Observing Systems Simulation Experiments on Abnormally High Surface Air Temperatures in the Tokyo Metropolitan Area Using WRF-VAR

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Abstract

The impact of a foehn phenomenon on the generation of abnormally high surface air temperatures in the Tokyo metropolitan area was investigated through Observing Systems Simulation Experiments (OSSEs) by the use of the variational data assimilation system equipped on Weather Research and Forecasting model (WRF-VAR). First, an abnormally hot weather event on August 16, 2007 was simulated using the JMA's operational meso-scale analysis data to produce "simulated observations". Then, the vertical profiles of the simulated observations over several sites were assimilated into an initial field. Results of OSSEs demonstrated that northwesterly winds and high-temperature air associated with the foehn strongly affect the generation of the abnormally high surface air temperatures. Also, the results indicated that southerly sea breezes prevent the impact of the foehn from spreading to the southern part of the metropolitan area.

1. Introduction

The generation of abnormally hot weather is a serious problem in the Tokyo metropolitan area that includes Tokyo Metropolis and Kanagawa, Chiba, Saitama, Ibaraki, Tochigi, and Gunma Prefectures (Fig. 1). The abnormally high surface air temperatures have an adverse influence on the health of approximately 40 million people living in the metropolitan area and on the infrastructures in the area. The resulting continuous use of air conditioners in the offices and houses causes the power shortages.

A climatological study by Fujibe (1998) showed that extremely hot days, which were defined as days when the maximum surface air temperature exceeded 36.0°C, increased after the 1970s in the northern part of the Tokyo metropolitan area, e.g., at Maebashi and Kumagaya cities (Fig. 1). His study and recent reports released by the Japan Meteorological Agency (JMA) indicated that one of the main causes of the increase in extremely hot days is an increase in the occurrence frequency of the pressure distribution that tends to produce the foehn phenomenon in the metropolitan area (The reports can be downloaded from the JMA's web site; http://www.data.kishou.go.jp/climate/cpdinfo/himr/index.html; in Japanese). The foehn causes extremely hot weather and generally results from the prevalence of a northwesterly airflow, which originates from a North Pacific anticyclone and blows across a mountainous region located to the north and west of the metropolitan area.

The record-breaking high surface air temperature in Japan, 40.9°C, was observed at Kumagaya on an extremely hot day, August 16, 2007. The above JMA's reports indicated that the main cause of the abnormally high surface air temperatures was the foehn, induced by the presence of a North Pacific anticyclone (Fig. 2). The effect of urbanization was relatively weak in this abnormally hot weather event as compared with other hot weather events. The impact of the foehn on the generation of the abnormally high surface air temperatures in this event, however, has not been demonstrated yet.

This study investigated the impact of the foehn on the generation of abnormally high surface air temperatures in the Tokyo metropolitan area on August 16, 2007. For the investigation, we performed observing systems simulation experiments (OSSEs). OSSEs are defined as a type of sensitivity study (Arnold and Dey 1986). We can examine the impact of the foehn on the generation of the abnormally high surface air temperatures by using "simulated observation" data, obtained from OSSEs themselves. Also, results of this study are

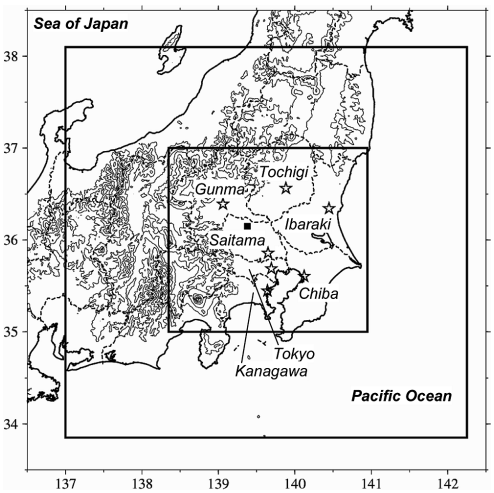

Fig. 1. Map and topography around the Tokyo metropolitan area located in Japan. The outer and inner boxes indicate domains of NATURE-RUN and CNTL- and 3DVAR-RUNs, respectively. The black square indicates Kumagaya. The stars indicate the locations of simulated observation sites: Tokyo, Yokohama in Kanagawa Pref., Chiba, Saitama, Mito in Ibaraki Pref., Utsunomiya in Tochigi Pref., and Maebashi in Gunma Pref. The dotted lines represent prefectural boundaries. The solid lines show the topography contours at intervals of 500 m.

