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Temperature Change in the Largest Industrial City, Korea

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ABSTRACT

This study analyzed a change trend of ambient temperature over the last sixty years in the largest industrial city in Korea, Ulsan. Linear warming rates in Ulsan over the last 25 (1985 to 2009), 40 (1970 to 2009), and 60 (1950 to 2009) years were 0.0507, 0.0416, and 0.0277°C/yr, respectively. The annual average temperature (AAT) and the annual average of the daily lowest temperature (AADLT) in Ulsan increased 1.3 and 2.9°C, respectively, over the last fifty years (1960 to 2009). The increasing slopes of the AAT and AADLT over the fifty years in Ulsan were higher or much higher than those in neighboring cities and on a global scale. In the comparison analysis of daily average temperature over the most recent ten years, the highest (15.9°C) was observed in the industrial area followed by the downtown, coastal, suburban, and rural areas with 14.6, 14.5, 14.0, and 12.8°C, respectively. The number of cold days less than 5.0°C decreased, while the number of hot days higher than 20.0°C increased. The decreasing slopes in the cold days in lower latitude cities were steeper than those in higher latitude cities in Korea.

Key words: Global warming, Ambient temperature, Cold days, Energy consumption, Air emissions

1. INTRODUCTION

Recently, there have been many reports on the occurrence of extreme or uncommon weather phenomena in hot or cold temperatures, rain or snow precipitation, hurricane or dust storm frequency, etc. For example, the global land and ocean temperatures in 2010 tied with those in 2005, which was the warmest year among the last 131-year historical records (NOAA, 2011). Temperature rise in the climate system resulted in increases in the global averages of air and the ocean temperatures, widespread melting of snow and ice, and rising global average sea levels. Thus climate change has become one of the most important global issues in the 21st century. Recently, according to the Fifth Assessment Report (AR5) prepared by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014; Hartmann *et al*., 2013), the globally average combined land and ocean surface temperature, i.e., average global temperature (AGT), over the world has increased 0.85 (0.65 to 1.06)°C in the last 133 years (1880-2012) and 0.72 (0.49 to 0.89)°C over the last 62 years (1951-2012). According to the summary of the IPCC AR5, the warming trends or the regional average temperature observed in the second half of 20th century in the northern Asian sector was above 2°C (>2°C per 50 years) (Hijioka *et al*., 2014; IPCC, 2014; Christensen *et al*., 2013). In particular, over the last 25 years, the rate of global warming has accelerated at over 0.18°C per decade, which is 2.4 times as high as the increase rate in the last 100 years (WHO, 2013). Climate anomalies accompanied by global climate change are being witnessed in many areas over the world (Smith *et al*., 2008; Smith and Reynolds, 2005; Quayle *et al*., 1999; Peterson and Vase, 1997). For example, the lowest air temperature and heaviest snowfall were observed in the United Kingdom and in the United States of America in the winter of 2010-2011 (NOAA, 2011), respectively. Also, summer heat waves were observed over Russo-European-Asian countries in 2010 (NOAA, 2011). In particular, high summer temperatures dominated the western parts of Russia during June and July of 2010.

Climate change or global warming can also affect human health (Khasnis and Nettleman, 2005). Human health effects of global warming can be divided into direct and indirect categories (Kurane, 2010; Confalonieri *et al*., 2008). The direct category represents adverse health effects from natural disasters generated due to climate anomalies. Direct adverse health effects can include short-term increases in mortality due to heat waves and accidental death by storms and floods. The indirect category represents adverse health effects from infectious diseases by increased mosquitoes or ticks (Kurane, 2010). Temperature increases in air and water systems can increase the number of mosquitoes or ticks per unit area, resulting in the expansion of infested areas. When ambient temperature increases from 15 to 20°C, the time required for growth of mosquitoes shortens from 15.5 to 9.5 days. Thus the increase in ambient temperature could be a cause of the prevalence of mosquito-borne pathogens to humans (Reiter, 2001). It can lead to increases in water and food contamination by bacteria resulting in an increase in infectious diseases (Kurane, 2010; McMichael *et al*., 2006; Patz *et al*., 2005; Russell, 1998). Global warming also affected rose sea level. For example, global mean sea level rose by 0.19 (0.17 to 0.21) m over the last 111 yeras (1901-2010) (IPCC, 2014).

The major cause of global warming has been linked to increased emissions of greenhouse gases (GHGs), including carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, etc. into the atmosphere from human activities (Pan *et al*., 2012). The main emission sources of greenhouse gases are human activities, such as fossil fuel combustion, biomass burning, and waste incineration and disposal, mainly as energy supplies for heating, electricity, industrial production and transportation, and also for agricultural purposes, waste disposal, etc (Lee *et al*., 2013). Increased air emissions of anthropogenic carbon dioxide (CO_2) have been identified as a major cause of global warming (Yu *et al*., 2012). According to the US EPA and IPCC, 57% of global GHGs emissions by gas are attributed to CO_2 emitted from use or combustion of fossil fuels (US EPA, 2015a; GWS, 2015; IPCC, 2007a). Global emissions of CO_2 from fossil fuel combustion were 2 Gt in 1900 and reached 38 Gt (49 Gt CO_2 equivalent/yr) in 2004 due to a rapid increase since the 1950s (IPCC, 2007b; Bartsch *et al*., 2000). In particular, the increase rate in CO_2 emissions from developing countries was much higher than that from developed countries. Major sources of CO_2 emissions in many countries are industrial combustion and processes (Ghosh *et al*., 2010). There have been many studies on environmental impacts associated with CO_2 emissions from industrial cities or industrial sectors (Lin *et al*., 2012).

