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# Long-term assessment of carbon monoxide using MOPITT satellite and surface data over Thailand

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**Abstract**

Long-term carbon monoxide (CO) total columns were retrieved from the MOPITT satellite to investigate long-term trends and seasonal variability of CO loads in the atmosphere of Thailand during 2001-2015. The results showed significantly high levels of CO total columns over the upper part of Thailand, especially in the northern region during March. Long range transport of CO plumes during biomass burning period can also be detected by the satellite. The comparisons between MOPITT CO total columns and surface CO emissions (from anthropogenic and biomass burning activities) were performed for five regions including the central, eastern, northern, northeastern, and southeastern parts of Thailand. The outputs presented similar seasonal patterns of MOPITT data and surface emissions with higher levels of CO during dry months and lower levels during wet months. Ground monitoring concentrations of CO were also comparably analyzed with MOPITT CO total columns in the central, eastern, and northern regions. The results gave relatively good consistency between these two datasets with the correlation coefficients (r) of 0.68-0.73. The analysis of the annual trends of CO total columns (2001-2015) and CO emissions (2001-2008) revealed slightly decreasing trends for most of the regions, except for the northern region, which showed the increase of CO emissions due to the intensive biomass burning in 2007. MOPITT observations were useful for tracking pollutant plumes and for monitoring CO loads in the atmosphere, particularly where there are limited data due to a lack of ground monitoring stations.

**Keywords:** CO, Emission inventory, MACCity, MOPITT, Satellite, Thailand

## 1. Introduction

Atmospheric CO plays an important role in tropospheric photochemical processes leading to the formation of ozone in this layer. Its presence in high levels affects the sink for hydroxyl radicals, which are the cleansing agents of the troposphere and therefore influence the oxidative capacity of the atmosphere [1]. The main sources of atmospheric CO are motor vehicles, seasonal biomass burning, and industrial facilities.

Satellite observations of CO loads in the atmosphere have been developed over the last decade. Since 2000, globally measured CO columns have been provided continuously by the satellite instrument of Measurements of Pollution in the Troposphere (MOPITT). Many studies have thoroughly evaluated and validated MOPITT CO measurements using *in situ* CO vertical profiles measured by aircraft over a variety of geographical regions and in multiple field campaigns [2-5]. Several studies also explored interannual and seasonal variabilities of satellite CO levels both over land and the ocean [6-8]. Worden et al. [9] reported that satellite data revealed decreasing decadal trends of CO levels in Europe, the Eastern USA, and Eastern China during the period of 2000-2011. Similar to Yin et al. [10], they investigated the trends of global CO emissions seen by MOPITT during 2002-2011 and found a large decrease in CO emissions over many regions of the globe. de Laat et al. [11] conducted a global evaluation of satellite observed CO levels during 2004-2005. They found that at middle and high latitudes, maximal CO levels occurred during the local winter and early spring for the northern and southern hemispheres. For tropical areas, CO levels increased due to the seasonal biomass burning. Edwards et al. [12] demonstrated that MOPITT measurements can be used to detect strong plumes of African biomass burning making their way into the Indian ocean. These affected the atmosphere of New Zealand and Australia in 2003. Sukitpaneenit and Kim Oanh [13] showed that MOPITT CO data could track the forest fire plumes during fire episodes in the north of Thailand. Their results also presented a consistent agreement between satellite observations, ground monitoring data, locations of hotpots, and prevalent winds in 2008-2010.

The current study focused on the use of MOPITT data to investigate the spatial distributions and temporal variability of atmospheric CO over Thailand during the 15 years from 2001-2015. MOPITT CO data were also comparably analyzed considering CO emissions and ground monitoring CO concentrations to explore the potential applications of MOPITT instrumentation to predict surface conditions.

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**Table 1** Summary of the locations of MOPITT grid boxes and PCD monitoring stations considered in this study