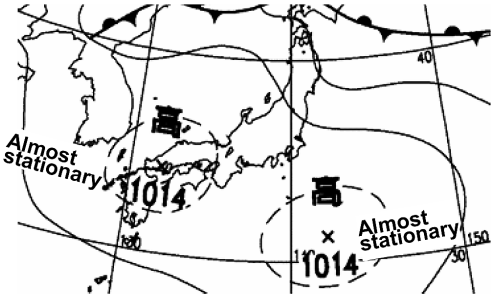

Fig. 2. Surface weather chart around the Japanese Islands at 0900 LST (Local Standard Time) on August 16, 2007.

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expected to be useful for considering real observing systems that contribute to forecasts of the generation of abnormally high surface air temperatures in the metropolitan area.

2. Experiment design

The advanced research version of the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005) was used for performing the OSSEs. A longwave radiation scheme based on Mlawer et al. (1997), a short-wave radiation scheme based on Dudhia (1989), a nonlocal boundary layer scheme based on Hong and Pan (1996), a surface layer scheme based on the Monin-Obukhov similarity theory, and the Noah land-surface model were adopted for the parameterization of physical processes.

The total number of experiments of OSSEs performed in this study is 33 (Supplement 1). The mesoscale 4DVAR analysis data of JMA (JMA-MANAL) were used for the initial and boundary conditions of an experiment "NATURE" (experiment no. 1 in Supplement 1). This experiment was carried out with 160 × 160 horizontal grids at intervals of 3.0 km and with an initial time at 0900 LST on August 15, 2007, as illustrated in Fig. 3 (see the box "NATURE-RUN"), which shows a schematic diagram of OSSEs in this study. Wind directions and velocities, air temperatures, and water vapor content on August 16, 2007 were simulated by NATURE-RUN, and then used the results as "simulated observation" data.

Experiments "CNTL" (experiment no. 2; "CNTL-RUN") and "3DVAR_..._..." (experiment nos. 3–33; "3DVAR-RUNs") were carried out with 40 × 40 horizontal grids at intervals of 6.0 km and with an initial time at 0900 LST on August 16, 2007. The global-scale objective analysis data of the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR reanalysis data; Kalnay et al. 1996) were used for the initial and boundary conditions.

The calculation domains of the experiments are shown in Fig. 1. The horizontal spatial resolution of geographical data used in the experiments is 30 s. The eta vertical coordinate was employed for all the experiments with 31 vertical levels. Also, the horizontal spatial resolutions of JMA-MANAL and NCEP/NCAR are 10 km and 2.5° in the latitudinal and longitudinal directions, respectively.

Wind profilers and temperature profilers such as RASS are useful for observing foehn phenomena that usually expand in vertical direction. Assuming that real observation data obtained from those instruments were assimilated into forecast models, the vertical profiles of the simulated observations at altitudes below 3.5 km above ground level at 0900 LST on August 16, 2007 were assimilated into the initial field of CNTL-RUN to create the initial fields of 3DVAR-RUNs. The three-dimensional variational data assimilation system of the WRF model (WRF-3DVAR; Barker et al. 2004) was used for the assimilation of simulated observation data.

