Temporal and spatial distribution of the mid-tropospheric CO\textsubscript{2} concentrations in Malaysia

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Abstract. Satellite observations of CO\textsubscript{2} offer a unique opportunities to improve our understanding of the carbon sources and sinks. Due to the lack of studies of carbon dioxide (CO\textsubscript{2}) concentration in this region, we first confirmed the reliability of the mid-tropospheric Atmospheric Infrared Sounder (AIRS) CO\textsubscript{2} data using atmospheric CO\textsubscript{2} concentration data from the only available Global Atmospheric Watch (GAW) ground-based station observation in Malaysia. In this study, the spatial and temporal distribution of mid-troposphere CO\textsubscript{2} in Malaysia from January 2009 to December 2012 was analyzed based on AIRS satellite product. The results show that the average CO\textsubscript{2} concentrations were high in the eastern part of the study area and lower in the west. From January 2009 to December 2012, the mid-tropospheric CO\textsubscript{2} concentrations increased gradually with annual growth rate about 1.293 ppmv/a. There was a significant seasonal CO\textsubscript{2} variation with peak concentration was observed during the North-East monsoon (NEM) and the lowest was during South-West monsoon (SWM). The temporal distribution of CO\textsubscript{2} concentrations was mainly affected by the amount of sunlight and precipitation received during both monsoons. The study suggested that mid-tropospheric AIRS CO\textsubscript{2} data product was able to help in understanding the variations of atmospheric CO\textsubscript{2} concentrations comprehensively.

1. Introduction

Raising potential of global warming can be attributed to increasing atmospheric concentrations of CO\textsubscript{2} that is emitted by various natural and anthropogenic sources. Additionally, CO\textsubscript{2} atmospheric concentration has risen nearly up to 30\% compared to the concentration in the past century. CO\textsubscript{2} possess the ability to increase the global warming due to its low ability to absorb infrared radiation and shorter atmospheric lifetime compared to other GHGs [1]. The greenhouse gas is also very stable, and hence it could take hundreds of years for natural processes to return the CO\textsubscript{2} concentrations to the pre-industrial levels. The adverse potential that could be brought by this gas thus signifies the importance of monitoring its concentration levels. Often, the monitoring requires a long-term observation in order to quantify the sources and sinks of its emission.

Despite the ground-based measurement network has grown since 1958, it is still quite sparse, especially in this region. Such a limitation could result in difficulties in interpolating the spatial pattern and therefore elucidating the mechanism process of CO\textsubscript{2} transportation and distribution. Because of the lack of spatial data, ecological studies for large regions often conducted at global scale can only
rely on the annual global mean CO$_2$ background values that are observed on a few scattered locations. Nonetheless, these data are unable to cover the temporal and spatial heterogeneity of the near-surface CO$_2$ concentrations due to their nature of measurements, which causes large uncertainties. One way to fill these measurement gaps is to acquire accurate global observations from space. With the development of satellite remote sensing instruments, it is now possible to conduct long-term, stable, and high frequency observations of the global coverage of CO$_2$.

The Atmospheric Infrared Sounder (AIRS) sensor on-board the NASA Aqua satellite is an instrument that uses thermal infrared radiation spectra to observe mid-tropospheric CO$_2$ concentrations across the globe. AIRS provides a new dimension to understand CO$_2$ spatial variability in response to natural dynamic in the climate system. The AIRS CO$_2$ retrievals utilize 15 µmeter region of the thermal spectrum, of which sensitive to CO$_2$ variations in the middle troposphere. The observation principle is that CO$_2$ has unique absorption properties in these bands. The AIRS data have been shown to be accurate within 1.20 ppm in comparison to simultaneous measurements by aircraft [2]. Data retrieval from AIRS has also been employed for temporal and spatial investigation in localized sources. For instance, [3] was able to provide evidence of the impact of biomass burning on the pollution levels in the study area and deduced the relationship between those two by visualizing level-3 AIRS monthly variation data that depicted CO$_2$ emission transportation from forest fires in neighbouring countries.

In spite of availability of sensors that could approximate greenhouse gasses such as AIRS and Thermal and Near-infrared Sensor for Carbon Observation Fourier Transform Spectrometer (TANSO-FTS) that is available on the Greenhouse Gases Observing Satellite (GOSAT) to monitor the concentrations of CO$_2$ and CH$_4$ at a global coverage, the instrumental specification does not respond to areas with high cloud abundance, such as areas near to the tropical equatorial line. Therefore, available assessment or utilization of this dataset for regions such as Malaysia is still limited. In this limelight, this paper aims to evaluate the applicability of the AIRS to assess the temporal and spatial distribution of CO$_2$ concentration in areas where dense clouds are abundant. This study utilized the mid-tropospheric CO$_2$ data product from the AIRS sensor to validate the suitability of the dataset in mapping the distribution of CO$_2$ concentration in study area and analyse the distribution of CO$_2$ concentrations in Malaysia from 2009 to 2012 and their annual and seasonal variations.