| Region | MOPITT Grid (Lat, Lon) | PCD Ground Monitoring Station<br>Station Name | City | Lat | Lon |
|---|---|---|---|---|---|
| C | 13.50-15.50°N, 99.50-101.50°E | Na Phralan Police Station | Saraburi | 14.69 | 100.87 |
| | | Khao Noi Fire Station | Saraburi | 14.52 | 100.92 |
| | | Ayutthaya Witthayalai School | Ayutthaya | 14.35 | 100.57 |
| | | Sukhothai Thammathirat Open University | Nonthaburi | 13.91 | 100.54 |
| | | Electricity Generating Authority of Thailand (EGAT) | Nonthaburi | 13.81 | 100.51 |
| | | Chandrakasem Rajabhat University | Bangkok | 13.82 | 100.58 |
| | | National Housing Stadium Huaykwang | Bangkok | 13.78 | 100.57 |
| | | Bodindecha Sing Singhaseni School | Bangkok | 13.77 | 100.61 |
| | | Thonburi Power Sub-Station | Bangkok | 13.73 | 100.47 |
| | | Highway District | Samut Sakhon | 13.71 | 100.32 |
| | | Prabadng Rehabilitation Center | Samut Prakan | 13.66 | 100.54 |
| | | Dept. of Mineral Resources | Samut Prakan | 13.65 | 100.53 |
| | | South Bangkok Power Plant | Samut Prakan | 13.62 | 100.56 |
| | | National Housing Authority Bangplee | Samut Prakan | 13.57 | 100.79 |
| E | 12.50-13.50°N, 100.50-101.50°E | Field Crop Research Center | Rayong | 12.74 | 101.14 |
| | | Health Promotion Hospital Maptaput | Rayong | 12.71 | 101.17 |
| | | Government Complex | Rayong | 12.71 | 101.18 |
| | | Agricultural Office | Rayong | 12.67 | 101.28 |
| N | 17.50-19.50°N, 97.50-101.50°E | Natural Resources and Environment Office | Mae Hongson | 19.30 | 97.97 |
| | | Knowledge Park | Phayao | 19.16 | 99.90 |
| | | Chiangmai City Hall | Chiangmai | 18.84 | 98.97 |
| | | Yupparaj Wittayalai School | Chiangmai | 18.79 | 98.99 |
| | | Municipality Office | Nan | 18.79 | 100.78 |
| | | Health Promotion Hospital Ta See | Lampang | 18.44 | 99.77 |
| | | City Pillar Shrine | Lampang | 18.29 | 99.51 |
| | | Provincial Waterworks Authority Mae Moh | Lampang | 18.29 | 99.68 |
| | | Health Promotion Hospital Sob Pad | Lampang | 18.25 | 99.77 |
| | | Meteorology Center | Phrae | 18.13 | 100.16 |
| NE | 14.50-17.50°N, 101.50-103.50°E | - | - | - | - |
| SE | 7.50-8.50°N, 99.50-100.50°E | - | - | - | - |

## 2. Materials and methods

### 2.1 Satellite data

Fifteen years of data measuring satellite-based CO total columns used in this study were retrieved from Version 5, a Level 2 product of MOPITT instrument for 2001-2015. MOPITT was launched in December 1999 aboard the EOS-Terra platform with an equator crossing time of approximately 10:30 local time (LT). Data are available for observations made since March 2000 [14-15]. The horizontal spatial resolution of the MOPITT observed products is 22 × 22 $km^2$ at nadir. MOPITT CO total columns with the units of molecules per square centimeter are available to download from the Atmospheric Science Data Center (ASDC) of NASA Langley Research Center website (https://eosweb.larc.nasa.gov/).

The MOPITT satellite data for total CO total columns were obtained in monthly format to perform long term analysis over Thailand in terms of both spatial distribution and by region. For the latter, five areas were examined in this study including the central (C), eastern (E), northern (N), northeastern (NE), and southeastern (SE) regions. The grid boxes of satellite data located in each region were set up for analysis as presented in Figure 1. All the satellite pixels falling within an individual grid boxes were grouped, averaged and presented as representatives of those particular regions. The information of the grid boxes are given in Table 1.

### 2.2 Ground monitoring data

Hourly ground based data of CO concentrations were obtained from 28 stations of the Pollution Control Department (PCD), over three regions of Thailand including the C (14 stations), E (4 stations), and N (10 stations) regions during the same period as MOPITT observations (2001-2015) to examine their relationship with total CO columns. The reference method applied for collecting ground based CO concentrations at all PCD monitoring stations was non-dispersive infrared (NDIR) detection. The hourly PCD CO concentrations were averaged from 09:00 to 12:00 LT corresponding to the MOPITT transit time of 10:30 LT, and then averaged as monthly data for comparison with monthly MOPITT total CO columns. All point based monthly CO concentrations collected from PCD stations located in the same grid boxes of MOPITT data were grouped and averaged to analyze with the averaged satellite data falling within these boxes for each region. The details and illustration of the locations of 28 PCD stations in three regions are provided in Table 1 and Figure 1, respectively.