Experiment nos. 03–09, 10–16, and 17–23 assimilated the individual vertical profiles of the simulated observations of winds, air temperatures, and water vapors, respectively (Supplement 1). Experiment nos. 24–33 assimilated the simultaneous vertical profiles of the simulated observations of both winds and air temperatures. Tokyo, Yokohama, Chiba, Saitama, Mito, Utsunomiya, and Maebashi cities were chosen as the simulated observation sites (see Fig. 1) by considering the feasibility of the real observations. Experiment nos. 03–30 and 31–33 assimilated the vertical profiles of the simulated observations at one of those sites and at two or three of those sites, respectively (Supplement 1).

Figures 4a–b show surface winds and temperatures

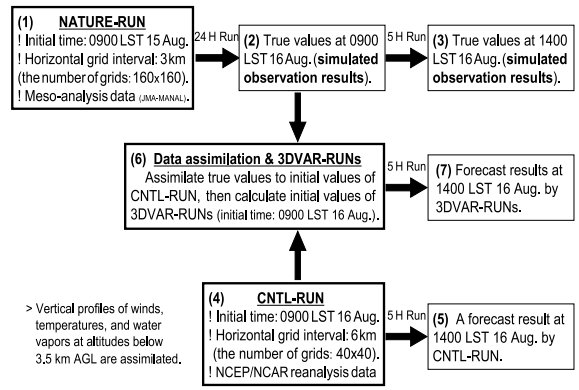

Fig. 3. Schematic diagram of OSSEs in this study. The numbers shown in the upper left corner of each box represent the execution procedure of OSSEs in this study.

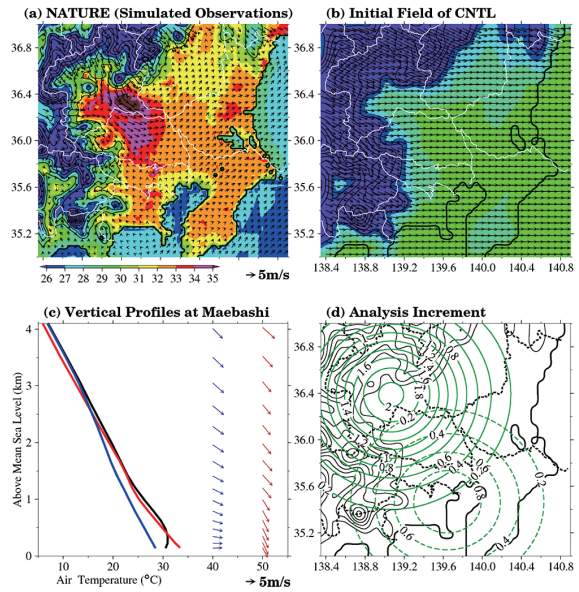

Fig. 4. Surface winds (m s^{-1}) and air temperatures (°C) at 0900 LST August 16, 2007, obtained from (a) NATURE- RUN (simulated observations) and (b) the initial field of CNTL-RUN. The black and white lines indicate the topography contours at intervals of 500 m and the prefectural boundaries, respectively. (c) Vertical profiles of air temperatures (°C) and horizontal wind vectors at Maebashi at 0900 LST August 16, 2007, obtained from experiments NATURE (red line and vectors), CNTL (blue line and vectors), and 3DVAR_TEMP_Maebashi (black line). (d) Analysis increments of air temperatures (°C) at the lowest level of the model at 0900 LST August 16, 2007, concerning experiments 3DVAR_TEMP_Maebashi (solid lines) and 3DVAR_TEMP_Yokohama (dashed lines).

at 0900 LST on August 16, 2007, obtained from the result of NATURE-RUN (simulated observations) and the initial field of CNTL-RUN. The simulated observations show that northwesterly winds blowing from the mountainous region prevail in the northwestern part of the Tokyo metropolitan area (Fig. 4a). Air temperatures in that area are relatively high, showing the occurrence of a foehn. The simulated observations, assimilated into the initial field of CNTL- RUN, therefore, include the influence of the foehn.

