

Influence of dense surface meteorological data assimilation on the prediction accuracy of ozone pollution in the southeastern coastal area of the Korean Peninsula

Soon-Hwan Lee^a, Yoo-Keun Kim^c, Heon-Sook Kim^b, Hwa-Woon Lee^{c,*}

^a*Research Institute for Basic Science, Pusan National University, Busan, Republic of Korea*

^b*Department of Atmospheric Science, University of Nagoya, Nagoya, Japan*

^c*Department of Atmospheric Science, Pusan National University, San 30 Jangjeon-Dong Geumjeong-Gu 609-735 Busan, Republic of Korea*

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Abstract

In order to clarify the influence of surface meteorological data assimilation with various resolutions on the photochemical ozone concentration in the southeastern Korean Peninsula, several numerical experiments were conducted. The meteorological and photochemical reaction models used in this study are the fifth-generation mesoscale model (MM5) and the three-dimensional photochemical urban airshed model (UAM-V), respectively. Dense meteorological data make it easier to obtain accurate estimates and surface characteristics than coarse-resolution data. As a result, the estimated temperature obtained from high resolution surface data assimilation in the Busan and Ulsan metropolitan areas is higher than that obtained from coarse resolution surface data assimilation. These high temperatures resulted in strong winds from the sea and a significant dispersion of ozone. In analyses involving an index of agreement (IOA) and root mean square deviation (RMSD), the temperature and wind speed estimated with dense surface data assimilation agreed well with those obtained from observations.

However, the influence of dense surface data assimilation tends to be stronger in the flat Ulsan metropolitan area than in the mountainous Busan metropolitan area. This is caused by the heterogeneity of the surface characteristics, including the topography. If the surface parameters induced by regional circulation, such as the topography and land use, are complex and heterogeneous, the efficiency of observational data on data assimilation has to be verified before air pollution is assessed.

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1. Introduction

As cities grow rapidly and the population converges to them, the emissions of precursors of photochemical pollutants, such as oxides of nitrogen

(NO_x) and volatile organic compounds (VOC), are increasing as a result of the vehicle use and human activities in urban areas. These precursors can produce secondary pollutants, such as ozone (O₃) and PAN, under certain meteorological conditions. The secondary pollutants are mainly created by photochemical reactions and meteorological conditions, which also helps to accumulate photochemical

*Corresponding author. Tel./fax: +82 51 583 2651.

E-mail address: hwlee@pusan.ac.kr (H.-W. Lee).

pollutants. Wind especially advects pollutants and influences mechanical turbulence associated with pollutant diffusion. It is well known that serious episodes of air pollution are not caused by sudden increases in air pollutants. Rather, they are the result of unfortunate weather conditions, which produce a weak dispersion of air pollutants. Thus, a thorough understanding of the meteorological field is fundamental to predicting and understanding air pollution in urban areas. The accuracy of precise meteorological assessments using a numerical model primarily depends on the accuracy of the initial and boundary conditions of the atmospheric fields. In several studies, it has been proposed that failures in meteorological assessment are frequently the result of a failure in the control of atmospheric initial and boundary conditions (Russel and Dennis, 2000; Lee and Kimura, 2001; Zhang and Zheng, 2004).

Hanna et al. (2001) and Biswas and Rao (2001) showed ground ozone concentrations in association with the mixing depth and wind field patterns and documented that meteorological fields may increase uncertainty in air quality modeling. Seaman (2000) also showed that the ozone concentration and its distribution had been influenced by meteorological factors, and the accuracy of the air quality modeling had increased as a result of the decrease in the uncertainty of meteorological factors. Kim and Ghim (2002) demonstrated the effects of the density of meteorological observations on diagnostic wind fields and the performance of photochemical modeling in the greater Seoul area. They also verified the surface wind data from automatic weather stations (AWS) in the Seoul metropolitan area and showed the utilization of dense AWS data for photochemical assessments using only a diagnostic model.

The decrease of an initial/boundary wind field error is also important to maintain a stable simulation for weather and air-pollution forecasting. In order to decrease modeling errors due to initial/boundary condition uncertainty, an effective and successive data assimilation technique of surface observation was proposed (Stauffer and Seaman, 1990, 1991; Fast, 1995; Barna and Lamb, 2000; Seaman, 2000). Lee et al. (2004) applied the data assimilation to meteorological simulations and then showed a positive relationship between the initial meteorological boundary condition and the predictability of atmospheric circulation. They also demonstrated that the success of wind field prediction in a complex terrain, such as that on the

Korean Peninsula, depends primarily on the precise evaluation of the surface parameters.

The success of the reduction of the initial and boundary conditions uncertainties mainly depends on the spatial resolution of observation data and its quality. Therefore, it is necessary to clarify the influence of density of observational data used in successive data assimilation. Although the formally observed wind data obtained by the weather station of the Korea meteorological administration (KMA) are entirely reliable, the observational density is absolutely insufficient for precise predictions of photochemical air pollution. As a result, the influence of local surface wind detected by AWS on the pattern of photochemical air pollution must be quantitatively clarified.

Numerical simulations were conducted to compare the impact of formally observed surface wind data with dense AWS wind data on photochemical air pollution in southeastern Korea. We also clarified the efficiency of an improved meteorological field on air pollution assessment according to the spatial density of surface observational data over complex terrain.

2. Case study description

The southeastern coastal area of the Korean Peninsula includes several populated areas, such as the metropolises of Busan and Ulsan (Fig. 1(b)). The Busan metropolitan area in southeastern Korea has a population of approximately 5 million people and 1 million cars. The Busan metropolitan area accounts for approximately 13% of Korea's population and 0.75% of the total area. Thus, the topography, geography, and high density of pollutant emissions from a small area are unfavorable for the atmospheric dispersion of pollutants. Moreover, the Ulsan metropolitan area is a well-known industrial center in Korea. Ulsan has approximately 1 million fewer inhabitants than Busan; however, the degree of air pollution is higher because of the high number of industries in the area. These two metropolitan areas are the main sources of pollutant emission in the southeastern part of the Korean Peninsula. The Busan metropolitan area is close to the mountains in the north and the sea in the southeast. On the other hand, Ulsan is relatively flat compared to the Busan metropolitan area. Thus, the local circulation induced by the topography over Busan may be more complicated than that over Ulsan.

