Greenhouse gases and air pollutants monitoring project around Jakarta megacity

M Nishihashi¹, H Mukai¹, Y Terao¹, S Hashimoto¹, Y Osonoi¹, R Boer², M Ardiansyah², B Budianto², G S Immanuel², A Rakhan², R Nugroho³, N Suwedi³, A Rifai³, I M Ihsan³, A Sulaiman³, D Gunawan³, E Suharguniyawan³, M S Nugraha⁴, R C Wattimena⁴ and A F Ilahi⁴

¹ National Institute for Environmental Studies (NIES), 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
² Bogor Agricultural University (IPB), Gedung Fisik dan Botani Lantai 2, Kampus IPB Baranangsiang, Jl. Pajajaran No.1, Bogor, Jawa Barat 16143, Indonesia
³ Agency for the Assessment and Application of Technology (BPPT), Laboratorium Geostech 820, Kawasan Puspiptek Serpong, Tangerang Selatan, Banten 15314, Indonesia
⁴ Meteorological, Climatological, and Geophysical Agency (BMKG), Jl. Angkasa I No.2, Kemayoran, Jakarta Pusat, DKI Jakarta 10610, Indonesia

nishihashi.masahide@nies.go.jp

Abstract. National Institute for Environmental Studies (NIES) has been implementing a joint monitoring project of greenhouse gases (GHGs) and air pollutants in Indonesia with Bogor Agricultural University (IPB), Agency for the Assessment and Application of Technology (BPPT), and Meteorological, Climatological, and Geophysical Agency (BMKG). To estimate the amount of anthropogenic emissions from Jakarta megacity (Jabodetabek) and compare with city activities, we developed a ground-based comprehensive monitoring system of GHGs and air pollutants and installed it at Bogor (center of Bogor city) in March 2016, Serpong (Jakarta suburb) in August 2016, and Cibeureum (mountainous area, background-like site) in March 2017. The monitoring system consists of data acquisition/control units and the instruments for continuous measurements of CO₂, CH₄, CO, NOₓ, SO₂, O₃, aerosol concentrations (PM₂.₅, PM₁₀, BC) and the chemical components, and meteorological parameters. Flask sampling of air is also done to analyze N₂O, SF₆, and carbon isotopes (¹³C, ¹⁴C) in CO₂ and to validate the continuous measurement data. The result shows that CO₂ mole fractions observed at three sites have clear diurnal variations representing the minimum values from 12 to 15 local time while the values at Bogor and Serpong are 6.8 and 7.1 ppm higher than Cibeureum, respectively.

Keywords : CO₂, CH₄, CO, NOₓ, SO₂, O₃, aerosol.

1. Introduction
Megacities, being hotspots of human activity, have emitted large quantities of greenhouse gases (GHGs) and air pollutants into the atmosphere with distinct climate effects [1]. Jakarta, the capital and largest city of the Republic of Indonesia, including suburban cities (Bogor, Depok, Tangerang, South Tangerang, and Bekasi; locally known as “Jabodetabek”), has a population of 32 million people and has been listed as the second largest megacity in the world and the largest megacity in Southeast Asia [2]. The increasing GHGs and air pollutants emissions from the megacity in developing country such as
Jakarta due to rapid economic growth in recent years have been recognized as one of the important issues to be solved [3]. Since reduction strategies of GHGs and air pollutants emissions in developing countries have been relatively insufficient compared to developed countries, further urbanization will lead to further increase of GHGs and deterioration of air quality. Urban climate change-related risks, such as heat stress, extreme precipitation, inland and coastal flooding, and air pollution, are increasing with widespread negative impacts on people (and their health, livelihoods, and assets) and on local and national economies and ecosystems [4]. Hence new interdisciplinary research studies have been needed to increase our current understanding of the interactions between emissions, air quality, and regional/global climates taking place in megacities [1].