The difference of surface air temperatures in the vicinity of Maebashi between the simulated observations and the initial values of CNTL-RUN is 5–7°C (Figs. 4a–b). This significant difference can be recognized from

near the ground surface up to altitudes of nearly 2.5 km above mean sea level (AMSL), as shown in Fig. 4c. In the same altitudes, the air-temperature values obtained from the simulated observations well correspond to the initial air-temperature values of the experiment 3DVAR _TEMP_ Maebashi, except for near the ground surface (Fig. 4c). This appears to show that the analyses created to use as the initial values of the experiment 3DVAR_ TEMP_ Maebashi strongly reflect the simulated observations, although somehow the analyses are slightly larger than the observations at altitudes of 0.4–1.3 km AMSL (Fig. 4c). The default background error statistics (BES) were created by using the results of the global forecast system (GFS) forecasts carried out with the T170 resolution, i.e., approximately 75 km horizontal resolution. Therefore, the regional differences of the background errors in the Tokyo metropolitan area scale are considered to be small. Since the main purpose of the experiments is not examinations for improving the forecasting accuracy, this study did not create the original BES. An example of horizontal distributions of the analysis increments is shown in Fig. 4d. In this study, the strength and radius of influence of the data assimilation were adjusted in order to enhance the impact of the data assimilation. These indicate that the initial fields of 3DVAR-RUNs are largely influenced by the assimilation of the simulated observation data.

To emphasize the impact of the assimilation of the simulated observation data on the model forecasts, the forecast accuracy of CNTL-RUN was purposely decreased by using the coarser spatial resolution objective analysis data, the coarser spatial resolution horizontal grids, the smaller calculation domain, and the shorter period numerical integration, as described above. We examined which of the results of 3DVAR-RUNs is closest to that of NATURE-RUN, i.e., simulated observations. Positive impacts of the assimilation of the simulated observation data on forecasts of abnormally high surface air temperatures should result in the smaller differences between the results of 3DVAR-RUNs and NATURE-RUN, as compared with the difference between the results of CNTL-RUN and NATURE-RUN.

3. Results and discussions

Figure 5 shows the surface wind and temperature fields at 1400 LST on August 16, 2007. These fields are derived from the results of NATURE-RUN (Fig. 5a), CNTL-RUN (Fig. 5b), and 3DVAR-RUNs that were carried out with the assimilation of the simulated observation data of only winds at Yokohama (Fig. 5c; experiment no. 4), only winds at Maebashi (Fig. 5d; experiment no. 9), both winds and temperatures at Yokohama (Fig. 5e; experiment no. 25), both winds and temperatures at Maebashi (Fig. 5f; experiment no. 30), both winds and temperatures at the two cities Maebashi and Yokohama (Fig. 5g; experiment no. 31), and both winds and temperatures at the three cities Maebashi, Saitama, and Yokohama (Fig. 5h; experiment no. 33).

There is a significant difference between the temperature field of NATURE (simulated observations) and that of CNTL (Figs. 5a–b). An area of abnormally high surface air temperatures exceeding 38.0°C is distributed mainly in the eastern part of Saitama Prefecture in NATURE, which corresponds to the real observations by the Automated Meteorological Data Acquisition System (AMeDAS) of JMA (figures not shown). This abnormal high-temperature area is absent in the result of CNTL. In the abnormal high-temperature area, northwesterly winds blowing from the mountainous region prevail. Also, sea breezes originating from the Pacific Ocean prevail in Tokyo Metropolis and Kanagawa and Chiba Prefectures.

The area of surface air temperatures higher than 36.0°C is confined to the northwestern part of the

