Analysis of Relationship between Meteorological Conditions and Ground O_3 Levels in Summer Over the Central Kanto Area

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ABSTRACT

The increasing trend in ground ozone (O_3) concentration has recently been recognized in Japan, though concentrations of ozone precursors have been decreased. It is well known the status of atmospheric has been changing on a long term, not only over the world, but also in Japan. Therefore, one of causes is possibly imagined that is the effect of meteorological conditions. In order to confirm whether the change of meteorological conditions contribute to the Japanese O_3 trend we examine the relationship between meteorological factors (e.g., temperature, wind speed) and ground O_3 levels concentration over the central Kanto area of Japan using both statistical analysis and numerical models. The nested grid system of numerical experiments which cover a region of Kanto with grid resolutions of 9 km, 3 km, and 1 km respectively, have been employed in this study. The results of analysis show there are close relationships between meteorological conditions and the peak O_3 and changes in meteorological conditions may be one of causes leading to the rising O_3 concentration levels in this area.

Keywords: Atmospheric Pollution; Urban Heat Island; MM5; CMAQ; Ozone

Introduction

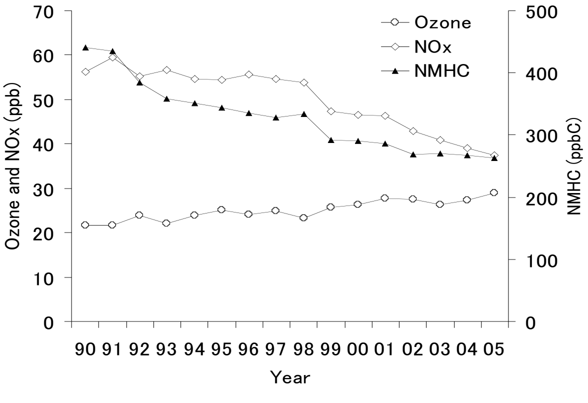
The Kanto area is the largest inland and the most highly developed, urbanized, and industrialized part of Japan. This area encompasses seven prefectures which overlap the Greater Tokyo Area: Gunma, Tochigi, Ibaraki, Saitama, Tokyo, Chiba, and Kanagawa, as shown in Fig. 1. Its area extends about 100 km in the E-W direction and 200 km in the N-S direction. With the increasing trend of city-growth and urbanization, the Kanto area also has to face air pollution problems. According to the Tokyo Metropolitan Government Environmental White Paper 2006 (http://www.kankyo.metro.tokyo.jp), the concentration of most of air pollutants are decreasing in Tokyo Metropolitan area due to the application of exhaust control regulations to factories and industrial complex, and introduction of regulations to control diesel emissions from automobiles. However, the concentration of photochemical oxidant has not achieved the Environmental Quality Standards (one-hour value of 0.06 ppm or less) and the number of the days which high concentration of O_3 is recorded has been increasing. Fig. 2 shows the annual averaged values of ozone, nitrogen oxides (NOx) and non-methane hydrocarbons (NMHC) from 1990 to 2005 in the Tokyo region. It is obvious that both NOx and NMHC have a decreasing tendency, while O_3 concentration has an increasing tendency for over two decades. Possible reasons for this trend of O_3 have discussed using both models and measurements (Ohara et al., 2001, 2008; Akimoto, 2003; Yamaji et al., 2006; Kannari et al., 2008). Most of these studies indicated that the long range transported ozone and its precursors from East Asia, particularly China, have been growing rapidly during the past two decades and mainly affect the recent increase of O_3 concentration over Japan. The contributions from change of trans-boundary air pollution are largest in the springtime (Ohara et al., 2001, 2008). However, there is a fact that the concentration of O_3, especially warning ozone levels (1-hour $O_3 \geqq 0.12$ ppm), around the big cities also has been rising in the summer, though in this season the clean air flow are mainly transported by southerly winds from Pacific Ocean. This phenomenon is a very interesting issue that has not been solved yet.

It is well known the changes of the ozone concentration in the troposphere are governed by complicated interaction of different mechanisms like precursors concentration changes, temperature, humidity, solar radiation, horizontal and vertical transport, chemistry, including photochemistry, internal atmospheric and surface sinks and so on. Of course this list should include meteorological conditions which can impact on the surface ozone regime either themselves or through the complex mentioned above mechanisms. Many previous studies showed a close relationship between meteorological conditions and air pollution in general and photochemical ozone in particular over Kanto area (Wakamatsu et al., 1983, 1990; Uno et al., 1984; Kurita et al., 1986; Fujibe et al., 1985; Yoshikado et al., 1994, 1996, 2004, 2007; etc). Most of previous researches use observational data to analysis the role of local meteorological conditions such as land/sea breeze, mountain/valley circulations, cold air lake, local fonts, the heat island of the Tokyo Metropolitan area, etc in formation and transportation of air pollution. Of the studies above, Yoshikado (2004) showed that recent increase of O_3 levels has relationship with increase of occurrence frequency of high pressure systems over Kanto area.