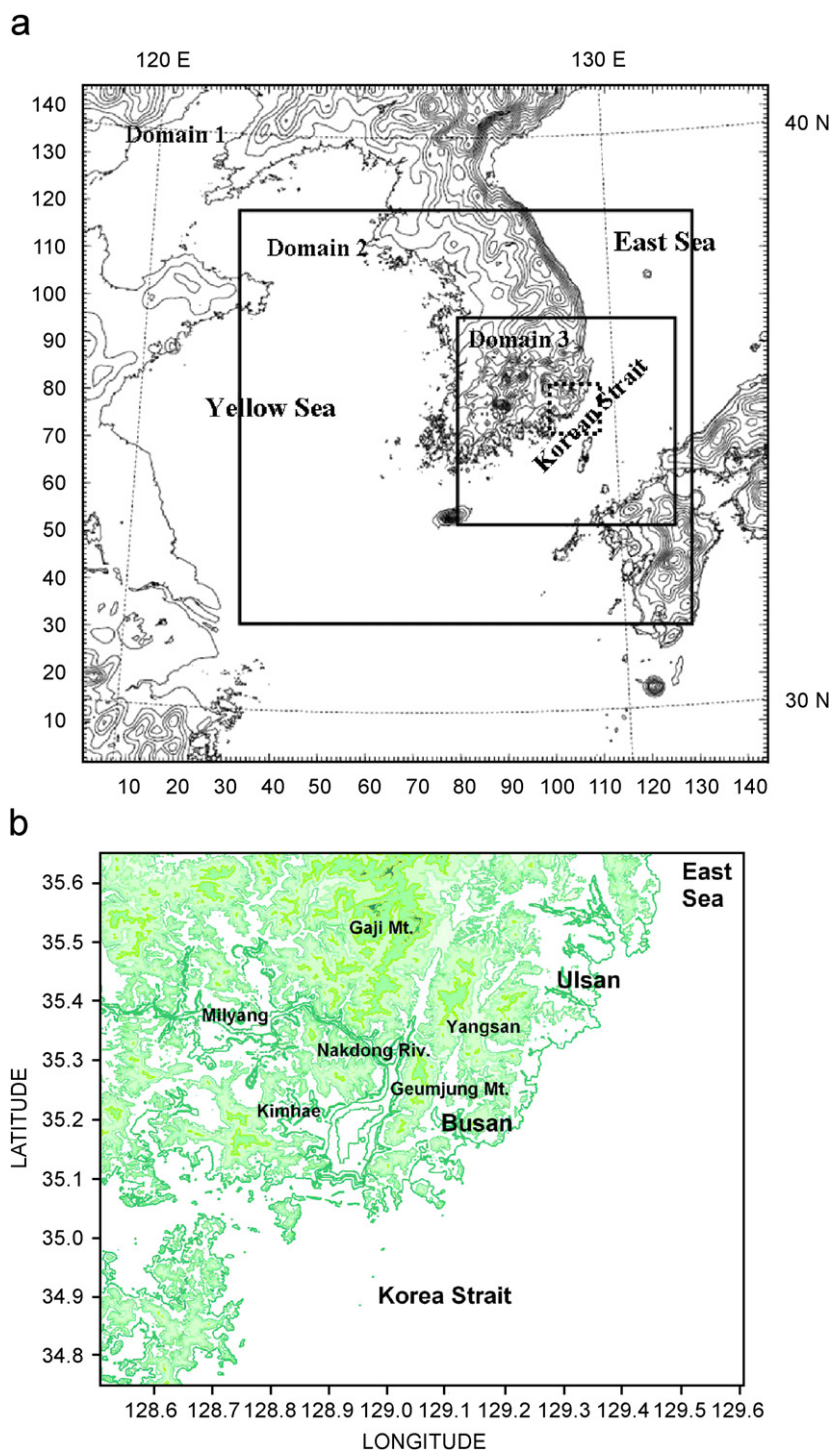


Fig. 1. Nested domains used in the study and precise topography in the finest domain. There are two major metropolitan areas (Busan and Ulsan) with satellite cities (Kimhae, Milyang, and Yangsan). The contour interval is 200 m, and the maximum height of the mountains is about 1200 m.

In this application, the episode day was chosen by the ozone concentration over the metropolises of Busan and Ulsan. A high-ozone episode is con-

sidered as follows by the Korea Environment Ministry: more than five sites with an 8 h average ozone concentration larger than 60 ppb and a 1 h

average ozone concentration larger than 80 ppb. Thus, 26 August 2001 was chosen as the high-ozone episode in this study. An analysis of the ozone concentration over as long a period as possible is desirable. However, because the focus of this study is on the influence of the assimilation of surface meteorological data with various spatial resolutions, the temporal variation of meteorological and photochemical factors over a period of several days is not discussed.

Synoptic conditions over the Busan and Ulsan metropolitan areas were calm, and fair weather was observed with a 2.3 m s^{-1} average wind speed due to high pressure over the East Sea. Solar radiation reached 850 W m^{-2} by mid noon (not shown). These synoptic conditions easily produce mesoscale circulation, such as sea/land breezes and anabatic/catabatic flows from the mountains and valleys, leading to increased concentration of pollution.

3. Description of numerical models

3.1. Frameworks of models

The air quality modeling system consists of two main parts: one is meteorological, and the other, photochemical. The meteorological model used in this study is the non-hydrostatic MM5, which contains a comprehensive description of motion, pressure, and temperature fields with turbulence, cloud, and precipitation formation. The MM5 is a nested-grid primitive equation model using a terrain-following sigma coordinate.

The MM5 simulation used in this study also employed a nested grid system (Fig. 1). The weather system over southeastern Korea is usually controlled by the development of a pressure system over the East Sea and Korean Strait. To accommodate these weather features, the mother domain (D1) includes the entire Korean Strait and Peninsula. The mother domain has 145×145 grid points with 9 km horizontal resolution. The second domain (D2) covers the southern Korean Peninsula and a part of the surrounding seas. Its horizontal resolution is 6 km with 95×85 grid points. The finest domain (D3) focuses on the Busan metropolitan area itself, including the neighboring satellite cities. Because the sea breeze induced by the East Sea and Korean Strait is also considered in this study, the D3 domain included the southeastern coastal area, which faces the East Sea. The D4 domain is more precise. The D3 and D4 domains have 100×100

and 170×160 grid points with 3 and 1 km horizontal resolution, respectively. Moreover, the first vertical layer is set at 30 m high and totally 33 layer sigma levels in total in all domains are designated with the first eight layers within 1 km above the ground level.

The air quality model used in this study is the urban airshed model with a variable grid (UAM-V). The UAM-V, developed by System Applications International, is designed for the estimation of photochemical pollutant concentrations induced by physical and chemical atmospheric processes (SAI, 1999). The UAM-V allows for the variability of the spacing of vertical layers, specification of three-dimensional meteorological variables, and explicit treatment of subgrid-scale photochemical plumes.

The chemical process used in this study is an extended version of the carbon bond mechanism (CBM-IV). The carbon bond approach is used for the lumping of organic species. The CBM-IV contains 33 chemical species and the reactions of four different types of species, inorganic species, organic species, carbon bond surrogates, and molecular surrogates, making up a lumpy structure (Gery et al., 1989; Dodge, 1989, 2000).

This mechanism is widely used in research and regular air quality models such as UAM-V and Model3/CMAQ (Byun and Ching, 1999). Jimenes et al. (2003) compared several photochemical models. The results of their comparative experiment showed that CBM-IV had an average performance of photochemical prediction and that, because the equation for the chemical reaction was revised, the use of organic and inorganic chemistry in air quality assessment is also reasonable when several air quality models are compared.