Several urban air quality monitoring studies in Indonesia were conducted in Jakarta [5, 6, 7, 8], Serpong [8, 9], Bandung [8, 10, 11], and Makassar [12]. However, highly accurate and continuous monitoring has been insufficient due to the limitations of environmental monitoring budgets and experts [3, 6]. Such situations may not promote better understanding of GHGs and air pollutants variability in Indonesia, which is considerably important for making quick actions for global warming mitigation.

National Institute for Environmental Studies (NIES) has been implementing a joint monitoring project of GHGs and air pollutants in Indonesia with Bogor Agricultural University (IPB), Agency for the Assessment and Application of Technology (BPPT), and Meteorological, Climatological, and Geophysical Agency (BMKG). To estimate the amount of anthropogenic emissions from Jakarta megacity (Jabodetabek) and compare with city activities, we developed a ground-based comprehensive monitoring system of GHGs and air pollutants and installed it at three sites around Jakarta. In this paper, we introduce the monitoring system and the initial results obtained at three monitoring sites.

2. Monitoring system

We developed a ground-based comprehensive monitoring system of GHGs and air pollutants. By monitoring both GHGs and air pollutants, it will be possible to gain a greater understanding of the complex relationships between these species during different seasons and times of day as a result of emissions from anthropogenic and natural sources as well as secondary atmospheric chemical reactions [13]. After developing the monitoring system in NIES, we transferred it from Japan to Indonesia and then installed it at Bogor (center of Bogor city) in March 2016, Serpong (Jakarta suburb) in August 2016, and Cibeureum (mountainous area, background-like site) in March 2017 (Figure 1, Table 1).

The monitoring system consists of data acquisition and system control units (GSCT-14, Kimoto) and the instruments for continuous measurements of carbon dioxide (CO₂), methane (CH₄) (G2301, Picarro), carbon monoxide (CO) (CO-30r, Los Gatos Research), nitrogen oxides (NOₓ) (Model 42i-TL, Thermo), sulfur dioxide (SO₂) (Model 43i-TLE, Thermo), ozone (O₃) (OA-787, Kimoto), aerosol concentrations (particulate matter (PM_{2.5}, PM_{10}), black carbon (BC)) and the chemical components of PM_{2.5} and PM_{10} (nitrate ion (NO₃⁻), sulfate ion (SO₄²⁻)) (ACSA-14, Kimoto), and meteorological parameters (WXT520, VAISALA) (Table 2). Flask sampling of air has also been done automatically at 1:30 PM in local time once a week to analyze nitrous oxide (N₂O), sulfur hexafluoride (SF₆), and carbon isotopes (¹³C, ¹⁴C) in CO₂ in NIES and to validate the continuous measurement data of CO₂, CH₄, and CO (these flask sampling data are not shown in this paper). Figures 2 and 3 show the framework and schematic diagram of the monitoring system, respectively. Also Figures 4 and 5 express the appearance of the system installed at IPB in Bogor. This system allows us to control remotely not only all instruments but also peripheral devices (e.g., pumps, valves) through the IPsec virtual private network constructed between three monitoring sites and NIES. The system also has an automatic operation function for power failures because electric power supply is sometimes unstable due to high lightning activity in Indonesia. Moreover, the system is corresponding to redundant operation for any device failures (i.e., there are dual air sampling lines, dual dust filters, dual sampling pumps, etc.; Figure 3). For instance, if any problems occur in one sampling pump, we can change the pump to alternative one remotely. To minimize missing data by any instrument and/or program errors, the system has an e-mail alert function to send alert mails on errors and also has a status mail function to send a status mail every morning. The monitoring data obtained from each measuring instrument and sensor, such as flow meters, pressure sensors, and temperature sensors, are visualized on the monitoring display (Figure 6) in real-time and recorded every
1 minute in unified data format with GPS time stamps. These data files are transferred to a cloud server at regular intervals. For highly accurate measurements, the observed values of CO₂, CH₄, CO, NOₓ, and SO₂ mole fractions have been automatically calibrated with standard gases periodically. We have utilized 9 standard gas cylinders in Bogor and Cibeureum and 6 standard gas cylinders in Serpong (4 concentrations of CO₂/CH₄, 3 concentrations of CO, 1 concentration of NO, and 1 concentration of SO₂). These standard gases of CO₂, CH₄, and CO were calibrated with NIES-09, NIES-94, and NIES-09 scales, respectively [14], in advance of the shipment from NIES. As for calibration for NOₓ and SO₂, we used commercially available NO and SO₂ standard gases which had higher concentrations (e.g., ppm level). Such gases were diluted by zero gas (i.e., NOₓ and SO₂ free air) to make span gases for the analyzers.