Busan (a typical portal city) and Ulsan (a typical industrial city) are neighboring metropolitan cities located in a short distance around 45 km (based on both city center locations). They have a similar latitude, costal situations, and weather patterns, but their major business types are very different from each other. The city average temperature (decade average) over the last 60 years (1950-2007) was increased from 14.0 to 15.3°C in Busan and from 13.2 to 15.0°C Ulsan (KNSO, 2008). The average temperature change in Ulsan (1.8°C) over the period was much larger than that in Busan (1.3°C). As the city of Ulsan is the largest industrial city in Korea, the general public have concerned that the increased industrial emissions, including carbon dioxide and air pollutants, in Ulsan would result in more environmental impacts including air pollution level and local warming. Air pollution situations in Ulsan have been reported (Lee and Hieu, 2013; Mutlu *et al*., 2012; Vu *et al*., 2011; Lee and Dong, 2010; Lee and Park, 2010). However, it has not been reported that how much local warming or temperature change in Ulsan has been occurred since industrial complex business in Ulsan was started in mid-1960s. Thus the purpose of this study is to analyze a warming trend in a typical Korean industrial city with a large amount of anthropogenic emissions of GHGs from industrial activities. This study also investigated a temperature change trend in Ulsan using the ambient temperature data observed over the past 50 years with a comparison of temperature change trends in other cities in Korea and with some limitations.

2. METHODS

2. 1 Site Description

The metropolitan city of Ulsan is the largest industrial city with a population of over 1.1 million in Korea. There are two national scale industrial complexes (ICs) including a large petrochemical and oil refining IC, a mechanics and automobile manufacturing IC, shipbuilding areas, a non-ferrous metal IC, and four regional scale ICs. The city of Ulsan has become the top-ranked city in terms of growth domestic production per capita, total amount of exports, and personal income among all Korean cities. About 12.5% of the total energy consumption in Korea is used in Ulsan (mostly for industrial sectors). This large amount of energy consumption leads to emissions of significant amounts of air pollutants, particularly, from industrial activities and traffic.

2. 2 Data Collection and Analysis

This study analyzed the total energy consumption and the types of fossil fuel and energy in Ulsan, Korea. Total emissions of carbon dioxide, as a representative greenhouse gas, were estimated depending upon the energy consumption sectors in Ulsan. Meteorological data observed in Ulsan (Table 1) for the last 60 years was analyzed to identify changes in the trend of the atmospheric temperature in a typical industrial city in Korea. To compare warming trends among cities with different latitudes, this study also analyzed total energy consumption, types of fossil fuel and energy, and meteorological data observed for the last 50 years in major metropolitan cities in Korea, including Chuncheon, Seoul, Daegu, and Jeju. In addition, the warming trend in Ulsan was compared to that of a neighboring city, Miryang, which has similar latitude but different environmental and city characteristics. This

Table 1. CO_2 emissions of industrial and non-industrial sectors in Ulsan.

Industrial sector	MT/yr	%
- Energy generation	39.2	62.5
- Industrial process	17.1	27.2
Sub total	56.3	89.7
Non-industrial sector	MT/yr	%
- Transportation	4.2	5.9
- Public/commercial & domestic heating/cooling	3.8	5.4
Sub total	8.0	11.3

study analyzed the annual average, the coldest and the warmest temperature, based on hourly, daily, monthly, and annual temperature data in the atmosphere observed from all the compared cities for the last 50 years. This study also analyzed the number of days in the winter and summer periods, which are usually defined in Korea as the days lower than 5°C and higher than 20 °C in daily average temperature, respectively, in all the study cities for the last 50 years. Then this study analyzed changes in the annual average wind speed based on daily average data and rainfall precipitation patterns in Ulsan for the last 50 years. This study also investigated average air temperature observed from the 7 weather monitoring sites with different environmental or areal characteristics in Ulsan for the last 10 years.

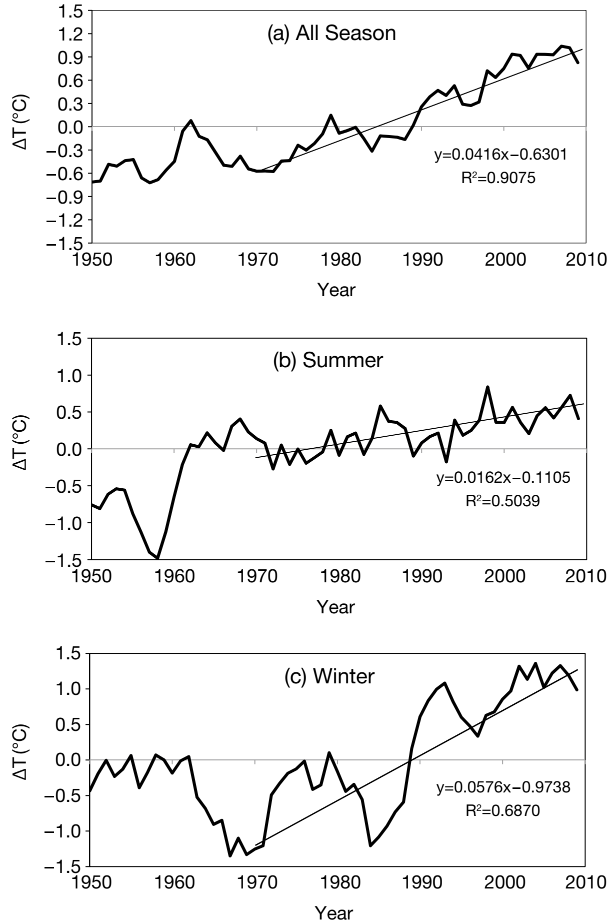

Fig. 1. Average temperature changes for the last 60 years in Ulsan, Korea.

3. RESULTS AND DISCUSSION

3. 1 Average Temperature Change

Feeling different air temperature is a major human response easily influenced by global warming. Thus it is concluded that there is a certain relationship between human activity and climate change. This study attempted to assess the extent of warming effects by analyzing the variation of annual average temperature in the atmosphere over the last 60 years in Ulsan (Fig. 1 was based on 5-year moving average data). There has been an increase of 0.85 [0.65 to 1.06]°C in global average temperature over the last 133 years (1880 to 2012). The linear global waming trend over the last 63 years (1951 to 2012) was 0.12 [0.08 to 0.14]°C per decade, which was almost 1.9 times that for the 133 years from 1880 to 2012 (IPCC, 2014).