In this paper, we will investigate relationships between the meteorological conditions and summertime O_3 levels over central Kanto area. We firstly analysis the variation of summertime ozone levels and its possible relation with change in meteorological conditions based on measurements. Then authors will consider these relationships based on numerical simulation using the coupled MM5/CMAQ model. The results of study may add to knowledge in effect of meteorological conditions on the variation of summertime O_3 levels over central Kanto area.

Fig 1. Perspective view of topography of Kanto area from the South Direction

Fig 2. Annual Average Pollutants during 1990 - 2005 in the Tokyo Region



Source: National Institute for Environmental Studies, Japan

Statistical method and measurements

Regression analysis

In order to estimate how meteorological conditions affect the variation of O_3 levels, authors carried out a multiple linear regression analysis. This is one of the most widely used methods for predicting ozone concentrations in dependence of meteorological factors. The general equation of the model is as follows:

$$y = a_0 + a_1 x_1 + ... + a_m x_m + \varepsilon \qquad (1)$$

Where, y is objective variable (ozone concentration), m is the number of independent variables (meteorological variables), x_j are independent variable, a_j are regression coefficients (estimated by least square procedure), and ε is error term associated with regression.

Measured data

The seasonally averaged daily maximum O_3 concentration (predictand) of environmental monitoring sites in Tokyo area over the past 21 years (1985 ~ 2005) is used to analysis the long-term variation of O_3 levels. This data was obtained from National Institute for Environmental Studies (NIES), Japan. For independent variables (predictors), determining which and how many meteorological variables need to be included in the model is somewhat subjective and difficult task because they are not really independent. For example, high temperature may associate with high solar radiation and lower humidity. Therefore, to minimize those confusions, authors only select two parameters to analysis. These are measurements of seasonally averaged daily maximum temperature, and seasonally averaged wind speed during 1985 ~ 2005 at Nerima meteorological site (Tokyo, 35°44.1′ N and 139°40.1′ E, 38m above sea level). This data was obtained from Japan Meteorological Agency (JMA), Japan. Additionally, the measurements of ozone, temperature, and wind speed of monitoring sites in Tokyo area during a typical month of summer (August, 2005) are also used to analysis the short-term variation of O_3 levels. This data was obtained from NIES.

Numerical model description

Meteorology and Air quality modeling

The Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) version 3.7, a limited-area, non-hydrostatic, terrain-following sigma-coordinate model (Dudhia et al., 2005), is used in this research to provide spatial and temporal distribution of meteorological fields to the air quality model. It has some characteristic such as: (i) a multiple-nest capability, (ii) non-hydrostatic dynamics, which allows the model to be used at a scale of several kilometers, (iii) multitasking capability on shared- and distributed-memory machines, (iv) a four-dimensional data-assimilation capability (FDDA), and (v) more physics options.

The Community Multi-scale Air Quality (CMAQ) modeling system version 4.6 developed by the Environmental Protection Agency (USA), which was released in 2006, was used in this study. It is a multi-scale and multiple pollutant chemistry-transport model that includes all the critical science processes such as atmospheric transport, deposition, cloud mixing, emissions, gas- and aqueous-phase chemical transformation processes, and aerosol dynamics and chemistry. The CMAQ system can simulate concentrations of tropospheric ozone, acid deposition, visibility, and fine particulates and other air pollutants in the context of a “one atmosphere” approach involving complex atmospheric pollutant interactions on regional and urban scales. The input meteorological data for CMAQ is typically generated by the MM5 model through a meteorology chemistry interface processor-MCIP (Byun and Ching, 1999)

Outline and setting of the numerical experiments

In this study, the MM5 simulation was performed with three nested domains (Fig. 3). A detailed configuration of the model is summarized in Table 1. The three domains cover a region of Kanto with grid resolutions of 9 km, 3 km, and 1 km, respectively. All of the domains have 23 vertical sigma levels from the surface to the 100-hPa level.