The UAM-V simulation used in this study also employed a nested grid system. The coarse and fine domains of the photochemical model have 144×124 grid points with 3 km resolution and 70×55 grid points with 1 km resolution, respectively. There are 20 layers in the vertical domains. The lowest layer is set to 50 m and the domain are on six sigma levels from the surface to 2 km. The meteorological variables required in the UAM-V simulation are presented from the MM5 simulation in the finest domain with 1 km horizontal resolution.

3.2. Design of numerical simulations

Two numerical experiments were conducted to determine the effects of data assimilation with

different observational resolution and to reconstruct the local circulation on the meteorological modeling in complex terrain. One was a numerical experiment with coarse resolution surface-weather data observed at the weather station (KWS) of KMA (hereafter referred to as case EX-KWS). The other is an identical experiment with AWS data with dense resolution for the initial conditions (hereafter referred to as case EX-AWS).

Fig. 2 shows the meteorological and photochemical air quality observational sites used in this study. The closed rectangles and triangles indicate the KWS and AWS sites in the EX-KWS and EX-AWS cases, respectively. The closed circles represent the air quality observation sites in the Busan and Ulsan metropolitan areas. The spatial resolution of the AWS observation is about 1 km in the downtown area of the Busan metropolitan and about 3 km in the rural area. However, although the weather data from the KWS is completely reliable, the KWS data used in this study were from two sites in the simulation domain. The air quality observation sites are concentrated in the Busan and Ulsan metropolises because of the heavy emissions from these two areas, as reported above. High resolution 3 arcsec topography and land-use data are used in this study. The validation

of the land-use classes is carried out in Lee et al. (2006).

The initial meteorological condition was determined using the regional data assimilation and prediction system (RDAPS), which was provided by KMA. The RDAPS was analyzed with a three-dimensional optimal interpolation method and used four-dimensional data assimilation (FDDA) for 12 h to reduce the initial problem presented by the model. Analysis nudging was applied to this application to enhance the boundary conditions using the Cressman scheme (Batchvarova et al., 1999; Dudhia et al., 2005). In this study, the meteorological fields are simulated from 18:00 UTC 24 to 00:00 UTC 27 August 2001, and fields of 48 h, excluding the data employed to stabilize the initial simulation, were analyzed and used in the air quality modeling as input. In addition, the qualified three-hourly data, 30 points, are used in analysis nudging.

The inventory information used in this study was analyzed with the Clean Air Policy Support System (CAPSS) of the Ministry of Environment with 1 km horizontal resolution. The CAPSS is an air quality control system based on the distribution of emission inventories. Fig. 3 contains the distributions of emissions in the finest domain. All emission sources including area, line and point sources were aggregated

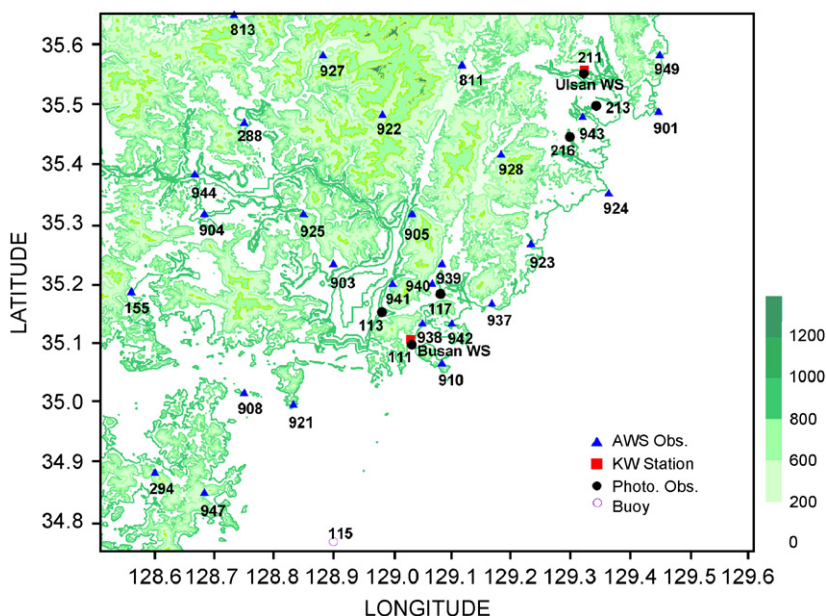


Fig. 2. Meteorological and photochemical observation sites used in this study. The triangles and rectangles indicate the AWS and KWS data observational sites, respectively. The closed circles are the observation site locations of the photochemical ozone concentrations. The numbers are the station identifiers granted by the Korea Meteorological Administration (KMA).