There has been an increase of 1.49±0.17°C in the annual average temperature in Ulsan over the last 60 years (1950 to 2009). There was a large fluctuation from 1950 to 1970; however, an almost constant increase (0.0416°C/year) with a very strong correlation coefficient (R^2 = 0.9075) was observed over the last 40 years (1970-2009) since main industrial activities were statred in Ulsan. A substantial increase (0.416°C per decade) in annual ambient temperature was observed over the last 40 (1970 to 2009) of the last 60 years (1950 to 2009). Linear increase rates in the annual average temperature in Ulsan over the last 25 years (1985 to 2009) and 40 years (1970 to 2009) were 0.0507°C/year (R^2 = 0.8704) and 0.0416°C/year (R^2 = 0.9075), respectively (Table 2). These warming trends were 1.8 and 1.5 times, respectively, higher than the corresponding trend, 0.0277°C/year (R^2 = 0.8114), over the last 60 years (1950-2009) in Ulsan. Compared to the global warming trend, the 25-year linear increase rate (0.0507 °C/year, R^2 = 0.8704) in the annual average temperature over the last 25 years from 1985 to 2009 in Ulsan was 2.8 times higher than the corresponding rate of 0.018°C/yr (R^2 = 0.7233) in the global annual temperature. Also, the 50-year linear warming trend (0.025°C

Table 2. Warming trends based on 5-yr moving average data of annual ambient temperatures in Ulsan.

Compared period	60 years		40 years		25 years			
Year	1950-2009		1970-2009		1980-2005		1985-2009	
Compared place or scale	Global*	Ulsan	Global*	Ulsan	Global*	Ulsan	Global*	Ulsan
Temp increase slope (°C/yr)	0.0120	0.0277	0.0166	0.0416	0.018	0.0494	0.0305**	0.0507
Net Temp increase slope (°C/yr)	–	0.0157		0.0250		0.0314	–	0.0202
R^2 (temperature vs year)	0.8041	0.8114	0.8301	0.9075	0.6875	0.8587	0.7238	0.8704
Ratio to global (same period)	1.0	2.3	1.0	2.5	1.0	2.7	1.0	2.8

*Source: NASA-GISS, 2015; IPCC, 2014, **period year: 1986-2005.

Table 3. Seasonal increasing trends based on 5-yr moving average data of annual ambient temperatures in Ulsan.

Average	Year		Summer		Winter	
Compared period	40 years	25 years	40 years	25 years	40 years	25 years
Year	1970-2009	1985-2009	1970-2009	1985-2009	1970-2009	1985-2009
Temp increase slope (°C/yr)	0.0416	0.0507	0.0162	0.0136	0.0576	0.0774
R^2 (temperature vs year)	0.9075	0.8704	0.5039	0.1928	0.6870	0.6319
Slope ratio (40-yr to 25-yr)	–	1.22	–	0.84	–	1.34

per decade) from 1960 to 2009 in Ulsan was twice as high as that (0.13°C per decade) in the global scale over the 50 years from 1946 to 2005.

Temperature change characteristics observed over the last 64 years (1946 to 2009) in Ulsan can be categorized into two distinct periods: a non-industrial period (before 1970) and an industrial period (after 1970). Warming trends during the non-industrial and industrial periods were very different (Fig. 1(a) and (b)). During the non-industrial period from 1950 to 1970, the annual temperature, based on 5-yr moving average data, slightly decreased with very high fluctuations. The period from 1950 to 1960 and the period from 1960 to 1970 showed different features. In particular, summer and winter trends during the decade from 1960 to 1970 seemed opposite each other. During the industrial period over the 40 years from 1970 to 2009, there were substantial increases in the annual, winter, and summer average temperatures. Table 3 shows the increasing trends in the annual, winter and summer average temperatures over the last 40 years (1970 to 2009) and the last 25 years (1985 to 2009) in Ulsan. Linear warming trends during winter over the last 40 and 25 years (0.0576 and 0.0774°C/yr, respectively) were much higher than those in the summer (0.0162 and 0.0136°C/yr, respectively). In particular, the winter linear warming trend showed a strong correlation versus year change (R^2 = 0.6319 to 0.6879). During the industrial period, the increase rate, based on the linear warming slope, in the winter average temeprature was almost 3.6 times higher than the summer increase rate. The winter average temperature increased approximately 2.3°C over 40 years (1970 to 2009), resulting in an increased annual average temperature of approximately 1.7°C. In particular, the warming trend or temperature change in the winter season in Ulsan over the short period 1970-2009 (40 years) was even close to the temperature chage (2.4°C) in the cold season between November and March in the midlatitude semiarid area of Asia over the relatively long period 1901-2009 (110 years) (Hijioka *et al.*, 2014). Air emissions of greenhouse gases (mostly CO_2) substantially increased during the industrial periods compared to the non-industrial period in Ulsan. There were also global warming trends during the industrial period (1970 to 2009) in Ulsan. However, the linear warming trend on the global scale was much smaller than that in Ulsan. This may indicate that the winter tempearture increase trend during the industrial period in Ulsan seems to be more likely affected by local warming or local emissions of greenhouse gases rather than the global warming trend. Table 2 analyzes temperature increase rates over the last 60 (1950-2009), 40 (1970-2009), and 25 (1985-2009) years in Ulsan with comparing the global rates during the same period as those in Ulsan. Also, the decadal average of asphalt pavement rate of the roads in Ulsan gradually increased over the period 1960-2009, however, the average number of winter days in Ulsan decrased over the same period. The number of wineter days over the period 1960-2009 are inversely proportional to the pavement rate increase in Ulsan (R^2 = 0.7924) (Table 5). The pavement area or rate increase means more operations of vehicles on the roads and more CO_2 emissions from traffic souces, which can somehow contribute to local warming particularly in winter period in Ulsan.