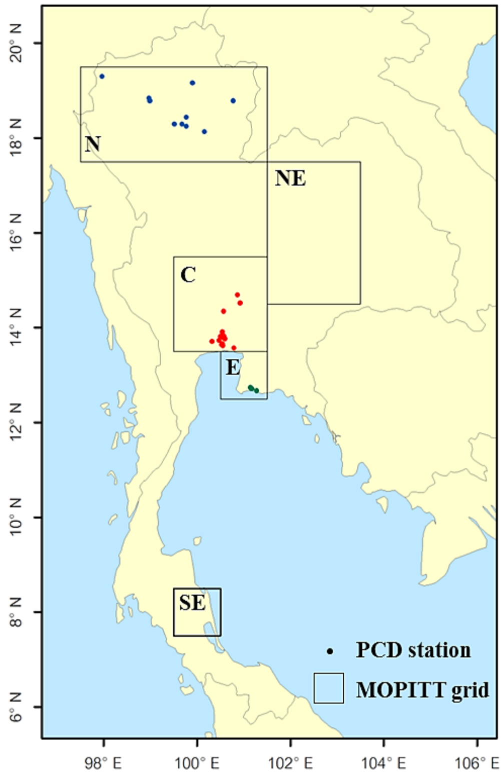


**Figure 1** MOPITT grid boxes and PCD monitoring stations

*2.3 Emission inventory*

The CO emissions used to in this study were derived from the MACCity inventory. The air pollutant emissions of the MACCity inventory are an adapted and extended version of the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) and the Representative Concentration Pathways (RCP) inventories, which were funded by the European Commission as part of the Monitoring Atmospheric Composition and Climate "MACC" and "CityZen" projects. MACCity emission datasets are available for both anthropogenic activities from 1960–2010 and biomass burning activities (forest, grassland, and savanna fires) for 1960–2008 on a monthly basis with gridded 0.5×0.5 decimal degrees spatial resolution products. The global emission datasets of the MACCity inventory are published through the website of Emissions of Atmospheric Compounds and Compilation of Ancillary Data (ECCAD-Ether) (http://eccad.sedoo.fr). More details of the development of the MACCity emission datasets are described in van der Werf et al., Lamarque et al., Granier et al., and Diehl et al. [16-19]. All the pixels of the gridded MACCity CO emissions that fall within the arranged satellite grid boxes in each region were comparatively analyzed with MOPITT total CO columns to investigate the consistency between them during the period of 2001-2008.

**3. Results and discussion**

*3.1 Spatial distribution of satellite CO*

The spatial distributions of the total CO columns retrieved from the MOPITT satellite during 2007-2015 over Thailand were averaged as monthly data and are illustrated in Figure 2 from January to December for those years. Overall, high levels of total CO columns were observed during the dry period of October to April with the maximum level in March. During this period, it is quite clear that the upper parts of Thailand (the N, NE, C and E regions) were the main contributors of CO columnar loads in Thailand. In the N region, CO loads were built up to their maximum levels in March due to the emissions from seasonal biomass burning activities (crop residue burning and forest fires) that in turn caused haze episodes in this region. The lowest levels of total CO columns considering all the regions were during June to August during the rainy season in Thailand. Additionally, long-range transport of CO plumes during the forest fire period from northeastern Indian [20] toward Bangladesh, Myanmar, and then Thailand was also detected by the MOPITT satellite during February to April. Similar results were elucidated in a previous study [21]. Based on a three-day backward trajectory simulation of air movement in Chiang Mai city (in Northern Thailand), it was found that during March in 2012-2014, the air mass traveling the longest distance was from India toward the Bay of Bengal, and Myanmar, before reaching Thailand. The transboundary transport of CO during this period enhanced CO levels from intensive biomass burning emissions already existing in Thailand. This subsequently led to a worse air quality problem, particularly in the N region. The results in this part showed that MOPITT observations were able to provide qualitative information on the dispersion patterns of CO plumes, especially in inaccessible areas.

*3.2 Comparison of satellite CO and emissions*

*3.2.1 Monthly analysis*

The MACCity emission inventory of CO was derived in terms of monthly averages from 2001 to 2008 to study the evolution and seasonal pattern of CO emissions over Thailand. It was also used to investigate the consistency between satellite and emissions datasets. Both anthropogenic and biomass burning emissions of CO were compared with MOPITT total CO columns. Figure 3 (left) presents a time series of the comparative analysis of seasonal variability of MOPITT total CO columns (2001-2015) versus total CO emissions (sum of anthropogenic and biomass burning emissions, 2001-2008) for the C, E, N, NE, and SE parts of Thailand. In general, the seasonal patterns of MOPITT total CO columns were similar to total CO emissions of the MACCity data for all the areas. Figure 3 (right) displays monthly means of MOPITT total CO columns versus total CO emissions from January to December averaged for 2001-2008. The results showed that the seasonal variations of both MOPITT total CO columns and MACCity CO emissions in all regions were commonly higher during the dry period from October to April and lower levels during the wet period from May to September.

