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A new emission inventory for nonagricultural open fires in Asia from 2000 to 2009

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Abstract

Open fires play a significant role in atmospheric pollution and climatic change. This work aims to develop an emission inventory for nonagricultural open fires in Asia using the newly released MODIS (Moderate Resolution Imaging Spectroradiometer) burned area product (MCD45A1), as the MODIS sensor cannot efficiently detect field crop residue burning. Country-level or province-specific biomass density data were used as fuel loads. Moisture contents were taken into account when calculating combustion factors for grass fuel. During the nine fire years 2000–2008, both burned areas and fire emissions clearly presented spatial and seasonal variations. Extensive nonagricultural open fires were concentrated in the months of February and March, while another peak was between August and October. Indonesia was the most important contributor to fire emission, which was largely attributable to peat burning. Myanmar, India, and Cambodia together contributed approximately half of the total burned area and emission. The annual emissions for CO₂, CO, CH₄, NMHCs, NOₓ, NH₃, SO₂, BC, OC, PM₂.₅, and PM₁₀ were 83 (69–103), 6.1 (4.6–8.2), 0.38 (0.24–0.57), 0.64 (0.36–1.0), 0.085 (0.074–0.10), 0.31 (0.17–0.48), 0.030 (0.024–0.037), 0.27 (0.22–0.33), 2.0 (1.6–2.6), and 2.2 (1.7–2.9) Tg yr⁻¹, respectively. This inventory has a daily temporal resolution and 500 m spatial resolution, and covers a long period, from April 2000 to February 2009. It could be used in global and regional air quality modeling.

Keywords: Asia, MCD45A1, burned area, fire emission

Online supplementary data available from stacks.iop.org/ERL/5/014014/mmedia

1. Introduction

Biomass burning has a huge influence on the atmospheric environment and a reliable emission inventory is in great demand for atmospheric chemistry and transport simulation. Burned area, fuel load, the combustion factor and the emission factor are the key parameters in estimating fire emissions (Seiler and Crutzen 1980). Previous studies calculating open fire emissions in Asia have some weaknesses, such as using official statistics or fire count data as a proxy for actual burned areas (Duncan et al 2003, Streets et al 2003), relying on a uniform fuel load across different countries (Michel et al 2005), or being limited in time (Ito and Penner 2004). The burning emission inventory of Streets et al (2003) (available at www.cgrer.uiowa.edu/EMISSION_DATA>New) has been widely used in air quality modeling (Hakami et al 2005, Fu et al 2007, Lin et al 2008). This inventory was developed on the basis of a variety of statistical data for the 1950s–1990s, and the total emissions were spatially distributed at 1° using AVHRR fire counts to produce the gridded data set. The data employed in that work are dated, as the burning activities in Asia have changed significantly, especially during the last two decades.

¹ Authors to whom any correspondence should be addressed.
debris (CWD) and soil organic carbon (SOC). We fully considered the geographical variation when employing above ground biomass density data. The living biomass densities in the large countries, i.e. China and India, were on a provincial or state basis (see supplementary data table S1 available at stacks.iop.org/ERL/5/014014/mmedia). In other regions, country-level biomass density data were used (see supplementary data table S1 available at stacks.iop.org/ERL/5/014014/mmedia). The mass of CWD and litterfall for different land covers were included in the overall above ground fuel load (Harmon and Hua 1991, Liu et al 2003, Chhabra and Dadhwal 2004). The World Reference Base (WRB) Map of World Soil Resources (FAO 2003) was utilized to determine the distribution of SOC (referred to as histosols, HS; figure 1). A mean value of 63.65 kg C m$^{-2}$ (Shimada et al 2000) and a single average of 51 cm (Page et al 2002) were applied as the SOC density and burn depth in Asian peatland.

The biomass density data were assigned by vegetation type, as defined by the 300 m European Space Agency (ESA) GlobCover land cover product (available at http://ionia1.esrin.esa.int/index.asp). We grouped the 43 vegetation classes for Asia in the GlobCover product (Bicheron et al 2008) into five broad types: forest (including broadleaf evergreen, broadleaf deciduous, needleleaf evergreen, needleleaf deciduous, and mixed forest), shrubland (including broadleaved or needleleaved, evergreen and deciduous shrubland), grassland (including close, open grassland, mosaic vegetation, sparse vegetation), cropland (including post-flooding or irrigated croplands, rainfed croplands, and mosaic cropland/vegetation) and other (including bare areas, water bodies, snow and ice, artificial surfaces and associated areas). The MODIS Vegetation Continuous Fields product (VCF, 500 m resolution) was applied to apportion the proportions of vegetative cover types: woody vegetation, herbaceous vegetation, and bare ground (Hansen et al 2003).