![Figure 1. Map of the monitoring sites.](image)

### Table 1. Location and affiliation of the monitoring sites and monitoring starting date.

| Location                          | Affiliation                                                                 | Latitude | Longitude | Altitude | Starting date     |
|-----------------------------------|------------------------------------------------------------------------------|----------|-----------|----------|-------------------|
| Serpong                           | Geostech Laboratory, Agency for the Assessment and Application of Technology (BPPT) | 6.36°S   | 106.67°E  | 63 m     | 26 Aug 2016       |
| (Jakarta suburb)                  | Center for Climate Risk and Opportunity Management in Southeast Asia Pacific, Bogor Agricultural University (IPB CCROM-SEAP) | 6.60°S   | 106.81°E  | 266 m    | 1 Jun 2016        |
| Bogor (center of Bogor city)     | Meteorology Station Cibeureum, Meteorological, Climatological, and Geophysical Agency (BMKG) | 6.71°S   | 106.95°E  | 1160 m   | 10 Mar 2017 (O₃, PM) |
| Cibeureum (mountainous area)      |                                                                              |          |           |          | 6 Jun 2017 (all)  |
### Table 2. Monitoring species and instruments.

| Species | Characteristics                  | Monitoring instrument                                                                 | Serpong | Bogor | Cibeureum |
|---------|----------------------------------|--------------------------------------------------------------------------------------|---------|-------|-----------|
| CO₂     | GHG                              | CO₂/CH₄/H₂O analyzer (G2301, Picarro)                                                | √       | √     | √         |
| CH₄     |                                  |                                                                                      |         |       |           |
| CO      | Air pollutant                    | CO analyser (CO-30r, Los Gatos Research)                                             |         | √     | √         |
| O₃      | GHG, air pollutant               | O₃ analyzer (OA-787, Kimoto)                                                         | √       | √     | √         |
| PM₂.₅, PM₁₀ | Air pollutant, radiation related material | Continuous dichotomous aerosol chemical speciation analyzer (ACSA-14, Kimoto) |         |       |           |
| NOₓ     | Air pollutant, converted to NO₃⁻ | NO₃ analyzer (Model 42i-TL, Thermo)                                                  | √       | √     | √         |
| SO₂     | Air pollutant, converted to SO₄²⁻ | SO₂ analyzer (Model 43i-TLE, Thermo)                                                 | √       | √     | √         |
| CO₂, CH₄, N₂O, SF₆ | GHG                            |                                                                                      |         |       |           |
| CO      | Air pollutant                    |                                                                                      |         |       |           |
| CO₂ stable isotope (¹³C and ¹⁸O) | CO₂ indicator                  | Automatic flask sampler (S-KM-1S, Koshin-RS) and analysis in NIES                  | √       | √     | √         |
| CO₂ radiocarbon (¹⁴C)                  |                                  |                                                                                      |         |       |           |