Figure 4 shows a comparison of MACCity CO emissions from anthropogenic versus biomass burning activities averaged for 2001-2008. In the N region, the seasonal cycle of CO emitted from biomass burning activities revealed higher levels during February-April compared to other months, while anthropogenic activities generated higher levels during November-February. However, since emissions from biomass burning during February-April were dominant in this region, the total CO emissions presented higher levels during this period. This was similar to MOPITT observed data for total CO columns, as can be seen in Figure 3 (right) with the maximum levels in March. In the SE area, the seasonal trends of MACCity CO emissions from both biomass burning and anthropogenic activities showed

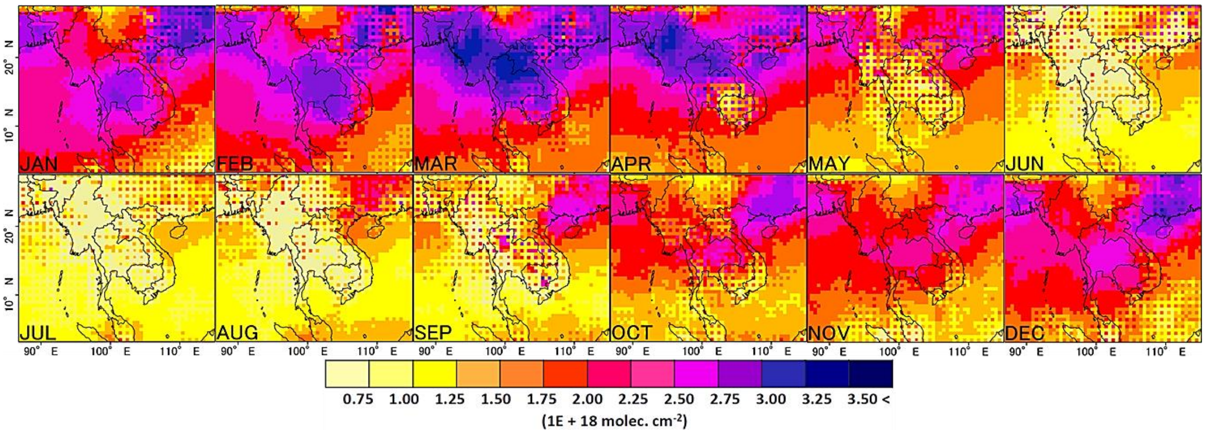


**Figure 2** Spatial distributions of monthly MOPITT total CO columns from January to December averaged from 2007-2015

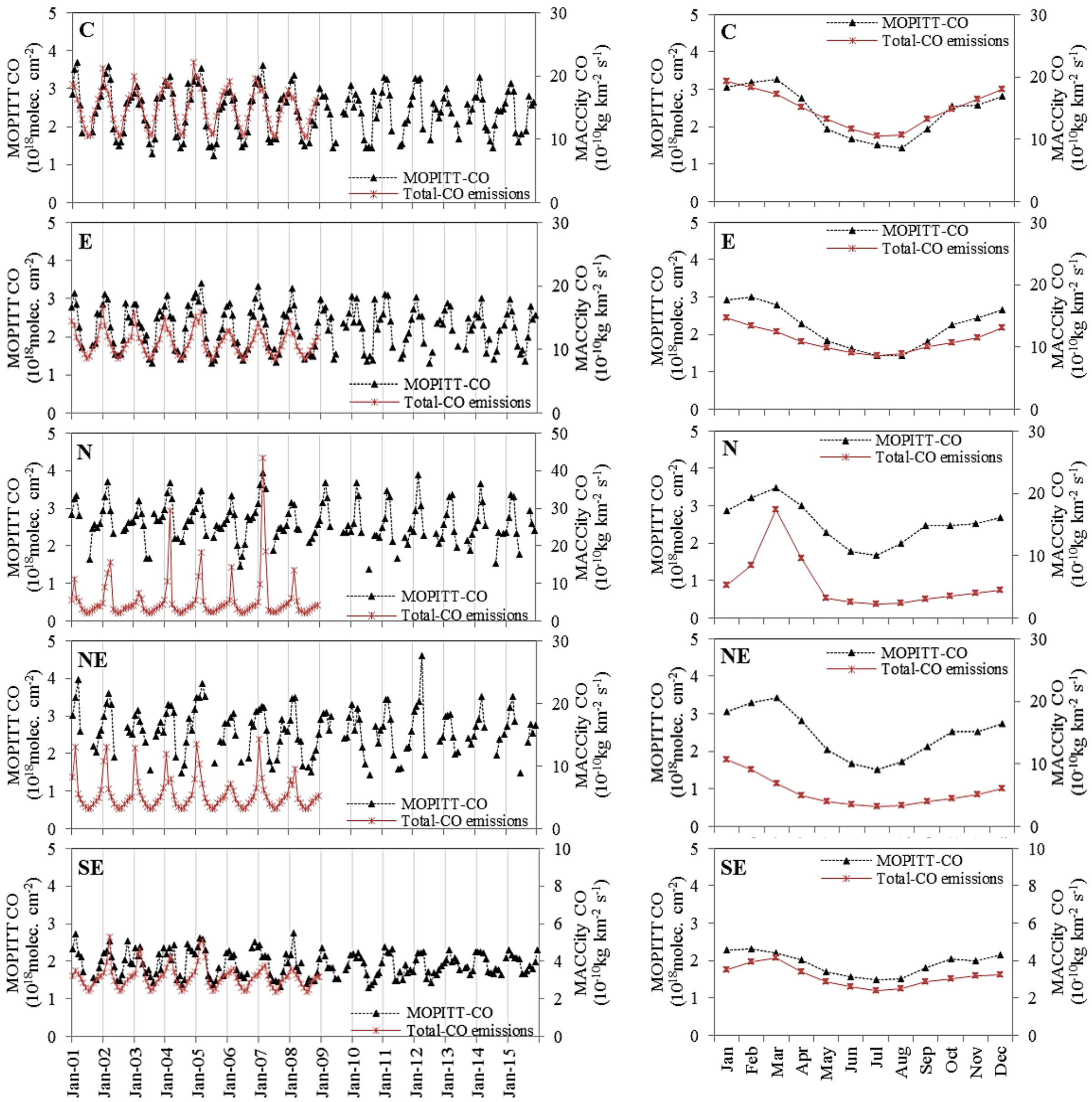