The physics options of the model configuration in the MM5 simulation are as follows: Grell cumulus parameterization scheme (Grell et al., 1994); MRF planetary boundary layer scheme (Hong et al., 1996); explicit simple ice microphysics (Hsie et al., 1984); cloud-radiation scheme (Dudhia, 1989) and FDDA. The cumulus parameterization scheme is not used for the 3- and 1-km domains. The CMAQ was configured with the following options: (1) CB-IV speciation with aerosol and aqueous chemistry; (2) the Piecewise Parabolic Method for both horizontal and vertical advection; (3) eddy vertical diffusion; (4) photolysis; (5) no Plume-in-Grid; (6) the EBI chemistry solver configured for CB-IV; (7) use of the 3rd-generation aerosol model; (8) use of the 2nd-generation aerosol deposition model; (9) use of RADM cloud model; and (10) 14 vertical layers. A more detailed description of the scientific mechanisms and implementations of CMAQ can be found in Byun and Ching (1999).

The August 2005, representing typical summer weather, was selected for MM5/CMAQ simulation. Several high ozone events are recorded in this month. Final analysis data (FNL) from the National Centers for Environmental Prediction (NCEP) with horizontal resolution of $1^0 \times 1^0$ and temporal resolution of six hours was used to provide initial and boundary conditions for the MM5 model and FDDA process. The terrain, land use and land-water masks datasets were obtained from the United States Geological Survey (USGS) global covers. The USGS 25-category land use/land cover classification was used to account of the single dominant land use for each computation cell. Hourly NMHC and NOx emission data used in this study are estimated by Hayami et al. (2004). For example, the data at 14:00 JST for the 3×3-km grid is shown in Fig. 4. This included biogenic source, area source, point source and mobile source emissions.

The MM5 simulation is done from 09:00 JST July 31 to 00:00 JST August 31, 2005. The first 15 h of MM5 simulation is a “spin up” period for cloud processes and it not used for CMAQ simulation. After MM5 simulation, CMAQ model was performed in domain 2 with the initial and boundary condition were derived from climatologic profile of atmospheric pollutants(clean air) as described in Byun and Ching (1999) and the observation report of Japan Clean Air Program (Table 2). During summer, Kanto area was mainly dominated by clean air masses with southerly winds from Pacific Ocean. Therefore, clean air condition is selected for south boundary to minimize the effect of boundary condition. Finally, output of CMAQ model in domain 2 used to produce initial and boundary condition for its simulation in domain 3. Results of CMAQ and MM5 simulation in domain 3 are used to analysis relationship between meteorological conditions and O_3 concentration.

Table 1. Analysis Domain Sizes and Grid Resolution

	Computation domain (X[km] x Y[km])	Grid number	Horizontal resolution (km)
D1	450x540	51x61x23	9
D2	216x261	73x88x23	3
D3	99x120	100x121x23	1

Table 2. Initial and Boundary Condition of Some Pollutants (ppb) for CMAQ

Species		O_3	NO	NO2	ALD	FORM	ETH	OLE	TOL	XYL	ISO	PAR
ICs		28	2.0	4.0	1.8	2.2	1.4	1.6	14.4	0.6	0.5	74.3
BCs	N	28	2.0	4.0	1.8	2.2	1.4	1.6	14.4	0.6	0.5	74.3
	E	25	2.0	4.0	1.8	2.2	1.4	1.6	14.4	0.6	0.5	74.3
	W	30	2.0	4.0	2.0	2.4	3.2	4.2	11.4	0.7	0.5	82.7
	S	CMAQ Default										