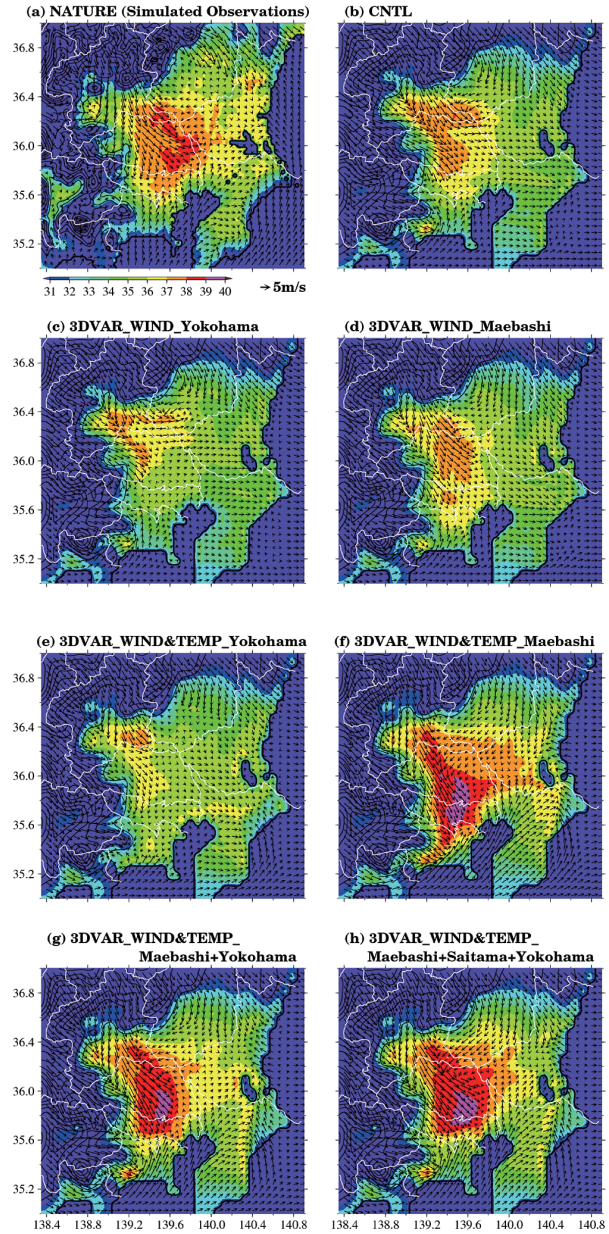

Fig. 5. Surface wind (m s^{-1}) and air temperature (°C) fields at 1400 LST on August 16, 2007, obtained from experiments (a) NATURE (simulated observations), (b) CNTL, (c) 3DVAR_ WIND_Yokohama, (d) 3DVAR_WIND_Maebashi, (e) 3DVAR_ WIND&TEMP_Yokohama, (f) 3DVAR_WIND&TEMP_Maebashi, (g) 3DVAR_WIND&TEMP_Maebashi+Yokohama, and (h) 3DVAR_WIND& TEMP_Maebashi+Saitama+Yokohama.

Tokyo metropolitan area in the case of the wind data assimilation at Yokohama (Fig. 5c). The result of the wind data assimilation at Maebashi, however, shows that the high-temperature area spreads to the northern part of Kanagawa Prefecture with northwesterly winds blowing from the mountainous region (Fig. 5d). The wind field at 0900 LST on August 16, 2007 simulated by NATURE, which was assimilated into the initial field of CNTL, shows that the northwesterly winds have already been prevalent in the northwestern part of the metropolitan area including Maebashi (Fig. 4a). These indicate that the assimilation of the northwesterly winds resulted in the southward transport of high-temperature air, thereby spreading the area of the high surface air temperatures to the southern part of the met-

ropolitan area.

The surface wind and temperature fields forecasted after the assimilation of both the wind and temperature data at Yokohama are similar to those forecasted after the assimilation of only the wind data at Yokohama (Figs. 5c and 5e). Note that the assimilation of both the wind and temperature data at Maebashi leads to a large area of abnormally high surface air temperatures exceeding 38.0°C and a strong northwesterly airflow in the western part of the Tokyo metropolitan area (Fig. 5f). Surface air temperatures higher than 39.0°C can also be recognized in Saitama Prefecture and Tokyo Metropolis. As described above, the result of NATURE at 0900 LST on August 16, 2007 shows that the northwesterly airflow and the resultant high-temperature air associated with the Foehn prevail in the northwestern part of the metropolitan area including Maebashi (Fig. 4a). This shows that the wind and temperature fields in Fig. 5f were forecasted after the assimilation of the foehn. The assimilation of both the northwesterly airflow and high-temperature air associated with the foehn, thus, resulted in the large area of the abnormally high surface air temperatures.