3. 2 Diurnal Temperature Range (DTR)

Diurnal temperature range (DTR) is the interval between the daily maximum temperature (DMxT) and daily minimum temperature (DMnT). A rise in surface temperature is commonly caused by an increase in daily minimum temperature (Houghton *et al.*, 2001). There was a decrease of 0.84±0.53°C in the annual average DTR value in Ulsan over the last 60 years (Fig. 2(a)). However, there were annual increases in both the DMxT and the DMnT in Ulsan over the last 60 years. In particular, the degree of increase in the DMnT was larger than that in the DMxT (Figs. 2(b) and 2(c)). Heat island effects in modernized urban areas are common, leading to increasing urban background temperatures. Local heat island effects or urban background temperature increases more easily affect DMnT than DMxT. Thus, DTRs in urban areas can be smaller than those in the surrounding rural areas. Also, industrial areas or downtown city areas which have relatively large amounts of heat release per unit surface area or space volume into the atmosphere could significantly decrease their DTRs compared to rural areas. The greater increase in the DMnT (or the decrease in the DTR) observed in Ulsan can be evidence to support an increasing or warming trend in the ambient temperature observed in Ulsan (Kim *et al.*, 2007; Hyun *et al.*, 2003; Easterling *et al.*, 1997).

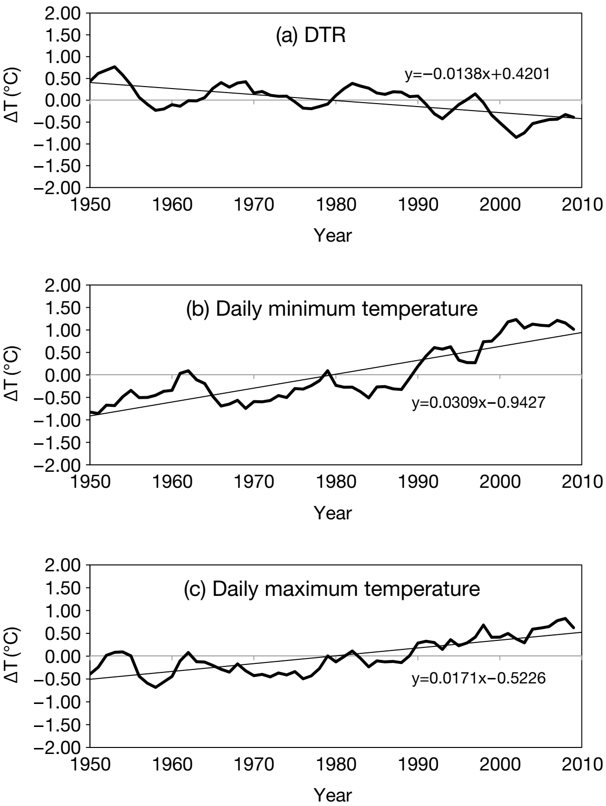

Fig. 2. Changes in the diurnal temperature range (DTR) and the daily minimum and maximum temperatures for the last 60 years in Ulsan, Korea.

This study also compared change patterns of annual average temperature in major Korean cities with different latitudes and city characteristics (Table 4). Miryang, located about 45 km away, has a similar latitude but quite different environmental characteristics from Ulsan. Table 4 clearly shows the difference in winter temperature changes in Ulsan and Miryang. Ulsan, an industrial city, showed a relatively large increase in winter average temperature (+2.2°C) over the last 50 years compared to that (+0.7°C) in Miryang, a neighbored-rural city. DTR in Ulsan decreased (−0.6°C) over the last 50 years, but DTR in Miryang increased (+0.9°C). Jeju is an island located near the south end of Korea with the lowest latitude. Daegu is a city with a basin area at a higher latitude than Ulsan. Seoul is the capital city and Chuncheon is a city with a big lake. Both cities are at similar latitudes located in the northern part of South Korea. The largest increase in the annual temperature change over the last 50 years was in Daegu, a basin city, while the lowest increase was observed in Jeju, an island area among the major cities. Among land cities, changes of the annual average temperature in Daegu (+1.4°C) and Ulsan (+1.3°C), located in the southern regions, were higher than those in Seoul (+1.2°C) and Chuncheon (+1.0°C), located in the northern regions in South Korea (Table 5). However, this study has limited information on the difference in DTR between 2000s and 1960s and thus there would be a key uncertainty to explain properly the sim-

Table 4. Decadal change of asphalt pavement rate of the roads and average number of winter days in Ulsan over the period 1960-2009.

Decade	1960s	1970s	1980s	1990s	2000s
Average temperature (°t/decade)	24.4	45.5	70.5	87.4	96.7
Standard deviation (°t)	12.8	11.5	6.2	2.9	3.7
Average number of winter days (per year)	89.6	81.1	79.2	67.7	62.0

Table 5. Change patterns of annual average temperatures and diurnal temperature ranges (DTR) in major Korean cities at different latitudes.

City		Average ± Standard Deviation (°C)						Daily Average ± Standard Deviation (°C)					
		Summer		Winter		Annual		Low		High		DTR (ΔT)	
Name	Latitude	1960s	2000s	1960s	2000s	1960s	2000s	1960s	2000s	1960s	2000s	1960s	2000s
Chuncheon	N37°88′	23.3 ±.6	23.8 ±.5	−3.6 ±1.2	−2.3 ±1.2	10.5 ±.5	11.4 ±.3	5.5 ±.5	6.2 ±.5	16.4 ±.5	17.6 ±.3	11.0 ±.4	11.3 ±.5
Seoul	N37°56′	23.9 ±.6	24.4 ±.7	−2.3 ±1.0	−0.1 ±1.5	11.7 ±.5	12.9 ±.3	7.6 ±.5	9.2 ±.4	16.5 ±.5	17.3 ±.4	8.9 ±.4	8.1 ±.2
Daegu	N35°87′	25.0 ±.7	25.2 ±.8	0.1 ±.9	2.7 ±1.1	13.1 ±.5	14.5 ±.4	8.4 ±.5	10.2 ±.4	18.7 ±.5	19.7 ±.6	10.3 ±.4	9.5 ±.4
Ulsan	N35°53′	24.0 ±.7	24.2 ±.7	1.8 ±.8	4.0 ±1.1	13.3 ±.5	14.6 ±.4	8.9 ±.3	10.4 ±.1	18.7 ±.4	19.5 ±.4	9.8 ±.5	9.2 ±.4
Miryang	N35°50′	24.3 ±.9	24.4 ±.7	1.2 ±.8	1.9 ±.9	13.1 ±.6	13.6 ±.5	7.4 ±.5	7.8 ±.4	19.3 ±.6	20.5 ±.7	11.9 ±.5	12.8 ±.6
Jeju	N33°50′	24.7 ±.7	24.9 ±.6	5.9 ±.6	7.1 ±.9	15.1 ±.5	16.1 ±.3	11.9 ±.5	13.3 ±.3	18.9 ±.5	19.3 ±.4	7.0 ±.2	6.0 ±.3