Fig 3. Analysis Domain for MM5/CMAQ Simulation

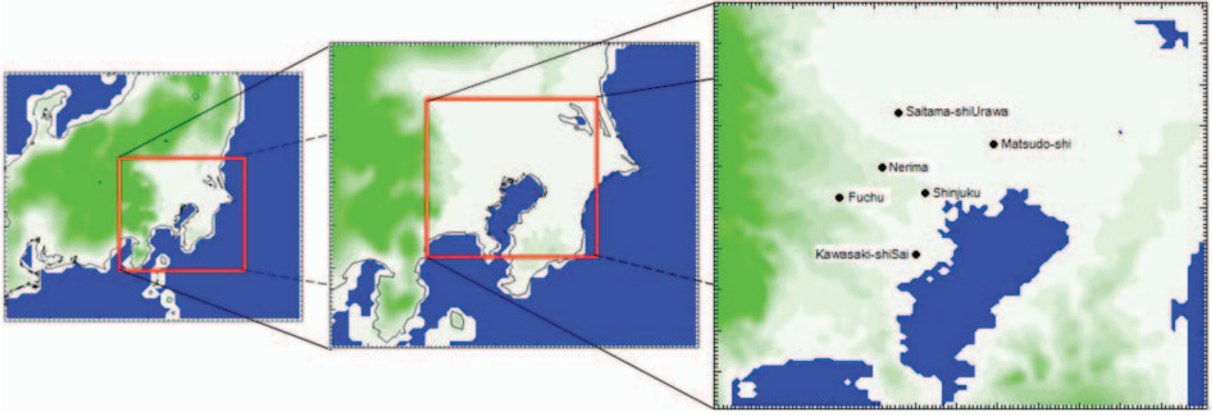
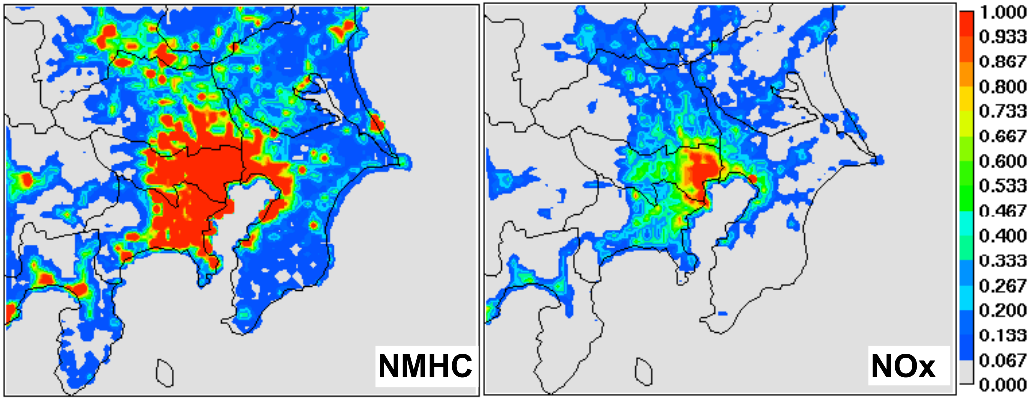


Fig 4. Hour Emission Data for CMAQ at 14 JST (mole/s/grid)



Results and Discussion

Relation between the long-term variation of measured O_3 levels and meteorological conditions in the summer

Using a multiple linear regression method, prediction equations for ozone concentrations were developed based on these meteorological parameters. The seasonally averaged daily maximum O_3 concentration was the dependent variable, while seasonally averaged daily maximum temperature and seasonally averaged wind speed were used as independents in multiple regression analysis. The data were standardized before the regression analysis procedure was applied. Multiple regression result for standardized value of the seasonally averaged daily maximum O_3 concentrations in summer is as follows:

$$O_3 = 0.80 * T - 0.49 * U, \quad R = 0.91, \quad R^2 = 84.1 \qquad (2)$$

Where, R is the multiple correlation coefficient and R^2 (expressed in per cent) is the fraction of the variance explained by the regression.

T-test based on student' distribution was done to test the equation (2). The results show that the regression coefficients of temperature and wind speed are statistically significant. The P-values for all coefficients are less than 0.05(P-value < 0.05). High multiple correlation coefficient (R=0.91) was found between two variables (temperature and wind speed) and the peak O_3 concentration. The peak O_3 concentration predicted by statistical regression model was plotted against the observed values as shown in Fig. 5. The results of high correlation from this analysis show that the peak O_3 concentration strongly affected by meteorological conditions. In the summer about 84.1% of the variation of the peak O_3 may be accounted for by changes in temperature, and wind speed.

Fig 5. The Seasonally Averaged Daily Maximum O_3 Concentration Observed and Predicted by the Regression Equation for Summer Season in Tokyo area.

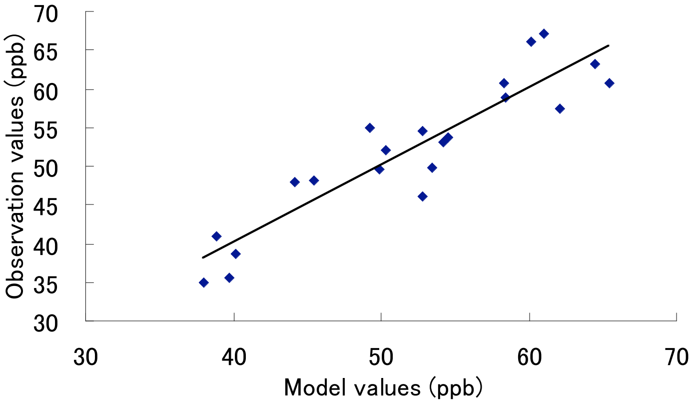


Table 3. Trend of the Seasonally Averaged Daily Maximum O_3 Concentration Observed and Predicted by the Statistical Model in Tokyo area

	Periods	Observation	Model
Averaged daily maximum concentrations (ppb)	1980s	41.04	41.51
	1990s	51.77	52.25
	2000s	61.80	60.60
Difference between periods (ppb)	1990s-1980s	10.73	10.74
	2000s-1990s	10.03	8.35