Fuel moisture was taken into account in calculating CFs for grass fuel (Hoffa et al 1999, Ito and Penner 2005), while CF for each coarse fuel type (living woody biomass and CWD) was assigned an average value (French et al 2002, Kasischke and Bruhwiler 2002, Ito and Penner 2004). The EFs are strongly influenced by vegetation type, fuel moisture, and combustion condition (e.g. flaming versus smoldering fires) (Hoffa et al 1999). Because of the paucity of available information on the effects of fuel moisture and combustion condition on EFs, we used the EF values published in previous studies for each land cover type and for each species (see supplementary data table S2 available at stacks.iop.org/ERL/5/014014/mmedia).

3. Results and discussion

3.1. MCD45A1 burned areas

As shown in table 1, the annual mean MCD45A1 burned area over the fire years 2000–2008 was 105,681 km$^{2}$ yr$^{-1}$. India, Myanmar, Cambodia, China, and Mongolia were the major contributors: 33%, 16%, 11%, 11%, and 11%.

More recently, the multi-year MODIS burned area product (MCD45A1) at a medium resolution (500 m) has become available (Roy et al 2008). It has been validated by Roy and Boschetti (2009) for southern Africa for a fire season in 2001 using Landsat ETM + data. Validation results suggested that MCD45A1 has a relatively high accuracy, capturing 75% of the true area burned. Chang and Song (2009) compared the MCD45A1 burned areas to independent reference data for several major burning regions (Canada, USA, Russia, and China), and found it to be reliable, especially for boreal forest regions. Song et al (2009) has calculated the emissions from the above ground living biomass, fine litter, coarse woody

Table 1. Summary of annual mean burned areas (km² yr⁻¹) for each vegetation type.

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Forest</th>
<th>Shrubland</th>
<th>Grassland</th>
<th>Cropland</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burned area</td>
<td>13,638</td>
<td>7,201</td>
<td>18,064</td>
<td>65,921</td>
<td>857</td>
<td>105,681</td>
</tr>
</tbody>
</table>

of the total, respectively. Although Indonesia was an important burning region in Asia (Page et al 2002), the burned area only accounted for about 2% of the total amount. The primary vegetation class burned was cropland (65,921 km² yr⁻¹), which accounted for 62% of the total burned area. The averaged annual burned areas in forest, shrubland, and grassland were 13,638 (13%), 7,201 (7%), and 18,064 (17%) km² yr⁻¹, respectively. In addition, the burned area observed in the peatland area was 247 km² yr⁻¹, almost all of which was in Indonesia. One peak month in the burned area was in February or March, which is the typical fire season for the primary contributors, i.e. India, Myanmar, Thailand, and Cambodia. Another peak month occurred in October, when Indonesia and Malaysia regions see extensive burning practices (Duncan et al 2003).

3.2. Nonagricultural open fire emissions

As described in section 3.1, the cropland burned area was estimated to be 62% of the total. However, the MCD45A1 product significantly underestimated the crop residue burning because the MODIS sensor, with a medium resolution of 500 m, cannot efficiently capture the field crop residue burning which is mostly small in extent in Asia (Roy et al 2008). The estimated emissions from cropland fires in our study were 39 Tg CO₂ yr⁻¹, 2.7 Tg CO yr⁻¹, 0.18 Tg CH₄ yr⁻¹, 0.012 Tg BC yr⁻¹, and 0.12 Tg OC yr⁻¹. These were only 10% of the results given in Streets et al (2003) which calculated the crop residue burning emissions by using country-specific statistical data (www.cgerer.uiowa.edu/EMISSION_DATA_new). The small amount of agricultural burning emissions derived from MCD45A1 also proved that most of crop residue burning could not be mapped by the MODIS sensor. Consequently, only nonagricultural open fire emissions are discussed in this section.