2. Materials and method

2.1. Study area

Malaysia is located immediately north of the Equator and in the Southeast Asia region. The geographical extent of the study area is 1-7° N and 99-120° E, which covers an area of approximately 330,269.59 km$^2$ with the population is approximately 31.7 million. Due to its geographical structure and location, Malaysia is frequently exposed to transboundary pollution contributed from its neighbouring countries. Forest fires originated from neighbouring countries such as Indonesia in the past have increased the air pollution, however, local source of air pollution is also an important factor that should be considered. Countries in Southeast Asia region such as Malaysia are often subject to two main monsoon regimes, the Northeast Monsoon (NEM), which occurs from November to March, and the Southwest Monsoon (SWM), which occurs from late May to September [4,5]. These monsoons are associated with the contribution of many regional pollutant sources that affect atmospheric parameters and the amount of pollutants transported to Malaysia[6]. This study adopted 28 meterological stations in Malaysia for better analysis and interpretations.

2.2. Data source and analysis

The research used multiple data sets, mainly including the NASA AIRS/AMSU L3 CO$_2$ data product and the Global Atmospheric Watch (GAW) measurements acquired from Lembah Danum, Sabah, Malaysia for the CO$_2$ ground observation data. The station is located around undisturbed lowland
tropical rain forest and the measurements are observed at 30m, 60m and 100m above ground level. Lembah Danum GAW data was retrieved from World Data Centre for Greenhouse Gases (WDCGG). Prior to the utilization of the AIRS data to study the temporal and spatial distributions of the mid-tropospheric CO$_2$ concentration in Malaysia, the reliability of the mid-tropospheric CO$_2$ concentrations from the AIRS data was first verified through statistical analysis such as coefficient of determination $R^2$ and correlation coefficient ($r$) at $p < 0.05$.

Further the assessment, the CO$_2$ concentration for 28 meteorological stations distributed throughout Malaysia was extracted from the NASA AIRS/AMSU Level 3 CO$_2$ data product from January 2009 until June 2012. The values were then averaged to obtain the 4-years average of CO$_2$ concentrations and later were interpolated by kriging method to estimate the CO$_2$ concentrations for Malaysia. Additionally, the annual growth rate for a given year was calculated by finding the CO$_2$ concentration difference at the end of that year minus the CO$_2$ concentration at the beginning of that year [7]. The seasonal average and fluctuation were also quantified and statistically compared according to the main two monsoons, NEM and SWM at $p < 0.05$.

2.3. Comparison of AIRS CO$_2$ observations with GAW ground observations

To assess accuracy of AIRS CO$_2$ data product, we compared AIRS daily data with ground-based GAW station data. Figure 1 shows scatter plots between the satellite-ground measured CO$_2$ pairs. This comparison indicated a strong relationship between these two data products over the 8 months of study period ($R^2 = 0.767$; $r = 0.897$, $p < 0.01$). Table 1 gives the average, standard deviation, maximum and minimum values, and coefficient of determination for both the ground and satellite observation. The average CO$_2$ reading for GAW ground station is 391.41 ppm which was slightly higher than AIRS satellite observation, nevertheless the deviation was less than 1 ppm. The monthly mean deviation between the ground observation and satellite measurements was less than 3 ppm, while the average standard deviation was less than 2 ppm. This concludes that AIRS data was comparable to the seasonal variations of CO$_2$ measured by the GAW. [8] demonstrated that a CO$_2$ concentration accuracy that was better than 1% (less than 2.5 ppmv) can decrease the uncertainty of estimates of regional CO$_2$ sources and sinks. To summarize, the AIRS mid-tropospheric CO$_2$ data possesses an acceptable accuracy to analyse the temporal and spatial distributions of CO$_2$ concentrations.

![Figure 1. The comparison of CO2 concentration from AIRS and GAW Lembah Danum ground observation](image-url)
Table 1. Comparison between ground-based and satellite measurements

|                | Mean  | Std. Dev. | Minimum | Maximum | $R^2$ |
|----------------|-------|-----------|---------|---------|-------|
| GAW ground-based | 391.41 | 1.82      | 388.83  | 394.34  | 0.767 |
| AIRS satellite measurement | 390.02 | 1.83      | 387.73  | 392.35  |       |

2.4. The Temporal and Spatial Distribution of Mid-Tropospheric CO$_2$ in Malaysia

Table 2 tabulates the average concentration, standard deviation, variance, range, a minimum and maximum of the observation from AIRS mid-tropospheric observation over 2009 to 2012. It was observed that the annual concentration of CO$_2$ had increased from 2009 to 2012. The mean annual growth rate of the CO$_2$ from the corresponding satellite inversion results showed that the rate was 1.293 ppmv/a.