**Figure 3** Time series of MOPITT total CO columns (2001-2015) versus MACCity CO emissions (2001-2008) in the C, E, N, NE, and SE regions (left) and monthly means (2001-2008) of MOPITT total CO columns versus MACCity CO emissions from January to December (right)

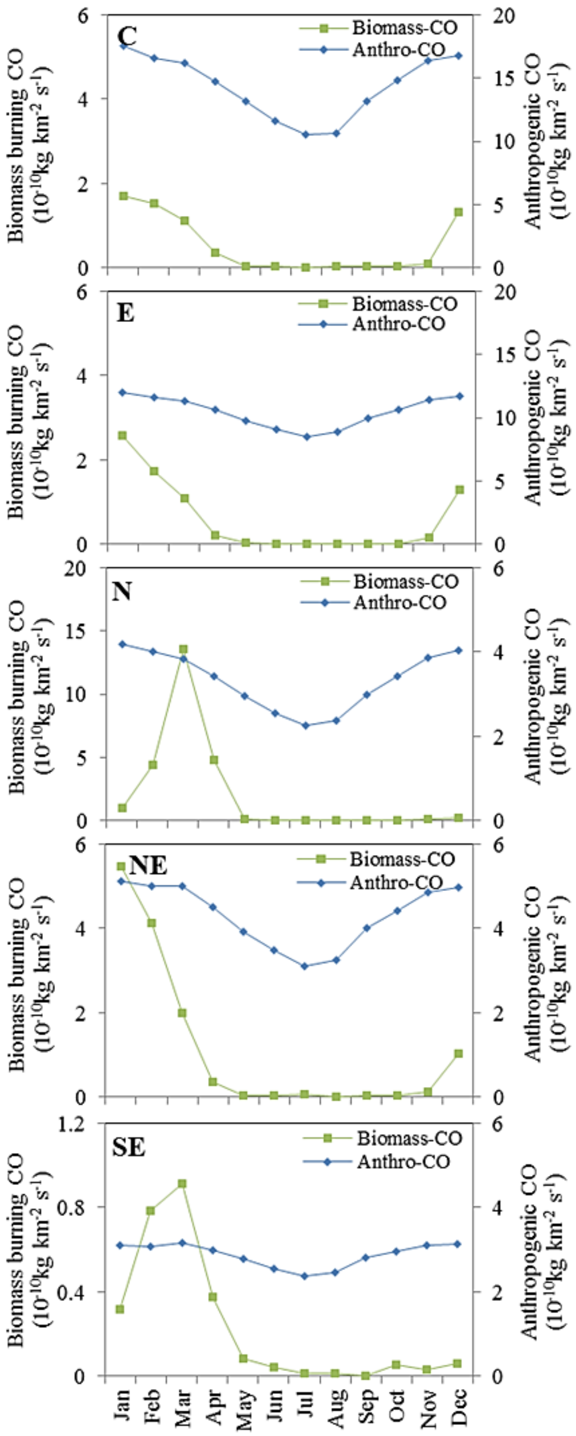


**Figure 4** Monthly means (2001-2008) of MACCity CO emissions from anthropogenic versus biomass burning activities from January to December in the C, E, N, NE, and SE regions

similar trends to the northern region. Nevertheless, anthropogenic emissions were dominant in this area. Therefore, the seasonal trend of total CO emissions in the SE region tended to follow the trend of anthropogenic emissions with the higher levels during October-April. The MOPITT observations also detected approximately the same trend of total CO columns in this region.