The location of the area of the abnormally high surface air temperatures exceeding 38.0°C in the result of the wind and temperature data assimilation at only one site Maebashi is inconsistent with the result of NATURE (Figs. 5a and 5f). The abnormal high-temperature area spreads to Kanagawa Prefecture with the northwesterly airflow (Fig. 5f), but in the result of NATURE, the area is confined to Saitama Prefecture (Fig. 5a). This implies that some factors other than the foehn also determined the area of the abnormally high surface air temperatures.

Compared with the result of the data assimilation at only Maebashi, the location of an area of the abnormally high surface air temperatures forecasted after the wind and temperature data assimilation at two sites Maebashi and Yokohama is relatively close to the result of NATURE, although the abnormal high-temperature area is still larger than that in NATURE and contains the temperatures higher than 39.0°C (Figs. 5a and 5g). The assimilation of the wind and temperature data at three sites Maebashi, Saitama, and Yokohama yields the wind and temperature fields that are closer to NATURE (Fig. 5h). The wind and temperature data assimilation at cities including Yokohama appears to have intensified the influences of southerly sea breezes that can prevent the northwesterly airflow and high-temperature air from spreading to the southern part of Tokyo Metropolis and the western part of Kanagawa Prefecture (Figs. 5f–h). The effect of the data assimilation at Saitama is unknown.

Incidentally, a result of the wind and temperature data assimilation at three cities confined to the northern part of the metropolitan area (Maebashi, Utsunomiya, and Mito; experiment no. 32; figure not shown) is almost the same as the result of the wind and temperature data assimilation at only Maebashi, which shows that the northwesterly airflow and the area of the abnormally high surface air temperatures spread to Kanagawa Prefecture (Fig. 5f). Also, all of the results of 3DVAR-RUNs carried out with the assimilation of the water vapor data resemble the result of CNTL (figures not shown), indicating that the impact of the assimilation of water vapor data was very small owing to the cloudless dry condition on August 16.

4. Summary and conclusion

In this study, OSSEs were performed for investigating the impact of a foehn on the generation of abnormally high surface air temperatures exceeding 38.0°C in the Tokyo metropolitan area on August 16, 2007, using WRF-3DVAR. The abnormally hot weather event was simulated by NATURE-RUN, and then termed the results as "simulated observations". Vertical profiles of the simulated observations were assimilated into the initial field of CNTL-RUN to create the initial fields of 3DVAR-RUNs.

A result of a 3DVAR-RUN carried out with the assimilation of the simulated observation data of both winds and temperatures at only Maebashi demonstrated that northwesterly winds and high-temperature air associated with the foehn strongly affect the generation of the abnormally high surface air temperatures. Also, surface wind and temperature fields, derived from results of the wind and temperature data assimilation at a few cities including Yokohama in addition to Maebashi, were relatively close to the simulated observations. This was probably due to increases in the effects of southerly sea breezes that can prevent the northwesterly winds and high-temperature air from spreading to the southern part of the Tokyo metropolitan area. These results indicate that both the foehn and the sea breezes determine where the abnormally high surface air temperatures generate.

In this study, OSSEs by the use of the default BES of WRF-VAR were applied to elucidation of the atmospheric phenomenon. However, the analyzed wind velocities were overestimated, which suggests inadequate adjustments on the radius of influence. Improvement of the data assimilation system, such as the creation of original BES, is the future subject.

Acknowledgments

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Supplements

A list of OSSEs carried out in this study is shown in Supplement 1. Supplements 2, 3, and 4 show surface wind and temperature fields at 1400 LST on August 16, 2007, derived from results of experiment nos. 3–9, 10–16, and 24–30, respectively.

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