| Meteorology | Weather sensor (WXT520, VAISALA) | √ | √ | √ |

**Figure 2.** Framework of the monitoring system.
Figure 3. Schematic diagram of the monitoring system.

Figure 4. Appearance of the monitoring site at Bogor. (1) Monitoring room and tower, (2) inlets on the tower (35 m above the ground), (3) GPS antenna and weather sensor (WXT520, VAISALA), (4) continuous dichotomous aerosol chemical speciation analyzer (ACSA-14, Kimoto).
Figure 5. Monitoring system in the monitoring room at Bogor site. (1) Data acquisition and system control units (GSCT-14, Kimoto), (2) CO₂/CH₄/H₂O analyzer (G2301, Picarro), (3) CO analyzer (CO-30r, Los Gatos Research), (4) NO analyzer (Model 42i-TL, Thermo), (5) SO₂ analyzer (Model 43i-TLE, Thermo), (6) O₃ analyzer (OA-787, Kimoto), (7) automatic flask sampler (S-KM-IS, Koshin-RS), freeze trap, and flask box, (8) flow path switching units for CO₂/CH₄/H₂O and CO analyzers (GJBT-2001-01, Glovebox Japan), (9) standard gas dilutors for NOₓ and SO₂ analyzers (103S, Nippon thermo), (10) zero gas generator for NOₓ and SO₂ analyzers and exhaust pump for NOₓ analyzer, (11) exhaust pumps for CO₂/CH₄/H₂O and CO analyzers, (12) uninterruptible power supplies, (13) power supply units for GSCT-14. There are three sets of dust filters for NOₓ (a), SO₂ (b), and O₃ (c) analyzers.

Figure 6. (a) Monitoring and controlling program for the monitoring system, (b) real-time monitoring data visualization program.

3. Monitoring data
We report the initial results obtained at Serpong, Bogor, and Cibeureum.

3.1. CO₂, CH₄, and CO
Figure 7 shows the temporal variation of hourly averaged CO₂, CH₄, and CO mole fractions observed at Serpong, Bogor, and Cibeureum from 1 June 2016 to 11 March 2018. The mole fractions of CO₂ and CH₄ at Serpong and Bogor and of CO at Bogor are relatively high value compared with those at Cibeureum. In particular, very high mole fraction (3–5 ppm) of CH₄ were observed at Serpong from
evening to early morning as well as CO₂ at Serpong (Figure 7, 8). Figure 9 shows the diurnal variations of CO₂ mole fractions (hourly median) observed at three sites from 1 June 2017 to 28 February 2018. They have clear diurnal variations representing the minimum values at 3 sites during early afternoon (12–15 local time) and the maximum values at Serpong and Bogor during early morning and at Cibeureum during midnight. Hence we computed daytime values of CO₂ mole fractions at each site using three hours averages from 12 to 15 local time (Figure 10). The daytime values at Bogor and Serpong are 6.8 and 7.1 ppm higher than Cibeureum in average between June 2017 and March 2018, respectively. These results indicate that the mole fractions of CO₂ at Serpong and Bogor and of CO at Bogor have been affected by anthropogenic emission originating from fossil fuel combustion and industrial processes in the urban area. Meanwhile, those values observed at Cibeureum indicate that they have background-like characteristics. Furthermore, we need to survey the reason of the high concentration of CH₄ and CO₂ at Serpong and also any effects of vegetation and anthropogenic emissions around three sites using carbon isotopes obtained from flask samplings.

The daytime values at Bogor and Serpong in December and January are 5–10 ppm lower than the other months. We also observed no frequent night-time enhancements of CO₂ and CH₄ mole fractions at Serpong in December and January. The wind rose diagrams of the three sites in April, July, and October 2017 and January 2018 in Figure 11 show that most of winds in January (mid-rainy-season around Jakarta) blow from westerly direction obviously, which is relatively strong wind compared with the other months. There are no large source in the west of Serpong and Bogor. Thus we estimate that the lower values of CO₂ mole fractions in December and January are caused by such distinctive westerly and relatively strong wind.