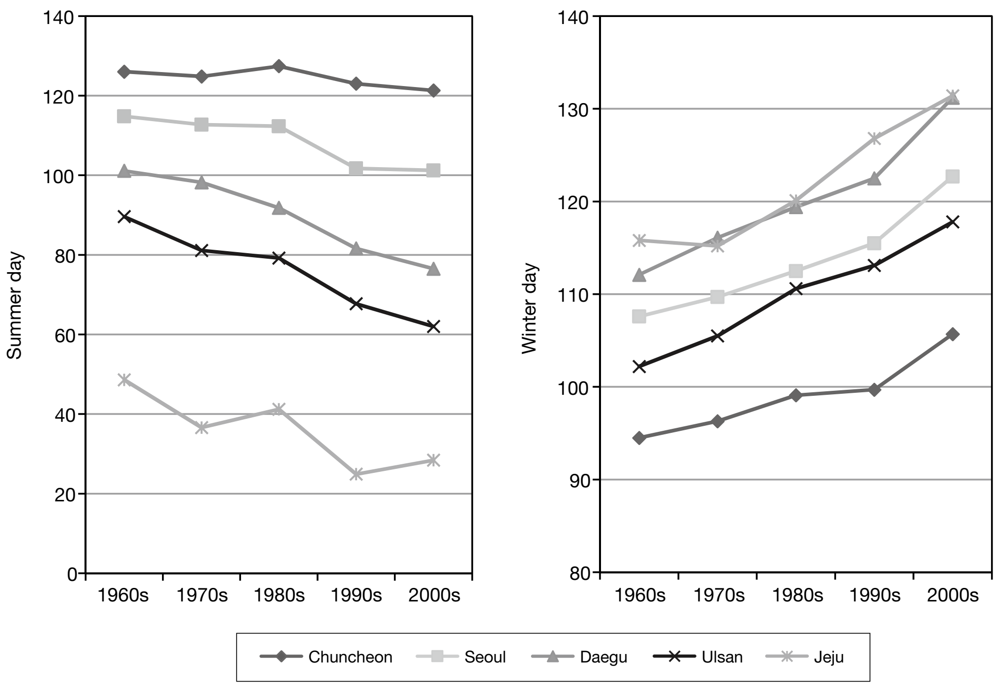

Fig. 3. Change trends of (a) the number of winter days (<5°C) and (b) the number of summer days (>20°C).

ilarity or difference among different areas (Hartmann *et al*., 2015).

3. 3 Change of Winter and Summer Periods

Figs. 3(a) and (b) show the calculated number of summer and winter days, defined as the days under 5°C and over 20°C, respectively, in the daily average temperature over the last 50 years with every 10-year interval. All the investigated cities showed a decrease in the number of winter days and an increase in the number of summer days. Among land cities, the largest decrease in the number of winter days was observed in Ulsan (−29.6 days), followed by Daegu (−24.6 days). The largest increase in the number of summer days was observed in Daegu (+19.1 days), followed by Ulsan (+15.6 days). Among land cities, larger decreases in winter days and larger increases in summer days were observed in cities located in the southern regions than

Table 6. 10-year average temperatures in areas with different environmental characteristics in Ulsan.

Area	Coastal	Downtown	Industrial	Suburban	Rural
Avg ± SD*, °C	14.5 ± 0.46	14.6 ± 0.36	15.9 ± 0.38	14.0 ± 0.39	12.8 ± 0.41
Difference (Area-Rural), ΔT°C	+ 1.7	+ 1.8	+ 3.1	+ 1.2	0

* Avg ± SD stand for average temperature ± standard deviation.

in the northern regions. Across the five cities, the average decrease in winter days was 18.5 ± 9.7 days, while the average increase in summer days was 15.3 ± 2.8 days. This indicates that the decrease in the winter days seems to be more easily affected by global or local warming than the increase in the summer days. Over the last 50 years, the difference (− Δ24.9 days) between the longest and shortest decreases in the number of winter days was much higher than (+ Δ7.9 days) the increases in the number of summer days. This fact also indicates that the decrease in winter days is more likely affected than the increase in the summer days by differences in regional or environmental characteristics of each city. Increases in average temperatures of the cold and hot seasons in Ulsan were also much higher than the increase in the global average temperature. In particular, the number of days of scorching heat in Ulsan during the summer seasons increased from 9.2 days in the 1950s to 14.8 days in the 2000s. The increase in scorching days resulted in increased operation of air conditioners during summer.

3. 4 Temperature Change in Different Environments

Table 6 shows the analysis results of the ten-year average temperatures, based on daily average temperature data monitored for the recent ten years from 2000 to 2009, from weather measurement sites with different environmental characteristics including coastal, downtown, industrial, suburban, and rural areas in Ulsan. The highest average of 15.9 ± 0.4°C was observed in the industrial area, followed by the downtown area of 14.6 ± 0.4°C, the coastal area of 14.5 ± 0.5°C, and the suburban area of 14.0 ± 0.4°C. The rural area enclosed by mountains showed the lowest average of 12.8 ± 0.4°C. The difference in decadal average temperature between the industrial area and the rural area, located around 15 km away, was 3.1°C, which would be large in between two areas located in a short distance. Companies in the industrial areas consumed about 85% of the total energy uses in Ulsan. A large amount of air pollutants and carbon dioxide were emitted from industrial activities or facilities near or in the industrial complexes. For example, CO_2 and N_2O gases contribute to 90.9 and 2.1%, 82 and 5%, and 77 and 8% of the total GHGs emissions in Korea, USA, and Global data, respectively (GIR, 2015; US EPA, 2015a, b). 87.2, 7.4 and 2.4% of the total GHGs emissions of Korea are attributed to energy production, industrial processes, and waste disposal sectors, respectively. In particular, major activities for energy production, industrial processes, and waste disposal businesses are mainly performed in the industrial complex areas in the metropolitan city of Ulsan with a population of 1.2 million and the registered number of vehicles of 510,573 in 2015 (UVRO, 2015). Thus, the highest average temperature observed in the industrial area in Ulsan over the 10 years (2000-2009) could be evidence for local warming phenomena affected by increased energy production, industrial and traffic emissions of mainly carbon dioxide and nitrogen oxides.