Averaged daily maximum concentrations and difference between periods of the peak summertime O_3 concentration estimated by multiple linear regression analysis are shown in Table 3. Similar to observed ozone trends, upward positive trends are found during this period (1985 ~ 2005). The high increases are detected in the summer with the averaged peak O_3 concentrations are 41.51, 52.25, and 60.60 ppb for the 1980s, 1990s, and 2000s, respectively. This suggests that meteorological conditions in Tokyo tend to increase the peak O_3 concentration. The peak O_3 trends from 1990s to 2000s due to the changes in meteorological variables are smaller than observed ozone trends. Any remaining variability could be attributed to other causes such as long range transported ozone and its precursors from East Asia, chemical reaction production, other meteorological variables which did not includes in statistical regression model.

Relation between the short-term variation of measured O_3 levels and meteorological conditions during a typical month of summer

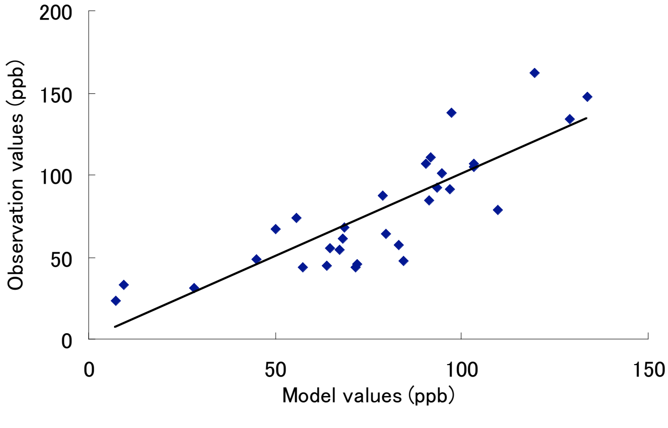
The changes of O_3 levels are expressed as the sum of the long-term and short-term change in meteorological conditions, ozone precursor changes, etc. To understand the daily maximum variations of O_3 concentrations caused by short-term changes in meteorological conditions, daily measurements of August 2005 will be used in an analysis. These are daily maximum ozone concentration, daily maximum temperature, and daily averaged wind speed which all measured at the same environmental monitoring sites in Tokyo area. Appling the same procedure of regression analysis, the statistical model for standardized value of daily maximum O_3 concentrations in Tokyo area during August, 2005 is as follows:

$$O_3 = 0.57 * T - 0.68 * U, \quad R = 0.84, \quad R^2 = 70.3 \qquad (3)$$

T-test based on student' distribution shows regression coefficients of temperature and wind speed in the equation (3) are statistical significant (P-value < 0.05). High correlation (R=0.84) was found between the day to day variation of the peak O_3 concentration and changes in meteorological conditions. The peak O_3 concentration predicted by statistical regression model for one month in summer (August) was plotted against the observed values as shown in Fig. 6, an R^2=70.3 was obtained which suggests that 70.3% of the variation of the daily maximum ozone depend on daily maximum temperature and daily averaged wind speed. The peak O_3 increased with increasing temperature and decreased with increasing wind speed in August, 2005.

It should be noted that the effect of meteorological conditions on ozone concentrations is very complex. Temperature and wind speed can be directly and indirectly related to ozone. For example, high temperature does not only affect photochemical reaction, but can enhance ozone precursor emission rates and thus lead to an increase in the ozone concentration (Narumi et al., 2009). It is therefore necessary to consider the effect of emission in relation between meteorological conditions and ozone concentration. This work will be done using numerical simulation and represent in next section.