In the C and E parts, CO emissions from biomass burning and anthropogenic activities showed the highest values during December-March and November-February, respectively. However, since CO emissions from anthropogenic activities were predominant in these two areas, the total CO emissions consequently followed the seasonal trends of such emissions. In the NE, there was not much difference between the levels of CO emissions from both sources. Therefore, the total CO emission followed the trends of both activities with higher levels from December-March. From Figure 3 (right), it is noteworthy that the maximum levels of MOPITT total CO columns in the C, E, and NE regions were in February-March while the maximum peaks of total CO emissions appeared in January and then started decreasing. The discrepancy between satellite observations and emissions can be first explained by the long lifetime of CO in the atmosphere. This generally ranges from weeks to months (depending on meteorological conditions) leading to accumulation of CO loads in the atmosphere even though the source of emissions decreased. Second, it can be explained by the long-range transport of CO plumes occurring regularly from February-April in the upper part of Thailand. This in turn caused higher loads of CO in the atmosphere during these months, as was observed by the MOPITT satellite.

*3.2.2 Yearly analysis*

Figures 5 and 6 demonstrate the annual means of the total MACCity CO emissions from 2001-2008 and MOPITT total CO columns from 2001-2015, respectively, in five regions (C, E, N, NE, and SE). In general, most of the areas had relatively constant trends for both total CO emissions and total CO columns. Table 2 summarizes the annual trends of the total MACCity CO emissions and MOPITT total CO columns for the considered areas. The trends of MOPITT total CO columns for all the regions revealed slightly decreasing trends ranging from -1.83 to -0.82 % over the seven years (ref. year 2001) from 2001-2008, and from -0.38 to -0.21 % over the 14 years (ref. year 2001) from 2001-2015. For the MACCity data, the trends of total CO emissions for the C, E, NE, and SE regions decreasing ranging from -0.85 to -0.39 % over the 7 years (ref. year 2001) from 2001-2008. For the N region, the trend showed an increase of 4.12 % over 7 years. The difference in the trend of the N region was due to the high levels of CO emissions from intensive biomass burning during a very bad air pollution episode in March 2007 [22]. However, the observed total CO columns in 2007 were not particularly pronounced due to the high background levels of CO in the atmosphere. It should be noted that total CO columns do not directly represent CO emission. Since CO gas has a relatively long lifetime and can be transported over a long distance, it is difficult to formulate trends for surface pollutant emissions using total CO columns retrieved by the satellite [23]. The decrease of MOPITT total CO columns in this study is similar to results in other Asian countries [24] and in the U.S. [9].

Table 2 also provides eight year averaged values of surface CO emissions and observed total CO columns. The C region had the highest value of total CO emissions of $14.88\times10^{-10}$ kg.km.$^{-2}$s.$^{-1}$ followed by the E, N, NE, and SE regions, in descending order. Nevertheless, the total CO columns in the N ($2.48\times10^{18}$ molec.cm.$^{-2}$) and NE ($2.42\times10^{18}$ molec.cm$^{-2}$) regions were larger than in the C region ($2.33\times10^{18}$ molec.cm$^{-2}$). The discrepancy in the order of these two datasets can be explained by the transboundary transport of CO plumes from the neighboring countries that added the CO loads in the N and NE areas. This implies that

