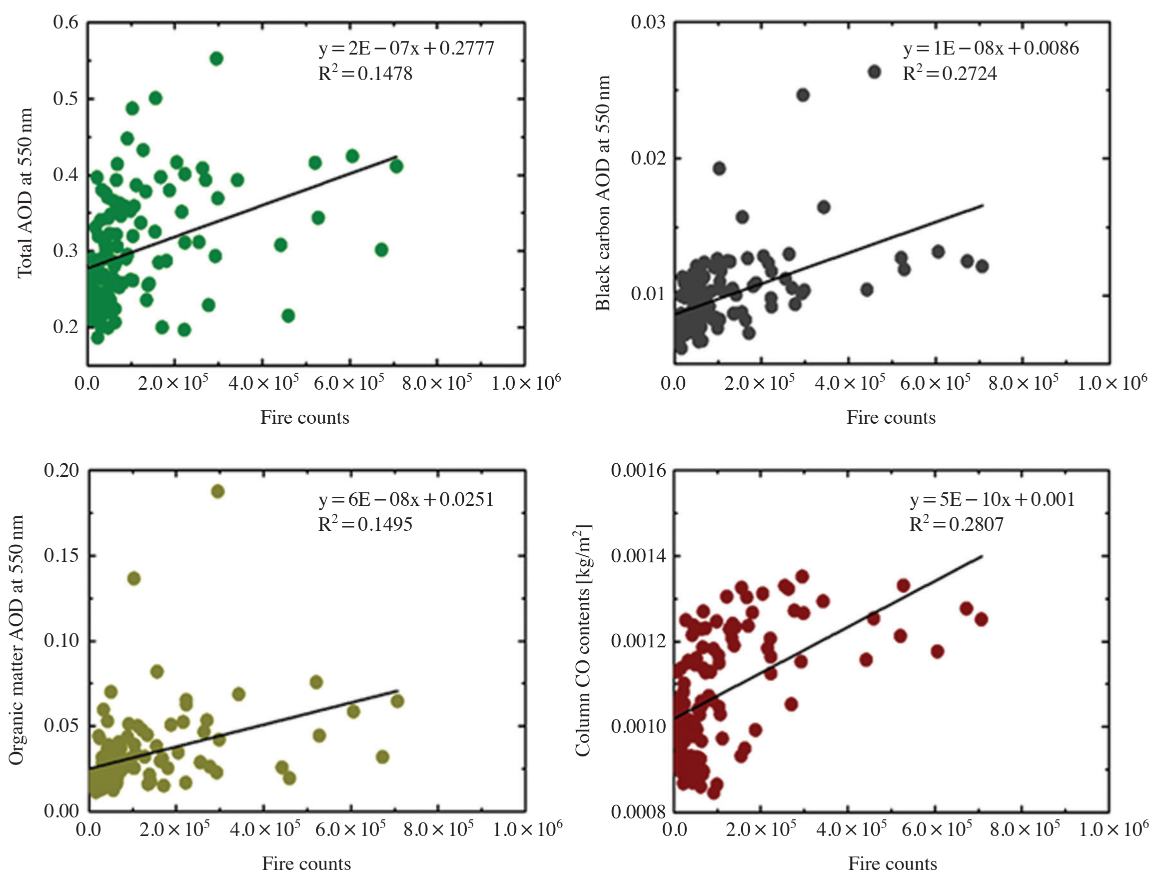

Fig. 8. Correlation between the occurrence of wildland fire and the AODs and the columnar CO content.

3.3 Influence of Wildland Fires on Atmospheric Environment

Fig. 7 shows the annual variation of the occurrence of wildland fire and the τ_{Tot}, τ_{BC}, τ_{OM}, and CO during the same period. The correlations between wildfire occurrences and the AOD of each aerosol and the total columnar carbon monoxide content also are revealed in this figure and were used to investigate the relation between the increment of wildland fire occurrence and the amount of air pollutants emitted from wildland fires.

The annual variation of wildland fire is relatively well matched to the annual variations of the AOD of each aerosol and the total columnar carbon monoxide content. The τ_{Tot}, τ_{BC}, τ_{OM}, and CO were highest in 2003, and the occurrence number of wildfire was also high in this year. It is considered that significant amounts of atmospheric pollutants were emitted from wildfire, and this is reflected in the increments of the atmospheric pollutants. The positive correlation of the occurrence of wildfire with the AOD and the columnar carbon monoxide contents indicates the impact of wildland fire on the atmospheric environment. Atmospheric pollution is increased with the occurrence of wildland fire, which is one source of emission of the atmospheric pollutants. As a result, the values of τ_{BC}, τ_{OM}, and CO were all increased.