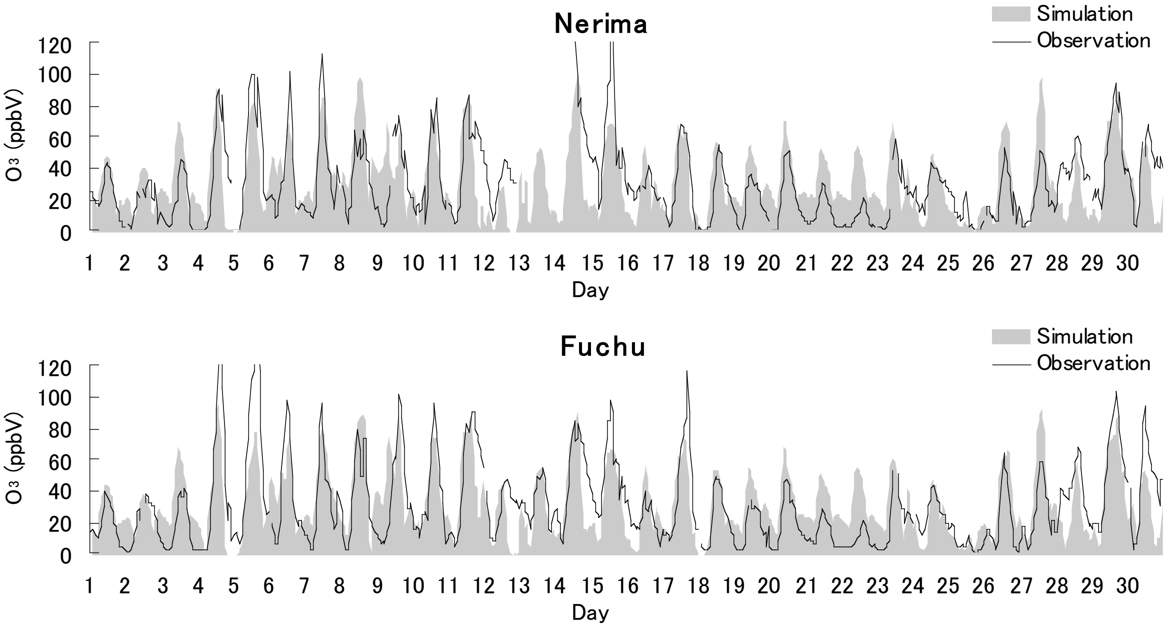
Fig 6. Daily Maximum O_3 Concentration Observed and Predicted by the Regression Equation for August, 2005 in Tokyo area.



Relation between O_3 levels and meteorological conditions based on numerical simulation

Comparison of time series between simulation and observation. In this study, the results from the CMAQ model in domain 3 were compared to measured data from air quality monitoring sites located within Kanto area; Shinjuku, Nerima, Fuchu, Saitama-shiUrawa, Matsudo-shi, and Kawasaki-shiSai, which are shown in Fig. 3. The hourly averaged O_3 comparison between the CMAQ simulation and observation at Nerima and Fuchu sites are shown in Fig. 7. Generally speaking, the model simulation shows different results depending

Fig 7. Hour Ozone Concentration Time Series Variation of Observation and Simulation at Two Sites during August 2005



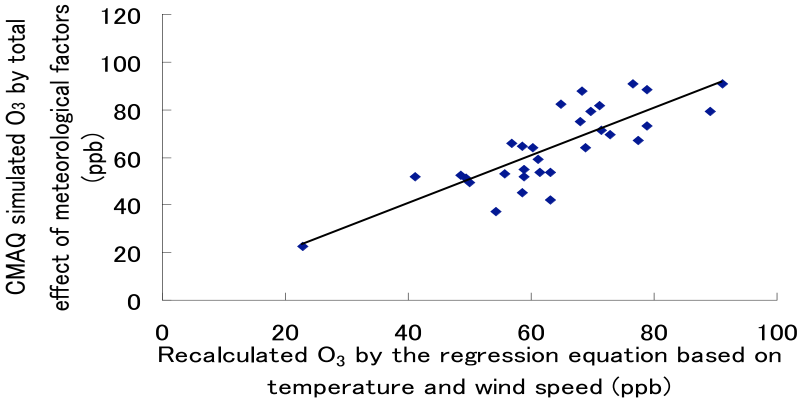
on the location of the monitoring site. It can be said that there is a good agreement between simulated O_3 concentration tendency and observation. For the days with low ozone, the simulated O_3 concentration tends to overestimate the maximum and minimum at all sites. Additionally, the CMAQ model also tends to underestimate the peak of maximum O_3 levels at some days having the extreme observed O_3 concentration. This may be related to surface boundary layer parameterization in the MM5 model (Vautard et al., 2004).

Relation between the short-term variation of simulated O_3 levels and meteorological conditions during a typical month of summer. In this section, the results of numerical simulation will be used to analysis. These are daily maximum ozone concentration, daily maximum temperature, and daily averaged wind speed which extracted from MM5/CMAQ simulation in Tokyo area. To avoid effect of ozone precursor emission changes due to changes in meteorological conditions, in this study emission data is fixed the same for all over simulation days. Appling the same procedure of regression analysis, the statistical model for standardized value of daily maximum O_3 concentrations in August is as follows:

$$O_3 = 0.45 * T - 0.66 * U, \qquad R = 0.81, \qquad R^2 = 66.0 \qquad (4)$$

T-test based on student' distribution was also done to test the equation (4). The result shows regression coefficients of temperature and wind speed are statistical significant (P-value < 0.05). As a result of the multiple linear regression method performed for one month in summer (August) shown in Fig 8, an R^2=66.0 was obtained which suggests that 66% of the variation of the daily maximum ozone may be accounted for by changes in temperature and wind speed. Comparing with analysis results of measurement data, the results obtained from numerical simulation analysis show that the peak O_3 concentration has a weaker level of relation with changes in meteorological conditions. One of reasons may be due to the effect of ozone precursor emission changes associated with changes in meteorological conditions. That change did not include in CMAQ simulations.