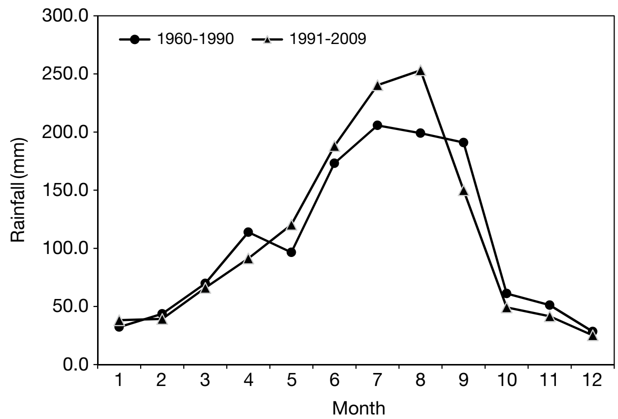

Fig. 4. Monthly average rainfall over the last 50 years.

3. 5 Rainfall Pattern Change

Global warming can lead to changes in local or regional or even global-scale climate or precipitation patterns including intensity, period, and frequency of rainfalls or snowfalls over the world (Kunkel *et al.*, 1999). Heavy rainfall in short periods of time has resulted in serious natural disasters including flooding, human casualties, and property damage. In Korea, heavy rainfalls have been observed during the summer seasons (Han *et al.*, 2009; Kim *et al.*, 2008). For example, over 40% of the annual precipitation has been commonly concentrated in three months (June to August) including the monsoon or rainy seasons. Fig. 4 shows the ave-

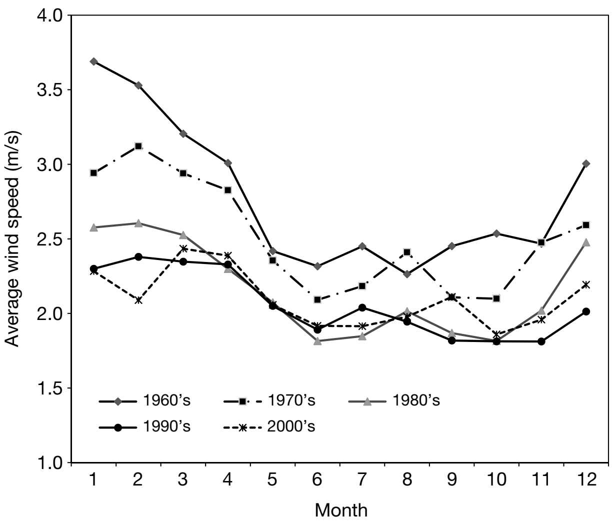

Fig. 5. Change in average wind speed for the last 50 years in Ulsan, Korea.

rage monthly precipitation (mostly rainfall) in Ulsan over the last 50 years (1960 to 2009) with two categories of periods (periods 1 and 2). Over period 1 (1960s-1980s) which had lower average temperatures or less warming phenomena, the largest amount of rainfall in Ulsan had been observed in July, followed in order by August, September, and June. Over period 2 (1990s to 2000s) which had higher average temperatures and more warming phenomena, the largest amount of rainfall in Ulsan had been observed in August, followed in order by July, June and September. The total amount of precipitation during period 2 was much higher than in period 1. In particular, rainfall precipitation in August and July during period 2 was much higher than during period 1. However, rainfall precipitation in September in period 2 was much lower than in period 1. This study has some limitations to explain clearly the difference in rainfall precipitation between period 1 and period 2. According to the IPCC AR-5 (Hijioka *et al.*, 2015), in the northern Asia thre are some increasing trends of heavy precipitation events. However, the trends in annual precipitation observed in most areas of the Asian region also did not draw solid conclusions because of strong variability and insufficient observational records (Hijioka *et al.*, 2015).

3. 6 Wind Speed

Surface winds are commonly affected by their local environmental conditions such as surface geography and topography. This study analyzed the average speed of surface winds in Ulsan for the last 50 years (1960 to 2009) [Figs. 5(a) and (b)]. The average wind speed observed in a downtown area slightly decreased over the period from the 1960s to 1990s, but there was no significant change in the average wind speed between the 1990s and 2000s. According to the IPCC AR-5, surface wind speeds over land in China seems to be weakening (with low confidence) of seasonal and annual mean winds from around 1960s or 1970s to the early 2000s (Hijioka *et al.*, 2015). This wind speed weakening phenomenon may be associated with the urbanization of the city. During city development periods, 1960 to 1990s, the number of tall buildings in the downtown areas greatly increased. Thus the decrease in wind speed may be attributed to increased wind-blocking or friction effects from frequent construction of tall buildings or structures such as large high-rise apartment complexes and commercial buildings over the city areas. The presence of tall buildings or structures can also disturb wind-flow patterns. However, construction activities of tall buildings or structures in the city of Ulsan have slowed since the 1990s, thus not greatly affecting average wind speed over the period of the 1990s-2000s (Blocken and Carmeliet, 2006).

The decrease in average wind speeds over the winter periods in Ulsan for the last 50 years from 1960 to 2009 was larger than in the summer periods (Fig. 5). The winter decrease in average wind speed was from 3.4 m/s to 2.2 m/s and the summer decrease was from 2.4 m/s to 1.9 m/s. This may be associated with less development of Siberian high pressure cells during winter periods due to gradually increased global warming effects since the 1960s (Heo and Lee, 2006; Im and Ahn, 2004; Gong *et al.*, 2002, 2000).