Table 2. Mid-troposphere CO2 concentration statistics during 2009-2012

| Year | Mean   | Std. Dev. | Variance | Range  | Minimum | Maximum |
|------|--------|-----------|----------|--------|---------|---------|
| 2009 | 386.77415 | 0.849873  | 0.722    | 2.711  | 384.977 | 387.688 |
| 2010 | 389.29889 | 1.098228  | 1.206    | 3.770  | 387.364 | 391.134 |
| 2011 | 391.11530 | 0.923577  | 0.853    | 2.987  | 389.237 | 392.225 |
| 2012 | 393.78250 | 1.949070  | 1.799    | 2.845  | 386.344 | 394.189 |

From Figure 2, multi-year average mid-tropospheric concentration of CO$_2$ illustrated a relatively heterogeneous distribution throughout the country. In the Peninsular of Malaysia, the regions with high CO$_2$ concentration levels were located in the northern division of Malaysia, while low concentrations were in the southern. An almost identical pattern was observed for the East of Malaysia, whereby the Sarawak state in the northern part was characterized by relatively lower mid-tropospheric CO$_2$ concentrations than the Sabah state that is located northward. The former is hypothesized to be affected by monsoonal change and forest land cover. The highly variable CO$_2$ concentrations throughout the country signify to have more CO$_2$ monitoring stations for precise monitoring.

Figure 2. 4-years average (January 2009 to December 2012) of distribution of mid-tropospheric CO$_2$ concentration in Malaysia
Table 3 tabulates the concentration of CO\(_2\) according to selected location of meteorology stations and monsoonal change. The yearly average concentration for all the stations was similar at approximately 388 ppm. The highest concentration was shown at Kudat station, Sabah (389.667 ppm). In general, the average annual growth rate indicated an increase in mid-troposphere CO\(_2\) concentrations each year. The highest annual growth rate was found in Bintulu (2.683 ppmv/a), followed by Sibu (2.062 ppmv/a), and Tawau (2.231 ppmv/a). Nonetheless, the growth rate for most of the stations were below than 2.000 ppmv/a. The possible sources to the increase in concentration may include increase in burning of fossil fuels, transboundary emissions and deforestation.