Fig 8. Daily Maximum O_3 Concentration Simulated and Estimated by the Regression Equation Against Based on Temperature and Wind Speed in Tokyo area.



It can be determined from equation (4) that the temperature effect on ozone is positive while wind speed effect is negative. There are some reasons to explain this relationship. The first of these is related to the increase in photolysis rates of ozone production with increasing temperature, while wind speed is important factor for the dispersion of ozone concentration. A second reason is attributed to stagnant meteorological patterns associated with high temperature and weak wind. The heat island phenomenon is an example associated with the above meteorological conditions and it will be analyzed below.

Relation between Ground Ozone Concentration and Urban Heat Island. In recent years, urban heat island is well known as one of environmental problems in cities over the world, especially big cities like Tokyo of Japan. The effect of UHI on air pollution over Kanto area has reported by authors. For example, Yoshikado et al. (1996) used observational analysis and indicated interaction between UHI and sea breeze is an important factor causing high air pollution during winter in this area. To examine relationship between UHI phenomenon and air pollution in summer, we select the result of simulation on August 4, 2005 which associated with daytime UHI event over Tokyo area for analysis. This day, the Pacific subtropical high pressure system expands to the west (Fig. 9), the Kanto area was covered by its ridge and the weather was fine. The descending air flow located at the ridge of high pressure system played an important role in high O_3 formation. Fig. 10a shows the spatial distribution of the temperature at 2-m height and 10-m high winds from the MM5 simulation in domain 3 at 12:00 JST. It can be observed that there exists a region of temperature higher than $36^{o}C$ over central Kanto area and the horizontal wind speed is a little weak. This high temperature condition is conducive to photochemical reactions that produce O_3 pollution. Moreover, the high temperature associated with UHI causes pressure deficiency over city and creates a circular pressure gradient pattern around the city as shown in Fig. 10b. In this situation, the sea breeze from Tokyo Bay (S-SE), Sagami Bay (SW-S) and Kashima sea (E) merged and combined with flow from suburban. This system remained without moving for some hours. Dispersion of ozone will be limited under that calm condition, and therefore, there is more O_3 accumulation leading to high O_3 concentration over city as shown in Fig. 11a.

Although the difference of temperature between land and sea is very high, the sea breeze cannot pass through city due to of persistence of UHI Interaction between UHI and sea breeze is also very important in high O_3 formation over Kanto area, it can be described by vertical cross of circulation vector from the shore to suburban AA’ as shown in Fig. 11b. This

Fig 9. Geopotential Height [gpm] and Wind at 850mb at 9 JST on August 4

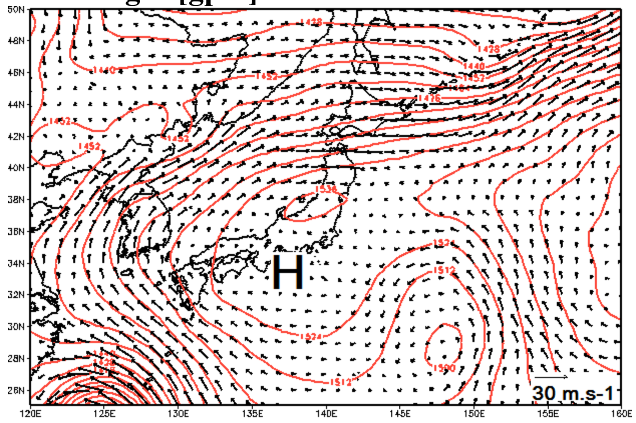


Fig 10. The Results of Simulation from MM5 Model at 12 JST August 4; (a) Simulated 2-m Temperature (^{o}C), 10-m Wind; (b) Sea Level Pressure (mb)