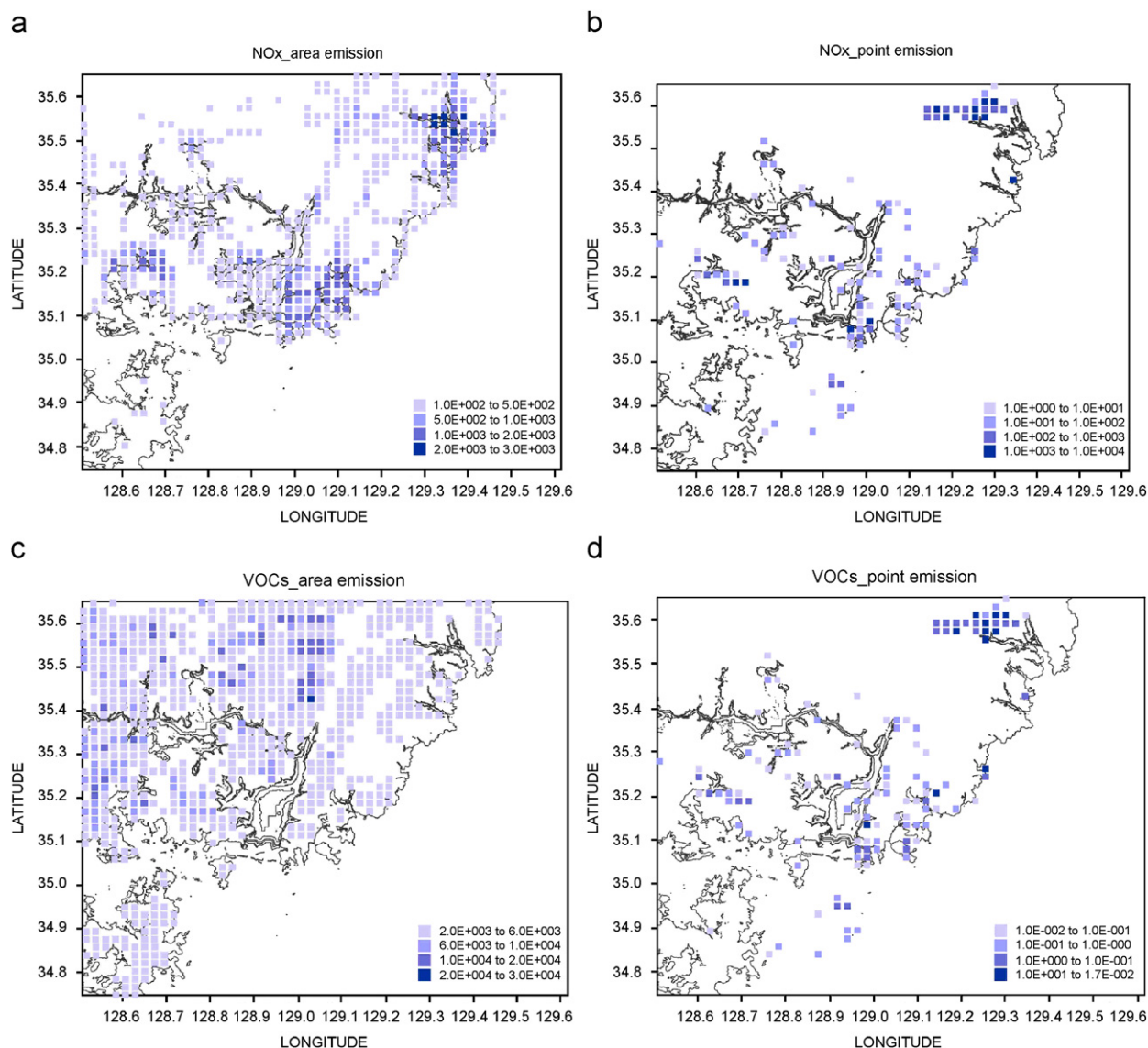


Fig. 3. Distributions of the area and point emissions for NO_x and VOC. Shading in the rectangles indicates the density of the pollutants. The unit used in the figure is kg per day.

into the UAM-V grids. The sources of NO_x are located primarily in Busan and Ulsan, and the VOC sources are located evenly throughout the domain. Especially the NO_x area and point emissions are particularly large in Busan and Ulsan when compared with other places. This is due to the dense population and the concentration of heavy industry in these two areas. The initial concentrations of O₃, NO₂, and SO₂, were horizontally interpolated from available observational data provided by the Ministry of Environment and Busan metropolitan city (BMC, 2002).

4. Results of the numerical simulations

4.1. Efficiency of dense data assimilation in the meteorological fields

Fig. 4 shows the wind and temperature field in the EX-KWS case on (a) 04:00 LST and (b) 16:00 LST 26 August 2001. The wind speed at night is generally weak because turbulence does not develop under stable conditions. A mountain wind was observed at 04:00 LST over the mountainous area. On the other hand, the wind over flat areas, such as that along the

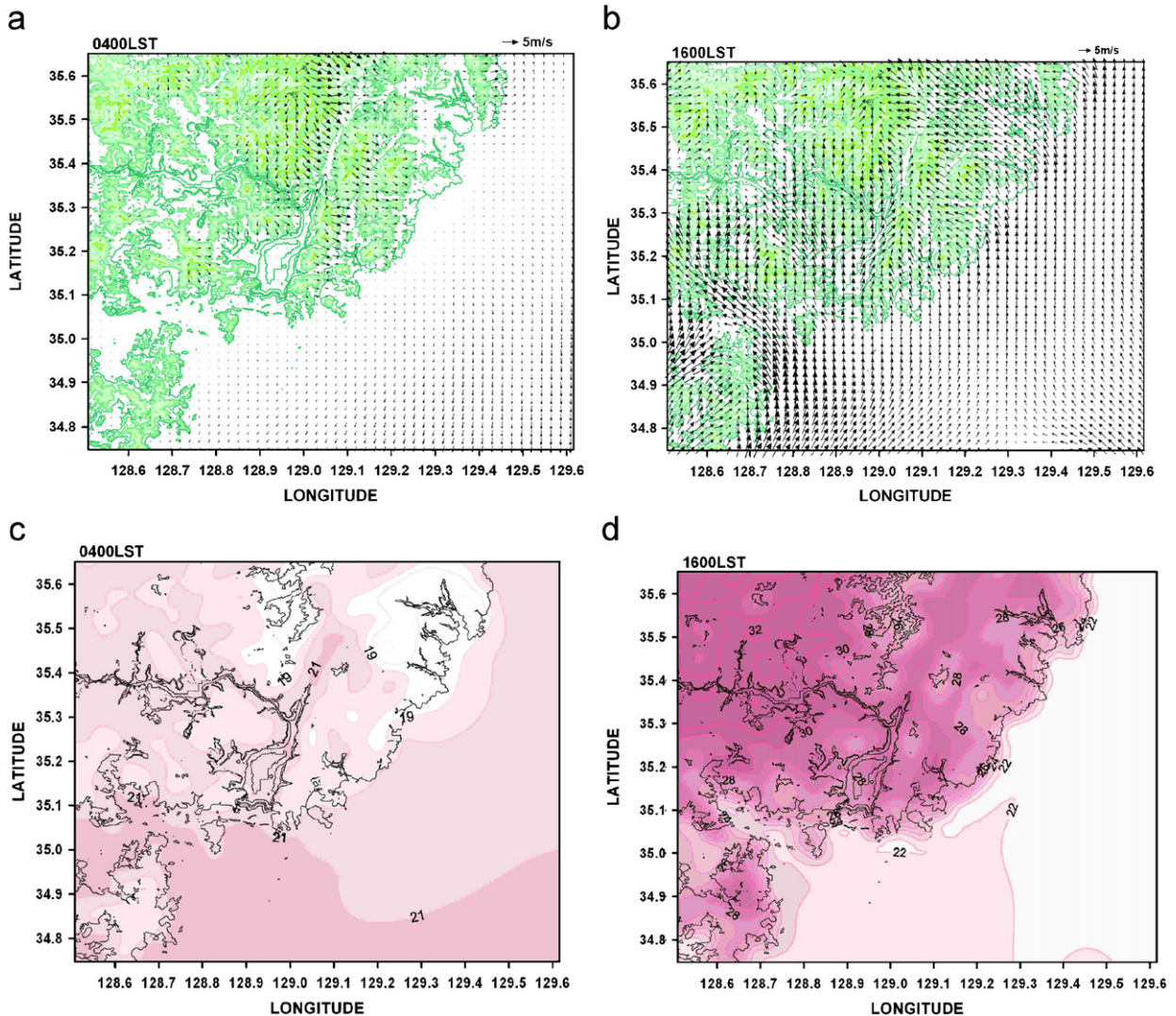


Fig. 4. Surface wind vectors and temperature distribution estimated by EX-KWS at 04:00 LST and 16:00 LST 26 August 2001. The contour interval is 1°C .

coast, was weak, with speeds below 0.5 m s^{-1} . A westerly land breeze began to develop later. However, although the wind at 850 hPa was primarily easterly (not shown), the mountain wind at the same time was primarily westerly. This means that the occurrence of mountain wind around the Busan metropolitan area is mainly caused by locally induced factors created by the topography and not by synoptic forcing. After sunrise, a sea breeze started to blow inland, and the strong sea breeze prevailed over warm land at 16:00 LST. The strong sea breeze blew deeply inland along the Nakdong River and into the flat valley at the same time. Its intensity was stronger at 04:00 LST because of the large gradient between the land and the sea.