The fire emissions for nonagricultural land cover regions during the fire years 2000–2008 are presented in table 2. The averaged annual amounts of CO₂, CO, CH₄, NMHC, NOₓ, NH₃, SO₂, BC, OC, PM₂.₅, and PM₁₀ emissions were 83, 6.1, 0.38, 0.64, 0.085, 0.31, 0.030, 0.023, 0.27, 2.0, and 2.2 Tg yr⁻¹, respectively. CO was used as an illustrative example in this work as it was widely studied in the open fire emission modeling (Streets et al 2003). Fire emissions were primarily concentrated in forested system, with an average of 3.2 Tg CO yr⁻¹ (53%). This was because of the high biomass density for forest. The annual mean CO emissions caused by shrubland and grassland fires were 1.7 (28%) and 1.2 (19%) Tg yr⁻¹, respectively. From the emission inventory of Streets et al (2003), the CO emissions from forest and savanna/grasslands regions were 35 and 10 Tg yr⁻¹ (www.cgerer.uiowa.edu/EMISSION_DATA_new), which were eleven and three times our results respectively. The data used in Streets et al (2003) were for the 1950s–1990s. For example, 1950–1992 forest fire data for China, 1987–1991 data for the Republic of Korea, and 1960–1997 data for Mongolia were used. The data from Hao and Liu (1994) for the mid-1970s were used for the countries in South and Southeast Asia. Most of wildland fires in Asia were caused by human practices. Recently, realizing the severe environmental pollution, health problems, and economic and ecological loss caused by fires, many governments have made great efforts to control wildfires through law enforcement, financial investment, publicity and education (e.g. in India—refer to Bahuguna (1999); in Thailand—refer to Akaakara (2002); in Indonesia—refer to Goldammer and Hoffmann (2002); in China—refer to Wang et al (2007)). According to the official sources (e.g. Forest Fire Control Division, Thailand; Chinese Forestry Yearbook), the wildfire occurrence in Asian countries has decreased sharply especially in the last two decades. Although the statistical data may underestimate the fire occurrence because of political intervention and practical difficulties, the decreasing trend was clear. Therefore, the emission inventory in Streets et al (2003) reflected the open fire status in the 1990s, which cannot represent the situation for the last decade.

Table 3 shows that most fire emissions originated in Indonesia, a region responsible for 41% of total CO emission, although the burned area was only 2% of the total in Asia. This may be because almost all of the peatland burning with high carbon density took place in this region, which contributed 96% of the CO emission in Indonesia. The CO emissions in Myanmar, India, Cambodia, Thailand, Laos, and China accounted for 19%, 11%, 11%, 8%, 3%, and 3% respectively. Burning activities of India often occurred in the central part including western Madhya Pradesh, eastern Maharashtra, and northwestern Andhra Pradesh, together contributing 55% of the national CO emission. In Thailand, the fire activities were often human caused and generally occurred in dry dipterocarp forests and in mixed deciduous forests (Akaakara 2002). It is worth noting that China only contributed about 3% of the total CO emission in Asia, and extensive burning was usually located in the northeastern part (Heilongjiang and Neimenggu), where there are the abundant boreal forests of Daxing’anling and Xiaoqing’anling. According to the forest fire data set compiled in Chinese Forest Yearbook, there has been a sharp decrease in forest fire activities in China since the late 1970s (Yan et al 2006). In particular, since the beginning of the 20th century, the Chinese government has implemented a series of policies to protect forestry resources and control the forest fires (e.g. the natural forest conservation program—refer to Zhang et al (2000); six key forestry programs—refer to Wang et al (2007)).

The seasonal distribution of fire emissions was in general agreement with that of burned areas (figure 2). The maximum emission was in February and March, and almost all of CO emission during these two months was attributed to the surface vegetation burning. Another peak occurred during August–October, and 92% of the CO emission aggregated over this period was released from peat burning. Streets et al (2003) also showed a similar seasonal pattern of fire emission in Asia.
Figure 2. Monthly nonagricultural burned areas and estimated CO emissions over the fire years 2000–2008 in Asia (Note: data for March 2000 and June 2001 are missing).

Table 2. Nonagricultural open fire emissions (Tg) during fire years from 2000 to 2008 in Asia. (Note: data for March 2000 and June 2001 are missing.)