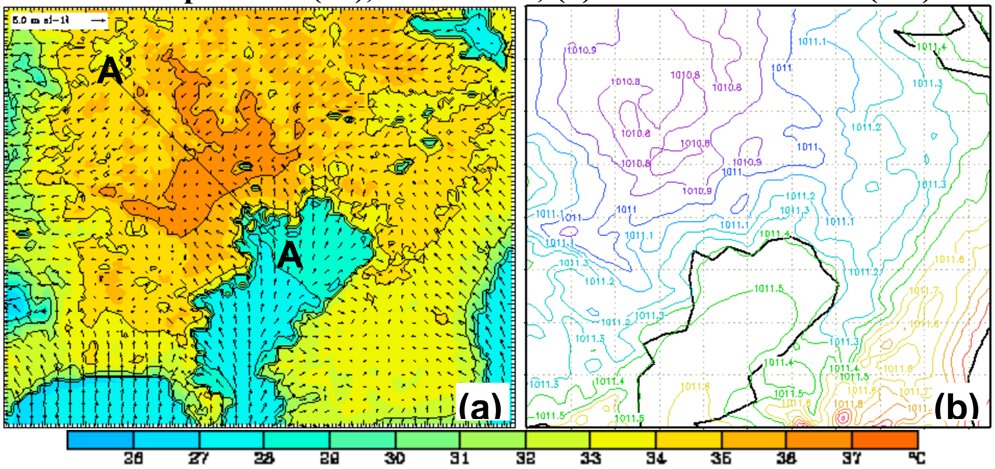
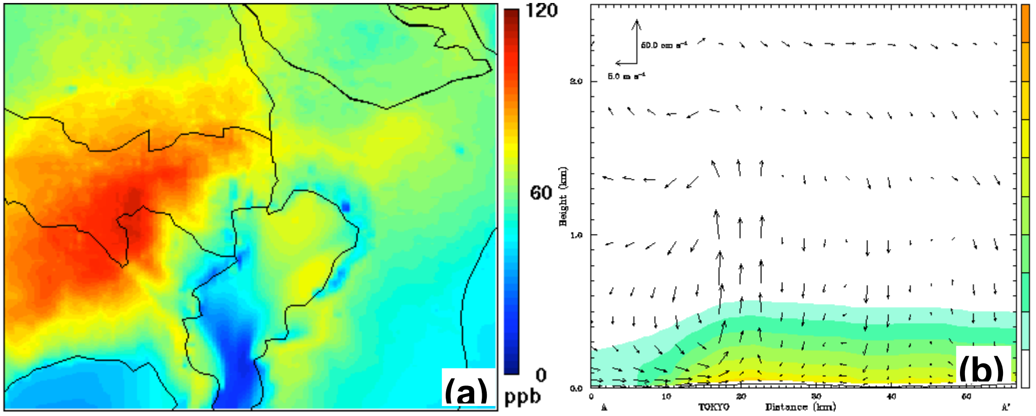


Fig 11. MM5/CMAQ Simulation on August 4; (a) ground O_3 at 14 JST; (b) Circulation Vector and Air Temperature in the Plain of the Cross Section A'A at 12 JST



day, there is no land breeze because the land surface remains hotter than sea surface from last night. During the early morning, the Tokyo Metropolitan area is calm. When the surface was heated by the sun, it created an area with high temperature over Tokyo city. The contrast of temperature between urban and suburban area creates an urban heat island circulation (HIC). At the surface, the flow from suburban meets sea breeze at city and goes up. This updraft of

HIC acts like ‘block’ preventing the penetration of the sea breeze inland. Therefore there is more O_3 accumulation over the city area and extreme pollution levels can result.

Conclusions

The authors have implemented statistical regression analysis and the numerical MM5/CMAQ model in order to investigate the contribution of meteorological conditions to ozone concentrations in summer. The results of this study showed that there is a close relationship between changes in meteorological conditions and the variation in ozone concentrations over the central Kanto area. In summer, up to 84.1% of the long-term variation in peak ozone may be accounted for by changes in the seasonally averaged daily maximum temperature, and seasonally averaged wind speed, while about 70.3% of the short-term variation in peak ozone depends on the daily maximum temperature and daily averaged wind speed. The results suggest changes in meteorological conditions may be one cause leading to the rising ozone concentrations in this area.

These results also indicated that significantly high ozone concentrations appear on days associated with urban heat islands. High temperatures and calm conditions under UHI can cause high ozone levels in this area. UHI and its interaction with the sea breeze strongly affect ozone concentrations. Although the temperature difference between land and sea helps to develop a summer sea breeze, the sea breeze cannot pass through the city due to the persistent UHI. Therefore, dispersion of ozone is limited and the high ozone concentrations can be understood.

This study suggests that the coupled MM5/CMAQ model can be a useful tool for urban environment analysis. However, since many processes and mechanisms affect the ozone concentration, it is necessary to develop a full model describing all chemical and physical processes – involving the complex interaction between topography, city building environment, land use, and anthropogenic emissions, etc. That will constitute our research interest in future studies.

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