In Fig. 4(c) and (d), a large difference in temperature over the inland and coastal regions could be observed at 16:00 LST, causing a deep inflow of the sea breeze. The gradient of the temperature was about 4°C larger inland, and the maximum difference was 10°C . In addition, the temperature gradient concentrated along the coast lines. This phenomenon caused a strong sea breeze along the Nakdong River between Busan and Kinhae, as reported above. Even if the valley wind far inland was clearly observed, that in the mountains near the coast was not clearly observed due to the well-developed sea breeze. On the other hand, the temperature difference is lower than 3°C , and the strong temperature gradient, shown at 16:00 LST, did not appear at 04:00 LST.

To clarify the effects of the AWS data assimilation on the meteorological fields, we compared the meteorological factors simulated in the EX-KWS and EX-AWS cases. Fig. 5 shows the difference in the temperature and wind speed between the EX-KWS and EX-AWS cases. In this figure, a negative value indicates an increase in the field of the temperature and wind speed of the EX-AWS case in comparison with those of the EX-KWS case. A positive value indicates a decrease in those values. At 04:00 LST, the temperature showed an increasing tendency in the AWS data assimilation in the industrial areas in Busan and Ulsan. The tempera-

ture increase over the Ulsan industrial complex was particularly clear. This was caused by the continuous operation of dense industrial equipment at night. In other words, the temperature pattern detected by the dense AWS agrees well with the land-use pattern over the target area.

At 16:00 LST, temperature increases and decreases were clearly evident in the coastal areas and Nakdong River basin, respectively. This pattern is caused by the high- and low-sensible heat over the Ulsan industrial area and the water body of the Nakdong River, respectively. This means that the results of the dense AWS data assimilation

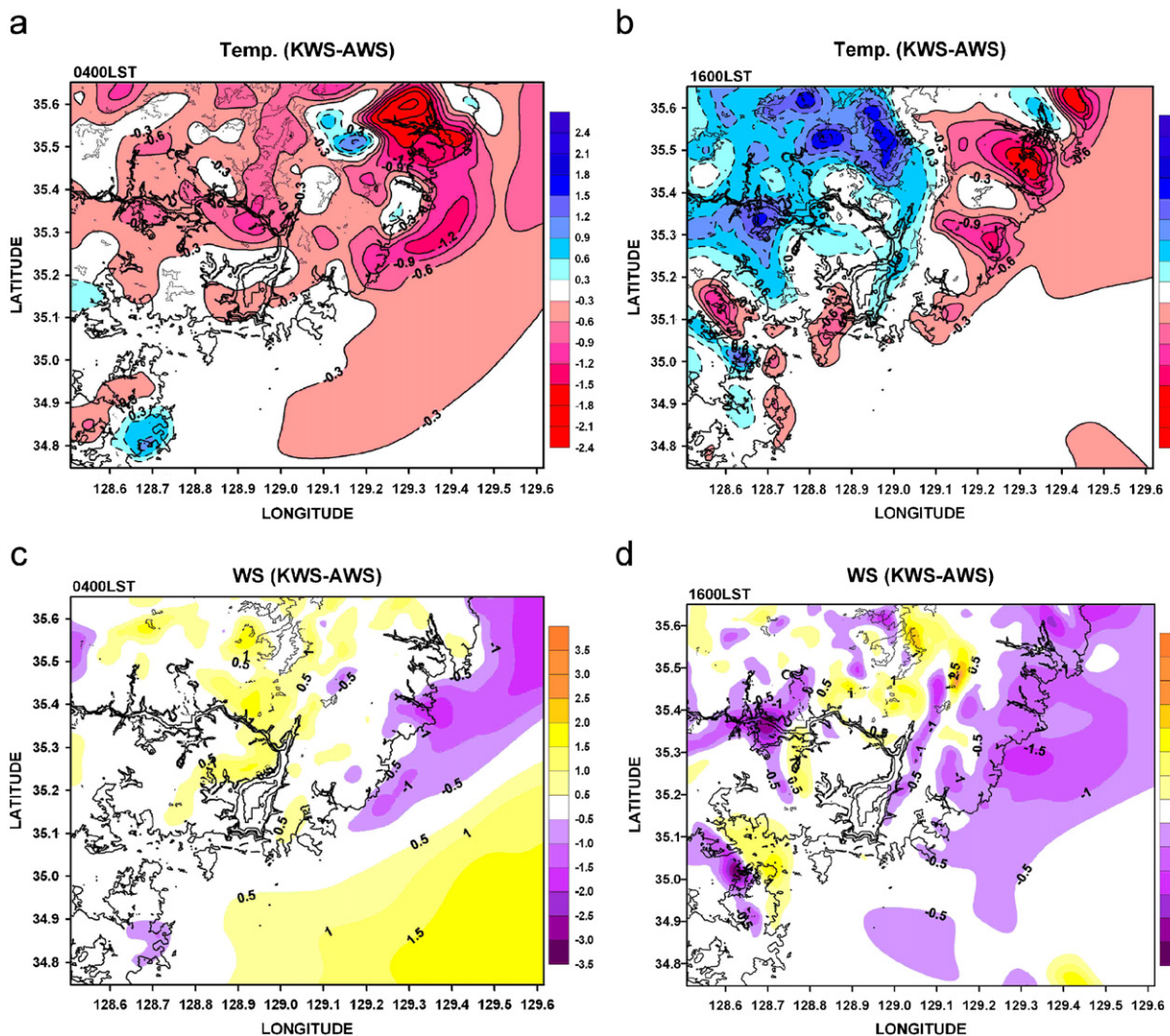


Fig. 5. Differences of estimated meteorological components from EX-KWS and EX-AWS at 04:00 LST and 16:00 LST 26 August 2001. The temperature fields are shown in (a) and (b), and the wind fields are shown in (c) and (d). Positive (negative) values indicate that the results of EX-KWS are larger (smaller) than those of EX-AWS.

reflect the actual land-use patterns, such as those in urban areas and water bodies, in the numerical assessment.

However, no clear increase in the temperature in downtown Busan was evident, and a dramatic increase in the temperature over Ulsan did not occur at 16:00 LST in comparison with that at 04:00 LST. It can be said that, although the quantity of the surface heat flux in the daytime is larger than that at nighttime, the influence of the surface heat flux from an artificial heat source, such as industrial equipment, urban asphalt, and urban heat sources, on mesoscale circulations was greater in the nighttime than in the daytime. As is well known, artificial heat energy is more important in the nighttime for the same reason in urban heat island studies. The difference between the two experiments in the patterns of the wind speed at 16:00 LST is more complicated than that at 04:00 LST because of the complicated daytime temperature patterns.

Even though the population and artificial heat sources are larger in Busan than they are in Ulsan, the temperature difference in the EX-KWS and EX-AWS cases was larger in the daytime in the Ulsan metropolitan area than it was in the Busan metropolitan area. This may account for the difference in the impact of dense meteorological surface data on the numerical assessment, which depends on the topographical conditions. This feature is quantitatively evaluated in the next section.