3.2. NO, NO₂, SO₂, and O₃
Figure 12 shows the temporal variations of hourly NO, NO₂, SO₂, and O₃ mole fractions observed at Serpong, Bogor, and Cibeureum from 1 June 2016 to 11 March 2018. The mole fractions of NO, NO₂, and SO₂ at Serpong and Bogor tend to be higher than those at Cibeureum. While the NO mole fractions at Cibeureum almost stayed at low level (1–2 ppb), the NO mole fractions at Serpong and Bogor sometimes exceeded 40 ppb. This result indicates that there are many anthropogenic emission sources around Serpong and Bogor while there are few sources around Cibeureum. The clear diurnal variations of O₃ mole fractions are recognized at three sites. Although the peak values of the O₃ mole fraction in the afternoon observed at three sites were almost same level, the values of O₃ mole fraction at Cibeureum during night-time were 10–20 ppb higher than Serpong and Bogor. Moreover, the mole fractions of NO₂, SO₂, and O₃ at three sites decreased in December and January as well as CO₂ and CH₄.

![Figure 7](image-url) Temporal variation of hourly CO₂, CH₄, and CO mole fractions observed at Serpong, Bogor, and Cibeureum from 1 June 2016 to 11 March 2018.
Figure 8. Temporal variation of hourly CO$_2$, CH$_4$, and CO mole fractions observed at Serpong, Bogor, and Cibeureum in July 2017.

Figure 9. Diurnal variation of hourly CO$_2$ mole fractions observed at Serpong, Bogor, and Cibeureum from 1 June 2017 to 28 February 2018.

Figure 10. Daytime value (average from noon to 3 PM) of CO$_2$ mole fraction observed at Serpong, Bogor, and Cibeureum from 1 June 2016 to 11 March 2018.
Figure 11. Wind rose diagrams of Serpong, Bogor, and Cibeureum in April, July, and October 2017 and January 2018.

Figure 12. Temporal variations of hourly NO, NO$_2$, SO$_2$, and O$_3$ mole fractions observed at Serpong, Bogor, and Cibeureum from 1 June 2016 to 11 March 2018.

3.3. $\text{PM}_{2.5}$, $\text{PM}_{10-2.5}$, and $\text{BC}$

Figure 13 shows the temporal variation of $\text{PM}_{2.5}$, $\text{PM}_{10-2.5}$, and $\text{BC}$ concentrations observed at Bogor and Cibeureum from 1 June 2016 to 11 March 2018. The measurement interval is 3 hours to extend the replacement interval of filter tape and chemical reagents for the chemical component analysis of $\text{PM}_{2.5}$ and $\text{PM}_{10-2.5}$. The average values of $\text{PM}_{2.5}$ observed at Bogor and Cibeureum during dry season,
approximately from May to October, are 2.0 and 2.7 times higher than those of wet season, from November to April, respectively. While the seasonal trend of PM\textsubscript{2.5} at Bogor is similar with Cibeureum, the average PM\textsubscript{2.5} at Bogor is 1.8 times larger than Cibeureum. The difference of PM\textsubscript{10-2.5} and BC between Bogor and Cibeureum is large, compared with PM\textsubscript{2.5}, and the average values of PM\textsubscript{10-2.5} and BC observed at Bogor is 2.8 and 4.2 times larger than Cibeureum, respectively. These results suggest that the PM\textsubscript{2.5}, PM\textsubscript{10-2.5}, and BC at Bogor is affected by peripheral anthropogenic emissions compared with Cibeureum.

![Figure 13](image_url) Temporal variation of PM\textsubscript{2.5}, PM\textsubscript{10-2.5}, and BC concentrations observed at Bogor and Cibeureum from 1 June 2016 to 11 March 2018. The measurement interval is 3 hours.