<table>
<thead>
<tr>
<th>Fire year</th>
<th>CO₂</th>
<th>CO</th>
<th>CH₄</th>
<th>NMHCs</th>
<th>NO₃</th>
<th>NH₃</th>
<th>SO₂</th>
<th>BC</th>
<th>OC</th>
<th>PM₂.₅</th>
<th>PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>45</td>
<td>2.76</td>
<td>0.12</td>
<td>0.15</td>
<td>0.05</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
<td>0.14</td>
<td>1.00</td>
<td>1.10</td>
</tr>
<tr>
<td>2001</td>
<td>58</td>
<td>3.94</td>
<td>0.23</td>
<td>0.37</td>
<td>0.06</td>
<td>0.17</td>
<td>0.02</td>
<td>0.02</td>
<td>0.18</td>
<td>1.23</td>
<td>1.34</td>
</tr>
<tr>
<td>2002</td>
<td>130</td>
<td>12.90</td>
<td>1.11</td>
<td>2.14</td>
<td>0.10</td>
<td>1.01</td>
<td>0.05</td>
<td>0.02</td>
<td>0.44</td>
<td>3.95</td>
<td>4.27</td>
</tr>
<tr>
<td>2003</td>
<td>79</td>
<td>4.97</td>
<td>0.24</td>
<td>0.34</td>
<td>0.09</td>
<td>0.16</td>
<td>0.03</td>
<td>0.03</td>
<td>0.25</td>
<td>1.73</td>
<td>1.89</td>
</tr>
<tr>
<td>2004</td>
<td>143</td>
<td>10.75</td>
<td>0.69</td>
<td>1.16</td>
<td>0.14</td>
<td>0.57</td>
<td>0.04</td>
<td>0.04</td>
<td>0.46</td>
<td>3.68</td>
<td>4.00</td>
</tr>
<tr>
<td>2005</td>
<td>51</td>
<td>3.28</td>
<td>0.17</td>
<td>0.25</td>
<td>0.06</td>
<td>0.12</td>
<td>0.02</td>
<td>0.02</td>
<td>0.16</td>
<td>1.10</td>
<td>1.20</td>
</tr>
<tr>
<td>2006</td>
<td>95</td>
<td>7.29</td>
<td>0.49</td>
<td>0.84</td>
<td>0.10</td>
<td>0.40</td>
<td>0.03</td>
<td>0.02</td>
<td>0.31</td>
<td>2.37</td>
<td>2.57</td>
</tr>
<tr>
<td>2007</td>
<td>83</td>
<td>5.14</td>
<td>0.23</td>
<td>0.29</td>
<td>0.09</td>
<td>0.15</td>
<td>0.03</td>
<td>0.03</td>
<td>0.26</td>
<td>1.94</td>
<td>2.12</td>
</tr>
<tr>
<td>2008</td>
<td>64</td>
<td>3.86</td>
<td>0.17</td>
<td>0.24</td>
<td>0.08</td>
<td>0.11</td>
<td>0.02</td>
<td>0.02</td>
<td>0.21</td>
<td>1.34</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Table 3. National nonagricultural open fire emissions (Gg yr⁻¹) in Asia.

<table>
<thead>
<tr>
<th>Country</th>
<th>CO₂</th>
<th>CO</th>
<th>NMHCs</th>
<th>NO₃</th>
<th>BC</th>
<th>OC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangladesh</td>
<td>846</td>
<td>54</td>
<td>2.6</td>
<td>0.92</td>
<td>0.267</td>
<td>2.41</td>
</tr>
<tr>
<td>Bhutan</td>
<td>45</td>
<td>2</td>
<td>0.2</td>
<td>0.08</td>
<td>0.017</td>
<td>0.16</td>
</tr>
<tr>
<td>Cambodia</td>
<td>11 002</td>
<td>693</td>
<td>34.8</td>
<td>10.54</td>
<td>3.741</td>
<td>33.80</td>
</tr>
<tr>
<td>China</td>
<td>3 785</td>
<td>191</td>
<td>15.4</td>
<td>7.95</td>
<td>1.252</td>
<td>11.82</td>
</tr>
<tr>
<td>India</td>
<td>11 990</td>
<td>708</td>
<td>44.6</td>
<td>14.74</td>
<td>4.203</td>
<td>38.59</td>
</tr>
<tr>
<td>Indonesia</td>
<td>22 566</td>
<td>2700</td>
<td>528.7</td>
<td>13.88</td>
<td>1.003</td>
<td>79.61</td>
</tr>
<tr>
<td>Japan</td>
<td>159</td>
<td>8</td>
<td>0.9</td>
<td>0.31</td>
<td>0.066</td>
<td>0.64</td>
</tr>
<tr>
<td>Korea, DPR</td>
<td>204</td>
<td>10</td>
<td>1.0</td>
<td>0.41</td>
<td>0.078</td>
<td>0.75</td>
</tr>
<tr>
<td>Korea, Rep. of</td>
<td>56</td>
<td>3</td>
<td>0.3</td>
<td>0.11</td>
<td>0.021</td>
<td>0.20</td>
</tr>
<tr>
<td>Laos</td>
<td>3 288</td>
<td>212</td>
<td>12.0</td>
<td>3.22</td>
<td>1.169</td>
<td>10.92</td>
</tr>
<tr>
<td>Malaysia</td>
<td>13</td>
<td>1</td>
<td>0.3</td>
<td>0.01</td>
<td>0.001</td>
<td>0.05</td>
</tr>
<tr>
<td>Mongolia</td>
<td>605</td>
<td>36</td>
<td>2.4</td>
<td>1.36</td>
<td>0.195</td>
<td>1.74</td>
</tr>
<tr>
<td>Myanmar</td>
<td>19 666</td>
<td>1346</td>
<td>67.3</td>
<td>20.13</td>
<td>6.773</td>
<td>61.64</td>
</tr>
<tr>
<td>Nepal</td>
<td>797</td>
<td>30</td>
<td>4.5</td>
<td>1.45</td>
<td>0.323</td>
<td>3.01</td>
</tr>
<tr>
<td>Pakistan</td>
<td>121</td>
<td>6</td>
<td>0.4</td>
<td>0.27</td>
<td>0.037</td>
<td>0.36</td>
</tr>
<tr>
<td>Philippines</td>
<td>159</td>
<td>11</td>
<td>0.5</td>
<td>0.16</td>
<td>0.049</td>
<td>0.44</td>
</tr>
<tr>
<td>Thailand</td>
<td>8 226</td>
<td>514</td>
<td>25.4</td>
<td>7.80</td>
<td>2.742</td>
<td>24.43</td>
</tr>
<tr>
<td>Timor Leste</td>
<td>25</td>
<td>2</td>
<td>0.1</td>
<td>0.02</td>
<td>0.009</td>
<td>0.08</td>
</tr>
<tr>
<td>Vietnam</td>
<td>2 245</td>
<td>147</td>
<td>8.5</td>
<td>2.22</td>
<td>0.808</td>
<td>7.51</td>
</tr>
</tbody>
</table>