4.2. Efficiency of dense data assimilation in the concentration fields

Fig. 6 is the ozone concentration field at 04:00 LST and 16:00 LST 26 August 2001 in the EX-KWS case. At 04:00 LST, low ozone was shown to be evenly dispersed in the domain. After sunrise, photochemical ozone began to form around the emission sources, which were located along the coastal line, and was diffused by daytime sea breezes. At 16:00 LST, high ozone with two major maximum values appeared due to the increase of the photo-dissociation of NO_2 near the industrial areas and the high density of the population in Busan and Ulsan. The maximum values over Busan and Ulsan are 85 and 145 ppb, respectively. One minor maximum also appears in Kimheia City. The high ozone moved with the sea breeze, and its area expanded to the inland area. After sunset, the high ozone disappears as a result of a chemical reaction,

$\text{O}_3 + \text{NO}_2 \rightarrow \text{NO}$, and dilution with the environmental air.

Fig. 7 shows the difference in the ozone concentration simulated by the EX-KSW and EX-AWS cases. Solid and dashed lines indicate an increase and decrease in the ozone concentrations in the EX-AWS case, which is greater than that in the EX-KWS case. At 04:00 LST, there is no great discrepancy in the ozone distribution between the two cases, except for that in the Ulsan area. This caused ozone concentrations created by strong solar radiation in the daytime to decrease and, that atmospheric condition at nighttime was unsuitable for ozone formation.

However, at 16:00 LST, the ozone difference between the two cases shown in Fig. 7(b) is greater than that at 04:00 LST. The decreases in the concentration in the Busan and Ulsan metropolitan areas in EX-AWS are shown in Fig. 7(b). The decrease in the ozone level around Ulsan in the EX-AWS case is particularly dramatic when compared to that over Busan. This decrease in the ozone level is associated with an increase in the wind speed over Ulsan and Busan in the EX-AWS case. The ozone induced by high solar radiation and large daytime emissions penetrates the rural area as a result of the increase in daytime sea breezes. Therefore, the ozone concentration in the Ulsan metropolitan area decreases. On the other hand, the ozone concentrations increase in the rural areas in the EX-AWS case, corresponding with the down slope wind shown in Fig. 7(b).

Fig. 8 shows the correlation between the observed and calculated ozone concentrations in Busan and Ulsan. The closed diamonds and triangles indicate the ozone concentrations calculated by EX-KWS and EX-AWS, respectively. The solid and dotted lines are the regression lines. In the ozone concentration at Busan, the regression line of EX-AWS is slightly lower than that of EX-KWS; however, the two regression lines have almost the same gradient as the correlation coefficients. Their coefficients (R^2) are 0.22 at EX-KWS and 0.21 at EX-AWS. This indicates that the dense spatial resolution of the surface meteorological observation has little influence on the ozone concentration in Busan. However, a significant difference is evident in the two experiments regarding the regression lines of the Ulsan metropolitan area. The slopes of EX-KWS and EX-AWS are 0.21 and 0.38, and the correlation coefficients (R^2) of the same experiments are 0.07 and 0.34, respectively. The overestimated ozone

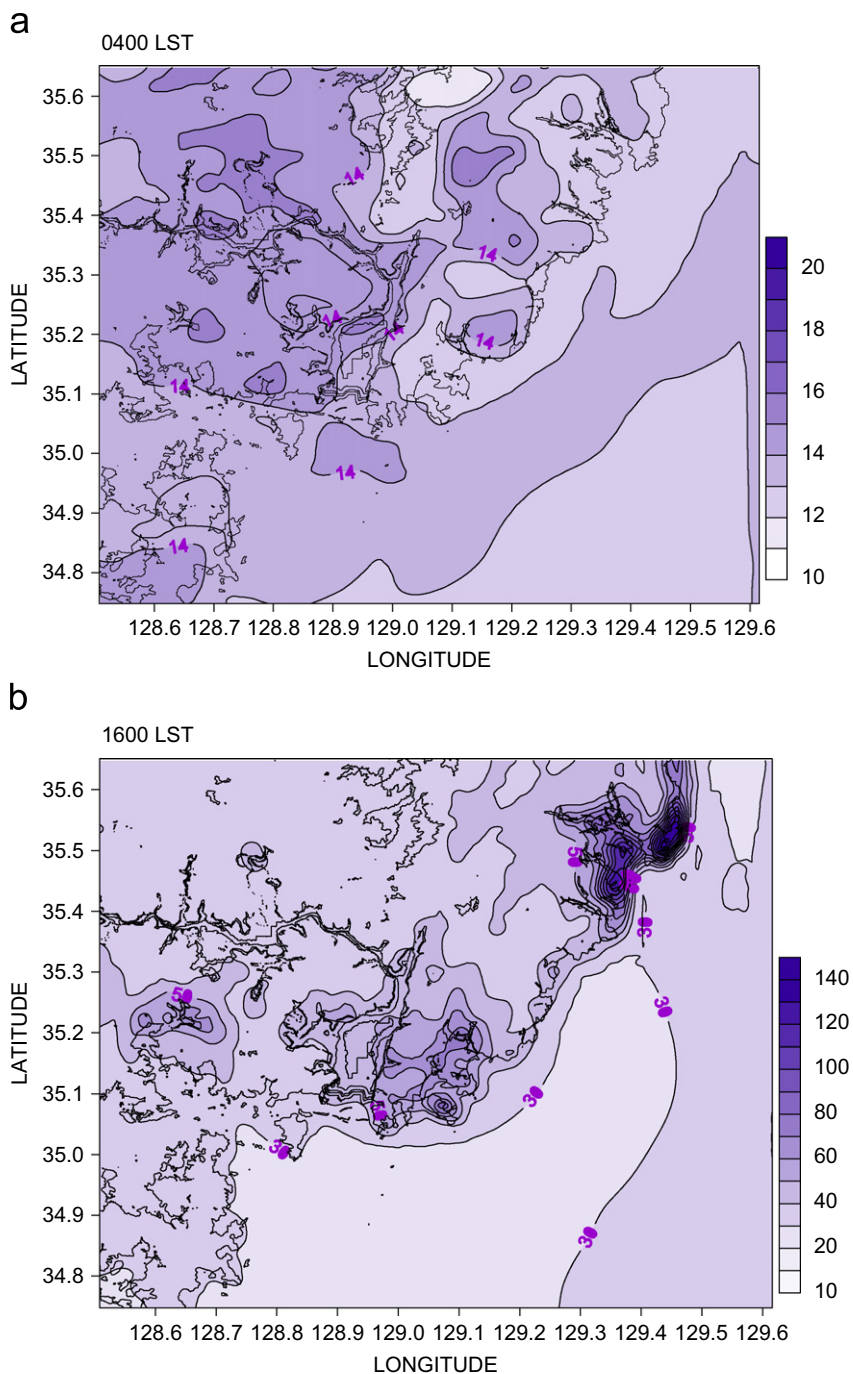


Fig. 6. Surface ozone concentration estimated by EX-KWS on 26 August 2001 at (a) 04:00 LST and (b) 16:00 LST. The contour intervals are 1 ppb at 04:00 LST and 10 ppb at 16:00 LST.

concentration shown in EX-KWS decreased in EX-AWS due to the dense surface observation. The ozone concentration values of EX-AWS in Ulsan agree well with those obtained from the observation.