4. **Summary**

We developed a ground-based comprehensive monitoring system of GHGs and air pollutants specialized for remote automatic operation in Indonesia and installed it at Bogor, Serpong, and Cibeureum in 2016–2017 to estimate the amount of anthropogenic emissions from Jakarta megacity and compare with city activities. The monitoring results indicate that the mole fractions of CO\textsubscript{2} at Serpong and Bogor and of CO at Bogor have urban characteristics affected by anthropogenic emission from the urban area while those values at Cibeureum have background-like characteristics. This characteristics are also recognized in the other species, NO\textsub{x}, SO\textsub{2}, PM\textsubscript{2.5}, PM\textsubscript{10-2.5}, and BC. Moreover, we found diurnal and seasonal characteristics. We need to continue the GHGs and air pollutants monitoring in Indonesia for a long time to observe the variability and to predict future local and global environment.

**Acknowledgement**

This monitoring project was funded by the Ministry of the Environment, Japan. We would like to thank Keiichi Katsumata for his support of installation and maintenance of instruments.

**References**

[1] Baklanov A, Molina L T and Gauss M 2016 Megacities, air quality and climate Atmos. Environ. 126 235–49

[2] Demographia 2018 Demographia world urban areas 14\textsuperscript{th} annual edition: 201804 (Belleville, Demographia)

[3] Santosa S J, Okuda T and Tanaka S 2008 Air pollution and urban air quality management in Indonesia Clean Soil Air Water 36 466–75

[4] IPCC 2014 Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change (Cambridge: Cambridge University Press)

[5] Hamonangan E, Kondo A, Kaga A and Inoue Y 2002 Simulation and monitoring of sulphur dioxide and nitrogen oxides in the Jakarta Metropolitan Area Asian J. Energy Environ 3 159–83
[6] Kondo A, Hamonangan E, Soda S, Kaga A, Inoue Y, Eguchi M and Yasaka Y 2007 Impacts of converting from leaded to unleaded gasoline on ambient lead concentrations in Jakarta metropolitan area J. Environ. Sci. 19 709–13

[7] Permadi D A and Kim Oanh N T 2008 Episodic ozone air quality in Jakarta in relation to meteorological conditions Atmos. Environ. 42 6806–15

[8] Santoso M, Lestiani D D and Hopke P K 2013 Atmospheric black carbon in PM$_{2.5}$ in Indonesian cities J. Air Waste Manag. Assoc. 63 1022–5

[9] Santoso M, Lestiani D D, Mukhtar R, Hamonangan E, Syafrul H, Markwitz A and Hopke P K 2011 Preliminary study of the sources of ambient air pollution in Serpong, Indonesia Atmos. Pollut. Res. 2 190–6

[10] Santoso M, Hopke P K, Hidayat A and Diah Dwiana L 2008 Sources identification of the atmospheric aerosol at urban and suburban sites in Indonesia by positive matrix factorization Sci. Total Environ. 397 229–37

[11] Lestari P and Mauliadi Y D 2009 Source apportionment of particulate matter at urban mixed site in Indonesia using PMF Atmos. Environ. 43 1760–70

[12] Rashid M, Yunus S, Mat R, Baharun S and Lestari P 2014 PM$_{10}$ black carbon and ionic species concentration of urban atmosphere in Makassar of South Sulawesi Province, Indonesia Atmos. Pollut. Res. 5 610–5

[13] Mitchell L E, Crosman E T, Jacques A A, Fasoli B, Leclair-Marzolf L, Horel J, Bowling D R, Ehleringer J R and Lin J C 2018 Monitoring of greenhouse gases and pollutants across an urban area using a light-rail public transit platform Atmos. Environ. 187 9–23

[14] Machida T, Tohjima Y, Katsumata K and Mukai H 2011 A new CO$_2$ calibration scale based on gravimetric one-step dilution cylinders at National Institute for Environmental Studies-NIES 09 CO$_2$ scale Proc. 15th WMO/IAEA Meeting of Experts on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (Jena) (Geneva: WMO) pp 114–8