Table 3. Mid-troposphere CO\(_2\) concentration statistics during 2009-2012

| Station          | Yearly Average Concentration (ppm) | Annual Growth (ppm/a) | Seasonal Average | Seasonal Fluctuation |
|------------------|------------------------------------|-----------------------|-----------------|----------------------|
|                  |                                    |                       | NEM             | SWM                  | Average Fluctuation | Maximum | Minimum   |
| Alor Setar       | 389.449                            | 1.721                 | 390.150         | 389.003              | 4.775               | 384.905 | 393.000   |
| Bintulu          | 389.002                            | 2.683                 | 389.249         | 388.942              | 2.036               | 384.813 | 393.014   |
| Butterworth      | 389.423                            | 1.656                 | 390.026         | 389.054              | 4.122               | 385.065 | 392.849   |
| Cameron          | 389.216                            |                       | 389.606         | 389.034              | 2.615               | 384.785 | 393.191   |
| Highlands        |                                    | 1.476                 |                 |                      |                     |         |           |
| Ipoh             | 389.302                            | 1.484                 | 389.716         | 389.090              | 2.814               | 384.959 | 392.929   |
| Johor Bharu      | 388.971                            | 0.293                 | 389.299         | 388.766              | 2.608               | 385.319 | 392.284   |
| Kota Bharu       | 389.664                            | 1.025                 | 390.415         | 389.161              | 4.608               | 384.331 | 394.476   |
| Kota             | 389.549                            |                       | 389.923         | 389.182              | 3.416               | 385.000 | 393.210   |
| Kinabalu         |                                    | 1.196                 |                 |                      |                     |         |           |
| Kuala Krai       | 389.577                            | 0.993                 | 390.213         | 389.165              | 3.950               | 384.539 | 394.531   |
| Sepang           | 388.813                            | 0.576                 | 389.133         | 388.620              | 2.464               | 385.091 | 392.592   |
| Subang           | 388.896                            | 1.010                 | 389.208         | 388.731              | 2.336               | 384.972 | 392.794   |
| Kuala            | 389.413                            |                       | 390.005         | 389.044              | 3.675               | 384.600 | 394.073   |
| Terengganu       |                                    | 1.155                 |                 |                      |                     |         |           |
| Kuantan          | 389.018                            | 1.423                 | 389.445         | 388.763              | 3.011               | 384.969 | 393.383   |
| Kuching          | 389.123                            | 1.680                 | 389.260         | 389.207              | 1.377               | 384.573 | 392.965   |
| Kudat            | 389.667                            | 1.200                 | 390.302         | 389.105              | 4.704               | 385.000 | 393.514   |
| Labuan           | 389.535                            | 1.280                 | 389.758         | 389.299              | 2.629               | 385.000 | 393.184   |
| Langkawi         | 389.404                            | 1.877                 | 390.058         | 388.988              | 4.648               | 385.006 | 393.285   |
| Malacca          | 388.774                            | -0.118                | 389.055         | 388.571              | 2.403               | 385.483 | 392.824   |
| Mersing          | 389.106                            | 0.534                 | 389.444         | 388.905              | 2.587               | 385.480 | 392.698   |
| Miri             | 389.338                            | 1.703                 | 389.536         | 389.191              | 2.427               | 385.019 | 393.123   |
| Bayan Lepas      | 389.424                            | 1.537                 | 389.967         | 389.101              | 3.739               | 385.171 | 392.849   |
| Petaling Jaya    | 388.890                            | 0.996                 | 389.194         | 388.732              | 2.289               | 384.968 | 392.794   |
| Sandakan         | 389.563                            | 0.911                 | 389.763         | 389.003              | 3.598               | 385.000 | 392.880   |
| Sibu             | 389.923                            | 2.062                 | 389.050         | 389.040              | 1.071               | 384.989 | 393.390   |
| Sitiawan         | 389.313                            | 1.244                 | 389.629         | 389.156              | 2.248               | 385.301 | 392.980   |
| Tawau            | 389.428                            | 1.977                 | 389.779         | 389.121              | 2.989               | 384.979 | 392.147   |
| Temerloh         | 388.840                            | 1.240                 | 389.115         | 388.730              | 2.074               | 384.671 | 392.127   |
| Lembah           | 389.375                            |                       | 389.734         | 389.056              | 3.202               | 385.000 | 392.591   |
| Danum            |                                    | 1.402                 |                 |                      |                     |         |           |
According to Table 3, there was an average fluctuation of 3.015 ppm of CO$_2$ between the two monsoons during the study period, suggesting a difference of more than 3.0 ppm which proves the suitability of the AIRS data to measure the season fluctuation [9]. The lowest concentration of 384.331 ppm occurred in January in Kota Bharu during the NEM, while the highest concentration of 394.531 ppm was found in May in Kuala Krai during the SWM. This is consistent with the findings from the One-Way Analysis of Variance which shows the concentration of CO$_2$ during NEM was significantly higher than that during SWM (p = 0.00) (Table 4). The CO$_2$ concentrations underwent seasonal differences may largely associated with the amount of sunlight and precipitation received during both monsoons. During the NEM, higher precipitations occur due to the upbring of prevailing winds from the North Pacific Ocean and from China. When there is an increase in precipitation, photosynthesis rate of green vegetation will decrease because less sunlight penetrates through the clouds, causing an abundance of unabsorbed CO$_2$ in the atmosphere. During the SWM, photosynthesis increases, and vegetation with good growth and high coverage can absorb large amounts of CO$_2$, so the near-surface CO$_2$ concentrations decrease during this period.

Table 4: One-Way Analysis of Variance of concentration of CO$_2$ by monsoons.

| Source               | df | SS     | MS     | F     | p    |
|----------------------|----|--------|--------|-------|------|
| Between groups       | 1  | 23.85  | 23.85  | 8.80  | 0.00 |
| Within groups        | 222| 601.87 | 2.71   |       |      |
| Total                | 223| 625.72 |        |       |      |

3. Conclusions
This study evaluated the AIRS mid-tropospheric data product against the GAW CO$_2$ measurement prior to the spatio-temporal assessment of the CO$_2$ concentrations in Malaysia. It is concluded that the mid-tropospheric CO$_2$ concentration extracted from AIRS data product was able to explain the variations in the ground observations up to 76.7%, with the mean monthly deviation that was less than 2 ppm. Additionally, the mid-tropospheric AIRS CO$_2$ concentrations in Malaysia were regionally heterogeneous, chiefly characterized by the monsoon change. Moreover, mid-tropospheric AIRS CO$_2$ concentration illustrated an annual increasing trend over the Malaysian region. These findings shows that the mid-tropospheric AIRS CO$_2$ concentrations were able to observe seasonal and annual cycles. In future, the AIRS product nevertheless should be bias-corrected for more accurate applications.

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