The influence of dense meteorological observation on the assessment of air pollution was not homogeneous. Namely, the impact of dense AWS observation data assimilation was greater regarding the ozone distribution over the Ulsan area than over

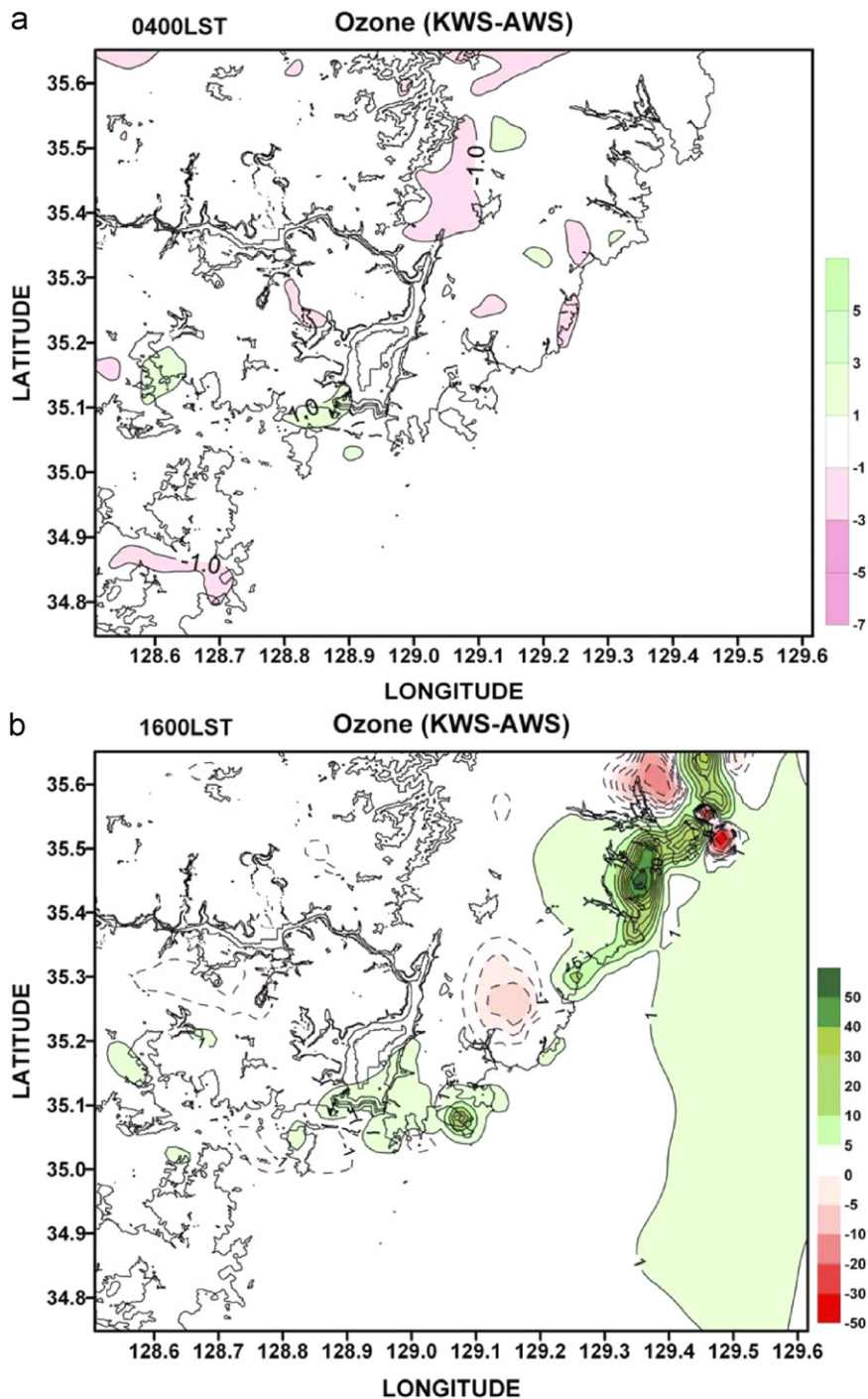


Fig. 7. Differences of the estimated ozone concentration from EX-KWS and EX-AWS at 04:00 LST and 16:00 LST 26 August 2001. The solid and dashed lines indicate positive and negative values with 5 ppb intervals from ± 1 ppb.

the Busan area. This inhomogeneous impact of the dense observation is also strongly associated with the inhomogeneity of the wind estimation shown in

Fig. 5(c). The large variations in wind produce significant changes in the ozone concentration in the Ulsan area.

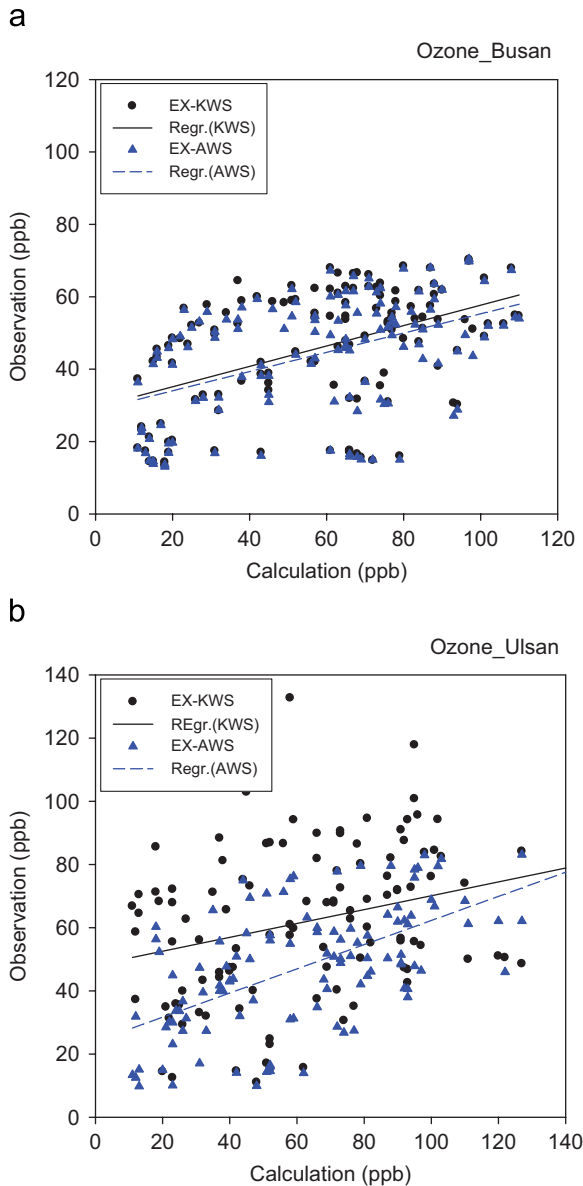


Fig. 8. Correlation between the observed and predicted ozone concentrations over Busan and Ulsan metropolitans on 26 August 2001. The triangles and circles indicated the correlation of the estimated data from EX-AWS and EX-KWS, respectively. The dashed and solid lines are the regression lines of EX-AWS and EX-KWS, respectively.