Wildland fire is significantly linked to the atmospheric environment. The correlations between wildfire occurrence and the values of AOD differed with respect to the different types of aerosols, although we did not find significant correlation between wildland fire occurrences and AOD (see Fig. 8). The correlation of wildfire with τ_{Tot} was relatively weak. This weak correlation ($R^2=0.1478$) is considered to be due to the fact that the τ_{Tot} reflected not only the amount of air pollutants emitted from wildland fire but also the amounts of various atmospheric pollutants emitted from anthropogenic activities, such as industry and automobiles, and natural sources. The correlation of wildland

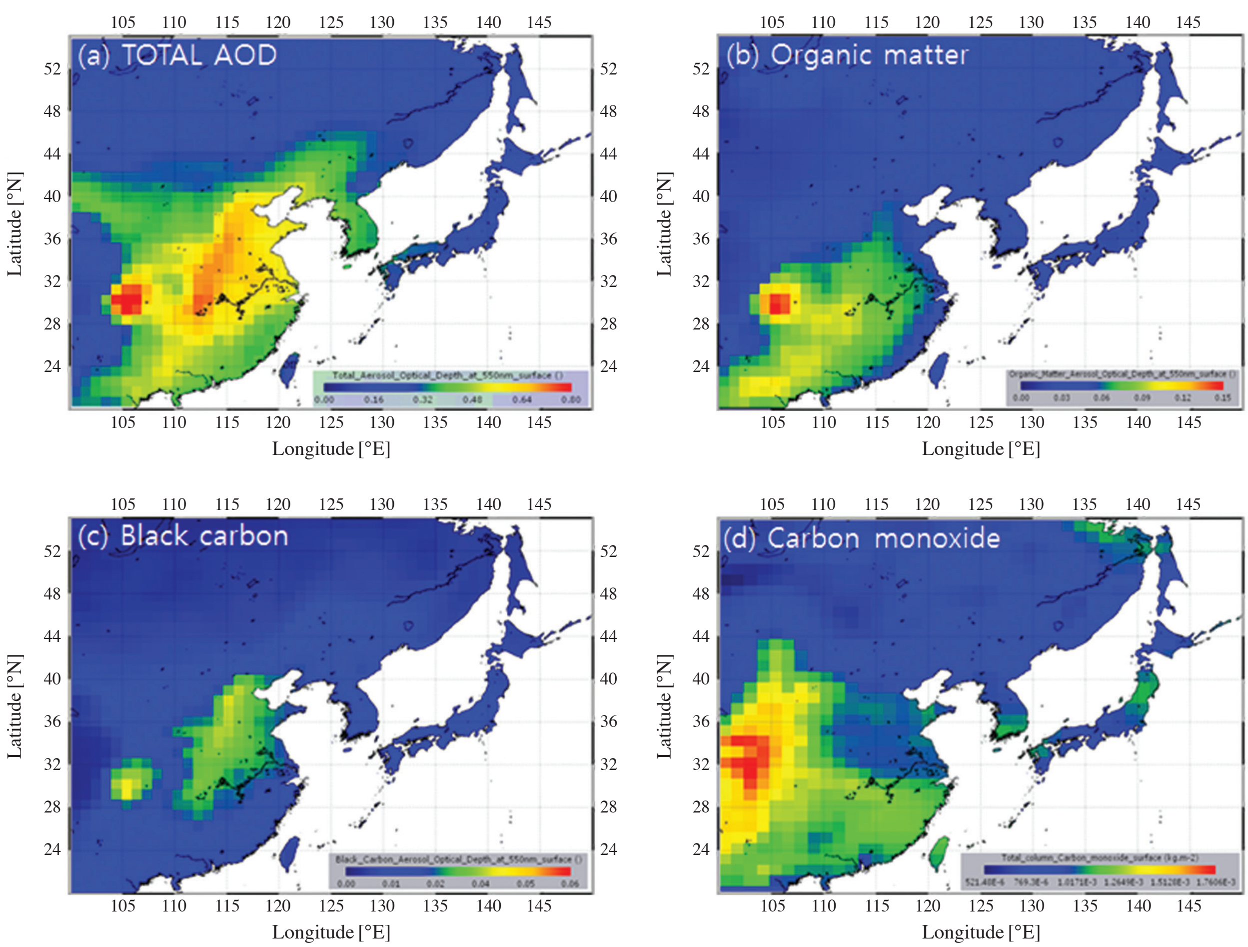

Fig. 9. Distribution of mean AOD for total, black carbon, and organic matter aerosol at 550 nm and total columnar carbon monoxide during 2003-2012.

fire with τ_{BC} is relatively better than that for τ_{Tot}. The correlation coefficient for this case was 0.2724. This better correlation between τ_{BC} and wildfire is considered to reflect that the emission of black carbon is significantly related with wildfire. Wildland fire is well known to be a main source of black carbon deposition in such plumes. A better correlation between occurrence of wildland fire and CO also resulted ($R^2=0.2807$) because carbon monoxide is also a well-known emission from burning.

The spatial distributions of the mean AOD values during 2003-2013 are shown in Fig. 9. Higher AOD is distributed mostly over the industrialized/densely polluted regions of China. It is clear that the emission of atmospheric pollution over East Asia is determined mainly by other sources. The poor correlations between wildland fire occurrence and pollution computed by the MACC model were likely caused by the effect of emissions of atmospheric pollution from other sources. We believe that it is necessary to assess atmospheric pollution with respect to each corresponding wildland fire event in order to more accurately investigate the influences of wildland fire on the atmospheric environment.