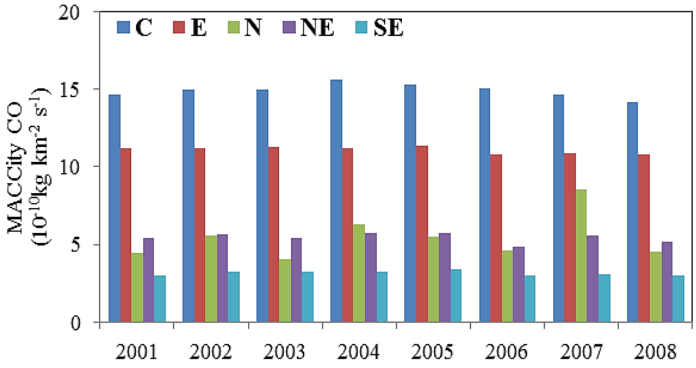


**Figure 5** Annual means of the total MACCity CO emissions from 2001-2008 in the C, E, N, NE, and SE regions

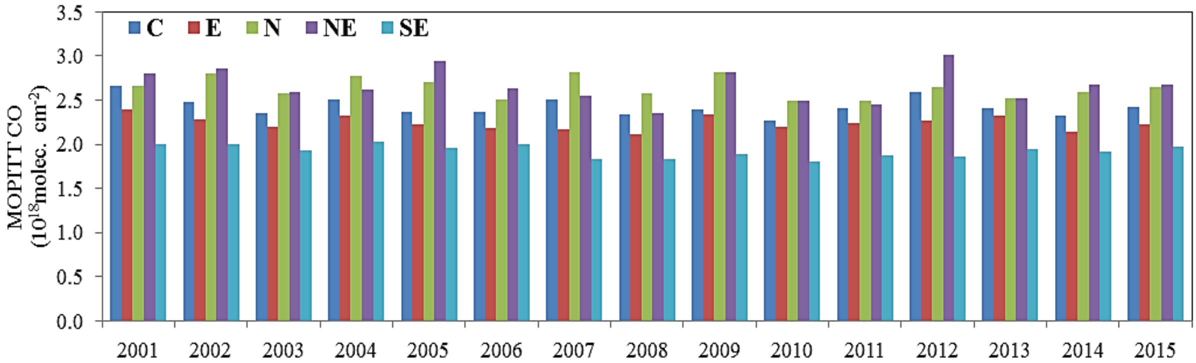


**Figure 6** Annual means of the MOPITT total CO columns from 2001-2015 in the C, E, N, NE, and SE regions

**Table 2** Summary of averaged levels and annual trends of the MOPITT total CO columns and total MACCity CO emissions in five regions of Thailand

| Region | MOPITT CO total columns ($10^{18}$molec.cm$^{-2}$) | | | | Total MACCity CO emission ($10^{-10}$kg.km.$^{-2}$s.$^{-1}$) | | |
|---|---|---|---|---|---|---|---|
| | Ref. 2001 | 8-yr trend (%yr$^{-1}$, 2001-08) | 15-yr trend (%yr$^{-1}$, 2001-15) | 8-yr average (2001-08) | Ref. 2001 | 8-yr trend (%yr$^{-1}$, 2001-08) | 8-yr average (2001-08) |
| C | 2.67 | -1.10 | -0.32 | 2.33 | 14.62 | -0.39 | 14.88 |
| E | 2.40 | -1.36 | -0.21 | 2.16 | 11.17 | -0.58 | 11.08 |
| N | 2.73 | -0.82 | -0.38 | 2.48 | 4.42 | *4.12* | 5.50 |
| NE | 2.80 | -1.83 | -0.30 | 2.42 | 5.41 | -0.85 | 5.43 |
| S | 2.00 | -1.09 | -0.33 | 1.92 | 2.98 | -0.49 | 3.15 |

long range transport of air pollutants, especially from biomass burning, from other counties plays a crucial role in the air quality of Thailand.

*3.3 Comparison of satellite and ground CO*

The ground-based CO concentrations were derived from 28 PCD stations, Thailand (Table 1) on a monthly basis from 2001-2015 to comparably correlate them with MOPITT total CO columns for concurrent periods and locations. The analysis was performed for three regions of Thailand, the C, E, and N regions, as illustrated in Figure 1. Figure 7 presents scatter plots of MOPITT total CO columns versus PCD CO concentrations for the considered regions. Overall, the correlations (r) between satellite and ground based measurements were in reasonable agreement with values ranging from 0.68 to 0.73, suggesting that the MOPITT total CO columns have the potential to reflect CO loads in the atmosphere. Similar analysis was performed by Sukitpaneenit and Kim Oanh [13]. They conducted the comparisons between satellite data and PCD data of CO and $PM_{10}$ in Northern Thailand. An association between them was found. The r-values of MOPITT and PCD based CO data were reported ranging from 0.35 to 0.71 for the months of February-April for 2008-2010.

Monthly means of MOPITT total CO columns and ground CO concentrations from January to December averaged during 2001-2015 were compared and are shown in Figure 8. These results are similar to the analysis between MOPITT total CO columns and MACCity CO emissions in the previous section. In the N region, both MOPITT and ground CO data showed higher levels during biomass burning period of January-April with the highest peak in March. However, in the C and E regions, the maximum levels of ground CO concentrations occurred during the dry period from December to February while the maximum

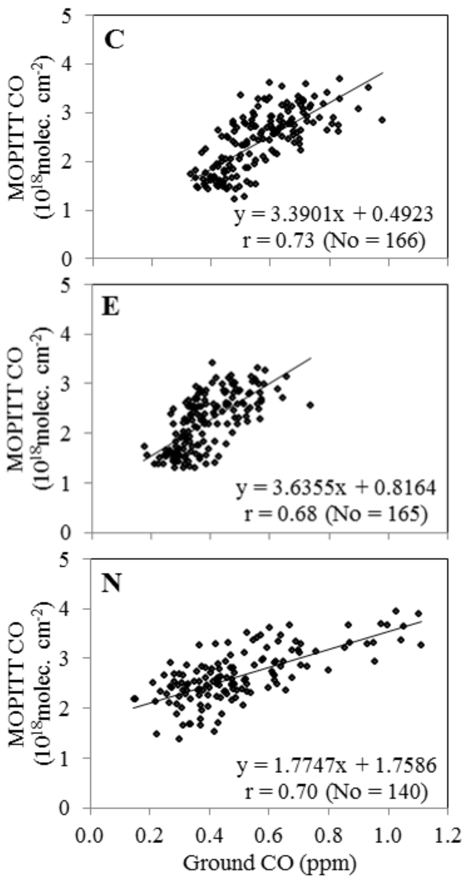


**Figure 7** Scatter plots of monthly MOPITT total CO columns versus ground CO concentrations from 2001-2015 in the C, E, and N regions