4. CONCLUSIONS

Through the analysis of warming trends in Ulsan, the largest industrial city of Korea, over the last 60 years (1950 to 2009), this study reached the following conclusions:

1) The total energy consumption in Ulsan with 2.2% of the population (1.1 million) of Korea was 182,847,000 TOE/yr, which accounts for 11.4% of the total energy consumption in Korea in 2009. Thus the converted energy consumption rate per capita, 18.5 TOE/capita-yr, in Ulsan was 5.1 times as high as the average value (3.6 TOE/capita-yr) in Korea. Industrial sectors (activities) were responsible for 87.6% of the total emissions of carbon dioxide in Ulsan.
2) The linear increase rates in the annual average temperature in Ulsan over the last 25 (1985 to 2009), 40 (1970 to 2009), and 60 (1950 to 2009) years were 0.0507, 0.0416, and 0.0277°C/yr, respectively. The

25- and 40-year linear warming trends in Ulsan were 2.5 and 2.8 times, respectively, higher than those for the corresponding trends of 0.0166 and 0.0180°C/yr, respectively, in the global scale.

3) The industrial area showed the highest annual average temperature over the last 10 years among areas with different environmental characteristics in Ulsan. There was a much higher increase (2.9°C) in annual minimum temperature in Ulsan over the last 50 years compared to a neighboring city.
4) The winter period shortened by 17.6 days over the last 50 years from 1960 to 2009, while summer lengthened by 15.6 days. Days of scorching heat during the summer increased from 9.2 days in the 1950s to 14.8 days in the 2000s.
5) There was a larger decrease in average wind speed in winter (from 3.4 to 2.2 m/s) than in summer (from 2.4 to 1.9 m/s) in Ulsan over the last 50 years.

REFERENCES

Ahn, J.H., Han, D.H. (2010) Projected Climate Change Impact on Surface Water Temperature in Korea. Journal of Korea Society on Water Quality 26, 133-139.

Bartsch, U., Muller, B., Aaheim, H.A. and Oxford Institute for Energy Studies (2000) Anthropogenic Greenhouse Gas emissions. in Bartsch U. and Muller B. (Eds), Fossil Fuels in a Changing Climate: Impacts of the Kyoto Protocol and developing country participation, Oxford University Press, pp. 148-158.

Blocken, B., Carmeliet, J. (2006) The influence of the wind-blocking effect by a building on its wind-driven rain exposure. Journal of Wind Engineering and Industrial Aerodynamics 94, 101-127.

Christensen, J.H., Krishna Kumar, K., Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., Xie, S.-P., Zhou, T. (2013) Climate Phenomena and their Relevance for Future Regional Climate Change. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter14_FINAL.pdf (Accessed 10 April 2015).

Conflonieri, U., Menne, B., Akhtar, R., Ebi, K.L., Hauengue, M., Kovats, R.S., Revich, B., Woodward, A. (2007) Human health. Climate change 2007: Impacts, Adaptation and Vulnerability. In Contribution of Working Group II to the Fourth Assessment Report of the intergovernmental Panel on Climate Change (Parry, M.L. *et al.* Eds), Cambridge, UK, pp. 391-431.

Easterling, D.R., Horton, B., Peterson, T.C., Karl, T.R., Salinger, M.J., Razuvayev, V., Plummer, N, Jamason, P., Folland, C.K. (1997) Maximun and minimum temperature trends for globe. Science 277, 365-367.

Ghosh, S., Jung, K., Jeon, E.-C., Kim, K.-H. (2010) Seasonal and diurnal Trend of Carbon Dioxide in a Mountainous Site in Seoul, Korea. Asian Journal of Atmospheric Environment 4, 166-176.

GIR Report (11-1480745-000003-100) (2015). 2014 National Greenhouse Gas Inventory Report of Korea. Available at: http://www.gir.go.kr (Accessed 15 April 2015).

Global Warming Science (GWS) (2015) GHG Emissions - Sources, Available at: http://www.appinsys.com/globalwarming/GW_5GH_CO2Sources.htm (Accessed 15 April 2015).

Gong, D.Y., Ho, C.H. (2002) The Siberian High and climate change over middle to high latitude Asia. Theoretical and Applied Climatology 72, 1-9.

Gong, D.Y., Wang, S.W., Zhu, J.H, (2000) East Asian winter monsoon and Arctic Oscillation. Geophysical Research Letter 28, 2073-2076.

Han, M., Mun, J., Kim, T. (2009) Climate Change Adaptation Strategy by Multipurpose, Proactive Rainwater Management and Case Studies in Korea. Journal of Korean Society of Water and Wastewater 23, 223-230.

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M., Zhai, P.M. (2013) Observations: Atmosphere and Surface. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter02_FINAL.pdf (Accessed 10 April 2015).

Heo, I., Lee, S. (2006) Changes of Unusual Temperature Events and their Controlling Factors in Korea. Journal of Korea Geography 41, 94-105.

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D., Lindgren, E., Surjan, A. (2014) Asia. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. Eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1327-1370. Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap24_FINAL.pdf (Accessed 10 April 2015).

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (Eds.) (2001) Climate Change 2001: The Scientific Basis, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press., Cambridge.

Hyun, M.S., Oh, S.N., Bang, S.Y., Lee, M.J. (2003) Trend Analysis of climate change using surface temperature in Korea. in Korea Society for Atmospheric Environment: Proceedings of the 36th Meeting of KOSAE, Seoul, Korea, pp. 516-517.

Im, E.-S., Ahn, J.-B. (2004) Analysis of Relationship between Korean Winter Temperature Variability and Global Circulation Indices. Journal of Korean Meteorological Society 40, 441-452.

Intergovernmental Panel on Climate Change (IPCC) (2007a). Climate Change 2007: Synthesis Report: Summary for Policy Makers. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf (Accessed 10 April 2015).

Intergovernmental Panel on Climate Change (IPCC) (2007b). Climate Change 2007: Synthesis Report. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf (Accessed 10 April 2015).

Intergovernmental Panel on Climate Change (IPCC) (2014). Climate Change 2014: Synthesis Report: Summary for Policy Makers. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf (Accessed 10 April 2015).