4.3. Statistical evaluation of dense observation data

It is necessary to carry out a qualitative evaluation of the influence of dense AWS data on the meteorological field and ozone distribution in a target area. To understand the assessment impact quantitatively, we conducted statistical analyses.

Model performance statistics included the observation and prediction mean, deviation, linear regression, Root Mean Square Difference (RMSD), and Index Of Agreement (IOA). The RMSD is defined as follows:

$$\text{RMSD} = \left[\frac{1}{N} \sum_{i=1}^N (P_i - O_i)^2 \right]^{1/2},$$

where P_i and O_i are the simulated and observed data, respectively, for measurement i . N is the total number of data. The skill level of the model is regarded as high if the RMSD is less than the standard deviation of observed data and if the standard deviation for simulated data is comparable with that for observed data.

IOA is defined as

$$\text{IOA} = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2},$$

where $\bar{O}$ is the average of the observed data. Its value of 1 indicates that there is perfect agreement between the predicted and observed data, and an IOA of zero shows no agreement at all.

Table 1 shows the IOA and RMSD of the meteorological and ozone concentrations at three observational sites around Busan and Ulsan for 48 h. The averaged difference between EX-AWS and EX-KWS IOA and RMSD are also shown in the same table. The comparison site numbers shown in Fig. 2 are 937, 940 and 942 in Busan and 901, 943, and 949 in Ulsan for meteorological data, and the numbers of photochemical observational data comparison are 111, 113, and 117 in Busan and 211, 213, and 216 in Ulsan.

Most wind speed and temperature IOAs are over 0.5, and the maximum value of the temperature IOA reaches 0.93 at site number 942 in Ulsan. The RMSD of two factors is also below 1.8 m s^{-1} in wind speed and 2.7° in temperature. These results indicate that the simulations of these experiments are reliable and sufficient for the analysis of meteorological data spatial resolution. The estimation accuracy of the wind speed and temperature at sites in Ulsan tended to be higher in the EX-AWS case than in the EX-KSW case. The accuracy over Busan in the EX-AWS case was also better; however, the overall accuracy was less than that over the Ulsan area. In particular, the average difference in the wind speed RMSD in Busan is positive (+0.124). These results indicate that the variation in wind speed was broad when reported

Table 1

Statistical performance of the meteorological and photochemical ozone concentrations estimated from EX-KWS and EX-AWS simulations

Meteorological data sites #		Wind speed		Temperature		Ozone data sites #		Ozone	
		IOA	RMSD	IOA	RMSD			IOA	RMSD
937	KSW	0.592	1.051	0.854	1.566	111	KSW	0.622	24.134
	AWS	0.693	1.160	0.857	1.531		AWS	0.618	24.122
940	KSW	0.463	0.986	0.922	1.661	113	KSW	0.788	24.186
	AWS	0.446	1.027	0.930	1.704		AWS	0.792	24.203
942	KSW	0.546	0.789	0.918	1.474	117	KSW	0.791	25.781
	AWS	0.577	1.009	0.929	1.385		AWS	0.792	25.752
	Average difference	+0.038	+0.124	+0.007	−0.027		Average difference	0.0003	−0.006
901	KSW	0.588	1.768	0.673	2.071	211	KSW	0.801	31.017
	AWS	0.660	1.557	0.725	1.699		AWS	0.872	25.159
943	KWS	0.565	1.089	0.831	2.630	213	KWS	0.803	30.936
	AWS	0.636	1.076	0.901	1.900		AWS	0.896	19.073
949	KWS	0.434	1.517	0.874	1.905	216	KWS	0.827	12.187
	AWS	0.437	1.422	0.888	1.913		AWS	0.853	9.1301
	Average difference	+0.049	−0.106	+0.045	−0.364		Average difference	0.063	−6.923

The “averaged difference” item indicates the averaged difference value between KSW and AWS. The positive and negative values mean that the values are larger and smaller at EX-AWS than those at EX-KWS, respectively.

from observation even when surface data with a dense spatial resolution are used for the numerical assessment. This may be caused by the complexity of the terrain in the Busan area. Due to the terrain in Busan, the wind pattern was complex and difficult to estimate precisely. On the other hand, the topography of Ulsan is relatively flat in comparison with that of Busan. Therefore, the topography may account for the efficiency of the dense data assimilation in the complex terrain.

The average IOA of the ozone concentration in Pusan and Ulsan was distributed at 0.733 and 0.842, respectively. These values indicate good agreement with the observation. The average difference in the ozone concentration IOA is 0.63, but the same value in Busan is nearly zero. The influence of dense meteorological data assimilation on the ozone concentration was greater in the Ulsan area than it was in the Busan metropolitan area, and the RMSD in EX-AWS improved significantly in Ulsan. Therefore, it seems reasonable to conclude that the influence of dense observation data assimilation on the ozone concentration was not the same in all areas.

5. Summary and conclusions

In order to verify the influence of dense surface meteorological data assimilation on the ozone

concentration, several numerical experiments with various spatial resolution data were conducted. The numerical models for meteorological and photochemical assessment were MM5 and CBM-IV, respectively. The coarse and human-controlled meteorological data used in the EX-KSW case were station data observed directly by the KMA. The dense data were from the Automatic Weather Station (AWS).

The estimated temperature of EX-AWS was higher than that of EX-KSW in the Busan and Ulsan areas. This was caused by the dense AWS data assimilation, which contained more precise information regarding urban land use. The increase of temperature in Ulsan was particularly clear. The average temperature IOA increased dramatically, and its value was 0.045. The wind speeds tend to increase because of the clear temperature increases in the Ulsan area. The same pattern occurs in the Busan metropolitan area, although the degree of intensity is clearly smaller. The patterns for increased wind in Busan depend primarily on the topography. The inland temperature and wind were the reverse of those in Busan and Ulsan.

The ozone concentrations in Ulsan and in the Busan metropolitan area decreased because of the increased wind speed in the same area. The decreased intensity in Ulsan is also larger and

clearer than that in Busan. An analysis of the correlation between the estimation and the observation demonstrates that the ozone concentration of EX-AWS is clearly improved in the Ulsan area. The slope of the correlation between EX-AWS and EX-KWS changes from 0.21 to 0.38. This clear improvement in the ozone concentration is caused by the dense surface data assimilation in EX-AWS. On the other hand, the correlation slopes of the ozone concentration in Busan in the two experiments were almost identical. The IOA and RMSD values of the experiments also showed the same tendency. The IOA and RMSD values of EX-AWS at Ulsan increased and decreased clearly, respectively, in comparison with their values of EX-KWS.

The influence of dense surface data assimilation is greater in flat areas without high mountains than in more complex topography. This is because mountainous topography produces regional circulation that results in wind in the mountains and valleys. Furthermore, the strong forcing decreases the effect of the difference between the observation data with dense and coarse resolution. However, it is noteworthy that the dense observation in the mountainous areas can lead to a decrease in the accuracy of assessments because representative data are difficult to acquire. Therefore, we strongly believe that if surface parameters induced by regional circulation, such as the topography and land use, are complex and heterogeneous, the efficiency of observational data on data assimilation has to be verified before air pollution can be assessed.

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