4. SUMMARY AND CONCLUSION

In this study, the trend of East Asian wildland fires was constructed from historical satellite observation records for the period from 2000 to 2015, and the frequency of fire occurrences was analyzed by using the MODIS dataset. The results from this trend analysis showed that the wildland fires were controlled mainly by land cover type on quasi-seasonal timescales. When the total counts in East Asia were compared to the total fire counts globally, a greater than 10% ratio between the two scaled data was found.

The highest frequencies were found for the evergreen and vegetation land cover types, 283,683 and 202,543 occurrences, respectively. For these land cover types, wildland fire occurred most frequently in the spring season. Increasing trends in wildland fire were found for cropland. Wildland fires in the rain-fed cropland and irrigated cropland areas occurred mostly in summer season. The agricultural burning activities following harvest in China (which usually occurred in early June) influenced this increment of increase of wildfire in cropland areas.

When we compared the variations of wildland fire with those of the air pollutants examined, the annual trends of AOD and CO were similar to the trend of fire occurrence. The correlation between wildland fire occurrence and τ_{BC} was better than those for the other types of aerosols. A higher correlation between wildland fire occurrence and CO was also confirmed, and wildland fire events are suspected to be the most important source of emission of black carbon and CO. The aforementioned results can be used as worthwhile information for assessment of the effects of strong emissions from wildfires on the atmospheric environment and on climate change.

ACKNOWLEDGEMENT

This work was funded by the Korea Meteorological Administration Research and Development Program under Grant KMIPA2015-2012.

REFERENCES

Bellouin, N., Quaas, J., Morcrette, J.-J., Boucher, O. (2013) Estimates of aerosol radiative forcing from the MACC re-analysis. Atmospheric Chemistry and Physics 13, 2045-2062, doi:10.5194/acp-13-2045-2013.

Cheng, L., McDonald, K.M., Angle, R.P., Sandhu, H.S. (1998) Forest fire enhanced photochemical air pollution. A case study. Atmospheric Environment 32(4), 673-681.

Crutzen, P.J., Andreae, M.O. (1990) Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 250(4988), 1669-1678.

Di Gregorio, A., Jansen, L.J. (2000) Land cover classification system (LCCS): classification concepts and user manual for software version 1.0. FAO, 2000.

Hauglustaine, D.A., Granier, C., Brasseur, G.P., Mégie, G. (1994) The importance of atmospheric chemistry in the calculation of radiative forcing on the climate system. Journal of Geophysical Research 99(D1), 1173-1186, doi:10.1029/93JD02987.

Huang, X., Li, M., Li, J., Song, Y. (2012) A high-resolution emission inventory of crop burning in fields in China based on MODIS Thermal Anomalies/Fire products. Atmospheric Environment 50, 9-15, http://dx.doi.org/10.1016/j.atmosenv.2012.01.017

Inness, A., Baier, F., Benedetti, A., Bouarar, I., Chabrillat, S., Clark, H., Clerbaux, C., Coheur, P., Engelen, R.J., Errera, Q., Flemming, J., George, M., Granier, C., Hadji-Lazaro, J., Huijnen, V., Hurtmans, D., Jones, L., Kaiser, J.W., Kapsomenakis, J., Lefever, K., Leitão, J., Razinger, M., Richter, A., Schultz, M.G., Simmons, A.J., Suttie, M., Stein, O., Thépaut, J.-N., Thouret, V., Vrekoussis, M., Zerefos, C., the MACC team (2013) The MACC reanalysis: an 8 yr data set of atmospheric composition. Atmospheric Chemistry and Physics 13, 4073-4109, doi:10.5194/acp-13-4073-2013.

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F., Kaufman, Y. (2002) The MODIS fire products. Remote Sensing of Environment 83(1-2), 244-262, http://dx.doi.org/10.1016/S0034-4257(02)00076-7

Lighty, J.S., Veranth, J.M., Sarofim, A.F. (2000) Combustion Aerosols: Factors Governing Their Size and Composition and Implications to Human Health. Journal of the Air & Waste Management Association 50(9), 1565-1618.

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J.T., Washington, W.M., Fu, Q., Sikka, D.R., Wild, M. (2005) Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle. Proceedings of National Academy of Sciences of the United States of America 102, 5326-5333.

Roy, D.P., Boschetti, L., Justice, C.O., Ju, J. (2008) The collection 5 MODIS burned area product - Global evaluation by comparison with the MODIS active fire product. Remote Sensing of Environment 112(9), 3690-3707, http://dx.doi.org/10.1016/j.rse.2008.05.013

Sophie, B., Pierre, D., Eric, V.B. (2010) GLOBCOVER 2009 Products Description and Validation Report. ESA, 2010.

Street, D.G., Bond, T.C., Carmichael, G.R., Fernandes, S.D., Fu, Q., He, D., Kilmont, Z., Nelson, S.M., Tsai, N.Y., Wang, M.Q., Woo, J.-H., Yarber, K.F. (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. Journal of Geophysical Research 108, 8809, doi:10.1029/2002JD003093, D21.

(Received 9 December 2015, revised 19 December 2015, accepted 21 December 2015)