3.3. Uncertainty

Emission uncertainty is associated with the burned area, fuel load, combustion factor, and emission factor. The MCD45A1 burned area product is at a medium resolution and has been validated to be reliable (Chang and Song 2009, Roy and Boschetti 2009). It is difficult to assess the uncertainty for the satellite-derived burned area (Hoelzemann et al 2004). In addition, the combustion factor was calculated from empirical formulae. Therefore, the fuel load and emission factor were the sources that caused the uncertainties in our study. We assumed that the fuel load was within an uncertainty range of about ±50% around the mean value. The typical uncertainty of the emission factor was in the order of 20–30% (Hoelzemann et al 2004). We ran 20 000 Monte Carlo simulations to estimate the range of fire emissions with a 90% confidence interval. The estimated emission ranges were 69–103 Tg CO₂ yr⁻¹, 4.6–8.2 Tg CO yr⁻¹, 0.24–0.57 Tg CH₄ yr⁻¹, 0.36–1.0 Tg NMHCs yr⁻¹, 0.074–0.1 Tg NO₃ yr⁻¹, 0.17–0.48 Tg NH₃ yr⁻¹, 0.024–0.037 Tg SO₂ yr⁻¹, 0.020–0.028 Tg BC yr⁻¹, 0.22–0.33 Tg OC yr⁻¹, 1.6–2.6 Tg PM₂.₅ yr⁻¹, 1.7–2.9 Tg PM₁₀ yr⁻¹.

4. Conclusion

We developed a comprehensive emission inventory for nonagricultural open burning in Asia by using the daily, 500 m MODIS burned area product (MCD45A1). This inventory covered the nine fire years 2000–2008, and showed large interannual variability. The lowest emissions usually
occurred in the fire year 2000, while high emissions were in the fire year 2002 or 2004. The total emissions for CO\(_2\), CO, NMHCs, NO\(_x\), BC, and OC were 83 (69–103), 6.1 (4.6–8.2), 0.64 (0.36–1.0), 0.085 (0.074–0.10), 0.023 (0.020–0.028), and 0.27 (0.22–0.33) Tg yr\(^{-1}\), respectively. At country level, Indonesia was the biggest contributor, which was mostly attributed to peat burning. Burning emission mainly originated from forest area because of the large biomass density. There were two peaks in biomass burning in Asia. The greatest one occurred during February and March, which was significantly associated with surface vegetation fires. Another peak was usually observed from August to October, which was attributed to peatland burning in the Indonesia–Malaysia region. This work provides an updated and detailed open burning emission inventory for Asia, and could be used for global and regional air quality simulation. (The database is available at stacks.iop.org/ERL/5/014014/raa. For further information please contact Y H Zhang, yhzhang@pku.edu.cn, or Y Song, songyu@pku.edu.cn. )

Acknowledgments

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