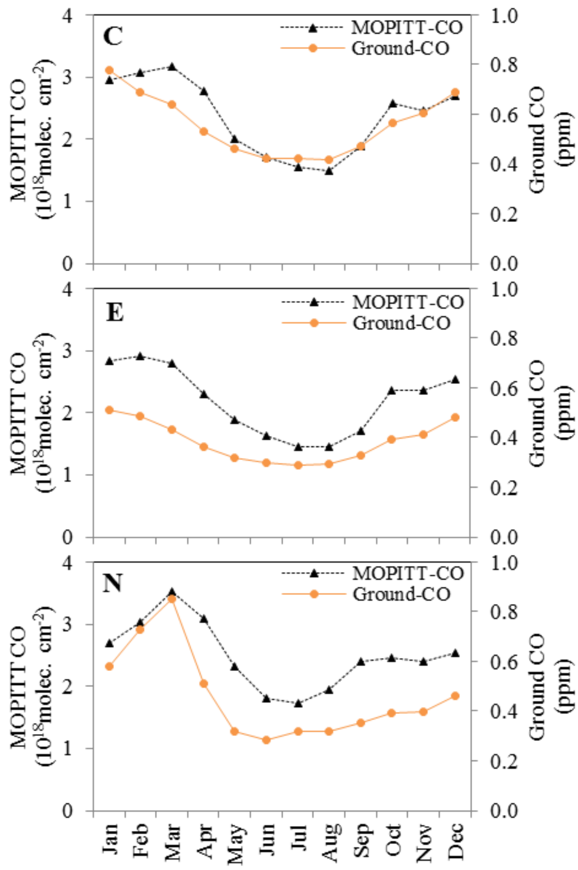


**Figure 8** Monthly means (2001-2015) of MOPITT CO total columns versus ground CO concentrations from January to December in the C, E, and N regions

levels of MOPITT total CO columns appeared from February to March. Since ground monitoring stations measure air pollutants near the Earth's surface, their information tend to represent surface emissions, whereas satellite instruments observe air pollutants from the surface up to the upper atmosphere. These measurements could be affected by pollutants aloft. Therefore, this supports the idea in the previous section that high levels of MOPITT observed total CO columns during February-March in the C and E regions could be caused by CO aloft from long-range transport of smoke plumes due to the high degree of biomass burning activities.

## 4. Conclusions

Long-term assessment of MOPITT retrieved total CO total columns was performed from 2001-2015 to investigate the seasonal variability and long term trends of CO loads in the atmosphere over Thailand. The spatial distribution of observed total CO columns showed maximal levels in March, especially in the upper parts of Thailand, resulted mainly from biomass burning activities within the country and also by the long-range transport of CO plumes from other countries. Comparative analysis of MOPITT total CO columns versus MACCity CO emissions in five regions (C, E, N, NE, and SE) and PCD CO concentrations in three regions (C, E, and N) showed that, in general, satellite observations were able to catch the seasonal cycle of CO emissions and ground-based CO concentration. There were higher levels during the dry period and lower levels during the wet period. However, the discrepancy between the satellite and surface datasets can be caused by the long-range transport of CO plumes and the accumulation of CO loads due to the long lifetime of CO in the atmosphere. The annual trends of MACCity CO emissions and MOPITT total CO columns showed slightly decreasing trends for most of the considered regions except for the N region. This area showed an increase in CO emissions due to an air pollution episode from biomass burning activities in 2007. Overall, the results of this study highlight that MOPITT observations can be applied as a tool to assess long-term trends and seasonal variability of CO loads in the atmosphere, especially where ground monitoring stations are limited. Additionally, MOPITT has the potential of tracking CO plume dispersion patterns, especially during air pollution episodes, on a regional scale. Further analysis of satellite CO data together with model simulations will provide useful information to track emissions back to their sources and to predict the downwind transport of smoke plumes to develop an early warning systems and mitigation plans for air quality management.

## 5. Acknowledgements

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& Compilation of Ancillary Data (ECCAD-Ether). Ground based monitoring data of CO concentrations were obtained from the Pollution Control Department (PCD), Thailand.

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