Lee, B.K., Dong, T. (2010) Effects of road characteristics on distribution and toxicity of polycyclic aromatic hydrocarbons in urban road dust of Ulsan, Korea. Journal of Hazardous Materials 175, 540-550.

Lee, B.-K., Hieu, N.T. (2013) Seasonal ion characteristics of fine and coarse particles from an urban residential area in a typical industrial city. Atmospheric Research 122, 362-377.

Lee, B.K., Park, G.H. (2010) Characteristics of Heavy Metals in Airborne Particulate Matter on Misty and Clear Days. Journal of Hazardous Materials 184, 406-416.

Kawk, T.-S., Ki, J.-H. Kim, Y.E., Jeon, H.M., Kim, S.J. (2008) A Study of GIS Prediction Model of Domestic Fruit Cultivation Location Changes by the Global Warming, Journal of Korea Society Spatial Information Systems 10, 93-106.

Khasnis, A.A., Nettleman, M.D. (2005) Global Warming and Infectious Disease. Archives of Medical Research 36, 689-696 .

Kim, J.Y., Choi, B.C., Lee, D.G. (2007) Regional Characteristics of Warming Trend Due to Climate Change in South Korea. Paper presented at the 2007 Environmental Societies Joint Conference, Seoul, Korea, pp. 1145-1148.

Kim, S., Kwon, Y.-A., Park, C., Chun, J.-H. (2008) Regional Characteristics of the Monthly Variability of Precipitation from May to September over South Korea. Climate Research 3, 64-75.

Korea National Statistics Office (KNSO) (2008) Economic and social status change over the last 60 years based on Korean statistics. http://www.nso.go.kr (Accessed 10 April 2015).

Korea National Statistics Office (KNSO) (2009) Report : trend in production of agriculture and fishing on Climate change.

Kunkel, K.E., Anasager, K., Easterling, D.R. (1999) Long-term trends in extreme precipitation events over the conterminous United States and Canada. Journal of Climate 12, 2515-2527.

Kurane, I. (2010) The Effect of Global Warming on Infectious Diseases. Osong Public Health and Research Perspectives, 1, 4-9 .

Lee, J., Cho, C.-S., Hong, K.-H., Jeong, J.-H., Kim, S., Jeon, E.C. (2013) A study on carbon dioxide emissions from bituminous coal in Korea. Environ Earth Science 70, 1709-1715.

Lin, S.J., Liu, C.H., Lewis, C. (2012) CO_2 Emission Multiplier Effects of Taiwan's Electricity Sector by Input-output Analysis. Aerosol and Air Quality Research 12, 180-190.

McMichael, A.J., Woodruff, R.E., Hales, S. (2006) Climate change and human health: present and future risks. The Lancet 367, 859-869.

Meynecke, J.-O., Lee, S.Y., Duke, N.C., Warnken, J. (2006) Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia, Estuarine. Coastal and Shelf Science 69, 491-504.

Mutlu, A., Lee, B.-K., Park, G.-H., Yu, B.-G., Lee, C.-H. (2012) Long-term Concentrations of Airborne Cadmium in Metropolitan Cities in Korea and Potential Health Risks. Atmospheric Environment 47, 164-173.

National Aeronautics and Space Administration-Goddard Institute for Space Studies (NASA- GISS) (2015) "GISS Surface Temperature Analysis (GISTEMP)", http://data.giss.nasa.gov/gistemp/ (Accessed 16 April 2015).

NOAA National Climatic Data Canter (2011) State of the Climate: Global Analysis for December 2010. Available at: http://www.ncdc.noaa.gov/sotc/global/2010/13 (Accessed 16 April 2015).

Pan, S.-Y., Chang, E.E., Chiang, P.-C. (2012) CO_2 Capture by Accelerated Carbonation of Alkaline Wastes: A Review on Its Principles and Applications. Aerosol and Air Quality Research 12, 770-791.

Patz, J.A., Campbell-Lendrum, D., Holloway, T., Foley, J.A. (2005) Impact of regional climate change on human health. Nature 438, 310-317.

Peterson, T.C., Vase. R.S. (1997) An Overview of the Global Historical Climatology Network Database. Bulletin of the American Meteorological Society 78, 2837-2849.

Quayle, R.G., Peterson, T.C., Basist, A.N., Godfrey, C.S. (1999) An operational near real-time global tempera-

ture index. Geophysical Research Letter 26, 333-335.
Reiter, P. (2001) Climate Change and Mosquito-Borne Disease. Environmental Health Perspectives 109, Supplement 1, 141-161.
Russell, R.C. (1998) Mosquito-borne arboviruses in Australia: the current scene and implications of climate change for human health. International Journal for Parasitology 28, 955-969.
Smith, T.M., Reynolds, R.W. (2005) A global merged land air and sea surface temperature reconstruction based on historical observations (1880-1997). Journal of Climate 18, 2021-2036.
Smith, T.M., Reynolds, R.W., Peterson, T.C., Lawrimore, J. (2008) Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006). Journal of Climate 21, 2283-2293.
Ulsan Vehicle Registeration Office (UVRG) (2015). Available at: http://dept.ulsan.go.kr/vehicle/help/help_03.jsp?actMode=view&iRecID=525.
U.S. Environmental Protection Agency (US EPA) (2015a) Global Greenhouse Gas Emissions Data. Available at: http://www.epa.gov/climatechange/ghgemissions/global.html.
U.S. Environmental Protection Agency (US EPA) (2015b) U.S. Greenhouse Gas Inventory Report: 1990-2013. Available at: http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.
Vu, V.T., Lee, B.-K., Kim, J.T., Lee, C.H., Kim, I.K. (2011) Assessment of Carcinogenic Risk due to Inhalation of Polycyclic Aromatic Hydrocarbons in PM_{10} from an Industrial City: a Korean Case-study. Journal of Hazardous Materials 189, 349-356.
Yu, C.-H., Huang, C.-H., Tan, C.-S. (2012) A Review of CO_2 Capture by Absorption and Adsorption. Aerosol and Air Quality Research 12, 745-769.

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