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Paper:

Meteorological Characteristics of Local Heavy Rainfall in the Fukuoka Plain

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Heavy local rainfall has been increasingly observed in urban Fukuoka on fine summer afternoons in recent years. Such rainfall tends to occur suddenly on calm afternoons and is considered to be caused by local wind conditions influenced by local topography rather than by weather fronts or typhoons. This local rainfall is considered to be caused by a mechanism different from similar rainfalls occurring on fine Kanto plain afternoons. We set up 14 rain gauges in urban Fukuoka in this study to clarify and confirm actual local rainfall conditions there. Maximum local rain is about 64 km^2 lasting 10 to 30 minutes. The maximum 10-minute rainfall was 13.8 mm. The average surface air temperature on days with local rainfall differs 2°–3°C from that on fine days. Upper atmosphere humidity distribution differs greatly between fine days and those with heavy local rain. Accordingly, heavy local rain is more likely to occur if surface air temperature and humidity in upper atmosphere rise above a certain level. Some difference is seen between days of heavy local rainfall and fine day in terms of the K index (*KI*), a measure of atmospheric stability. We confirmed that the atmospheric state becomes more unstable on days with heavy local rainfall than on fine days. Heavy local rainfall often begins in either the eastern or western inland Fukuoka plain and moves toward the coast. That is, based on numerical simulation using the meteorological mesoscale weather research and forecasting (WRF) model, wind blowing opposite to the sea wind blows in the upper atmosphere, moving cumulonimbus clouds causing heavy local rainfall toward the coast. We also confirmed that heavy local rainfall tends to occur in eastern inland areas with wind from the west, but tends to occur in western areas with wind from the east. We therefore assumed that heavy local rainfall in urban Fukuoka was triggered by updrafts generated when wind struck the inland Fukuoka plain mountain system.

Keywords: heavy local rainfall, heat island, WRF

1. Introduction

Local torrential urban downpours recently began occurring in a narrow area of 100 km^2 and lasting 1 to 2 hours. In some cases, this intensive hourly rain exceeded 100 mm – well beyond the maximum 60 mm hitting many municipalities. Drainage becomes unable to process such heavy urban rainfall, causing damage such as inundations leading to human casualties. The torrential July 21, 1999, downpour in Nerima Ward and that in Zoshigaya in Toshima Ward August 5, 2008, caused several persons to lose their lives. In these local torrential downpours, it was fine in the morning but cumulonimbus clouds developed suddenly later, followed by intensive rain. In both cases, these was torrential downpours occurred locally in a very short time.

Many studies have been conducted on the frequency and intensification of torrential downpours, which are considered to be influenced by global warming [1–3]. We studied heavy rainfall occurring in the afternoon on fine days in upper urban air rather than that caused by typhoons or weather fronts. Urban heat islands, global warming, and changing atmosphere conditions above urban area caused by changes in urban structures and the greenhouse effect are considered to contribute to the occurrence of such heavy local rainfall. One example of the effects of urban change in torrential downpours involves urban heating due to artificial land cover such as asphalt and automobile exhaust increasing precipitation [4]. It has also been pointed out that urban areas intensify wind convergence in the upper atmosphere [5]. The occurrence of torrential downpours in Tokyo made it clear that the east wind from the Kashima Sea and the south wind from Sagami Bay merge at Tokyo [6–9]. Another study indicates that these winds are induced by the barometric gradient on the Kanto region scale, including mountainous Chubu [10]. It is difficult to determine rain area and measure precipitation accurately using only data from meteorological stations because considerable heavy rainfall may occur locally. In Tokyo, for example, the meteorological apparatus and instruments are set to high density, and detailed weather change are reported [7]. Sea surface temperature are rising due to global warming, evaporation from the sea surface is increasing, and water vapor content in the air is growing, intensifying torrential downpours [1, 2].

The Fukuoka plain is about 1/60 the area of the Kanto plain and its urban area is much smaller, and it was believed that heavy local rainfall peculiar to urban areas was unlikely to occur in Fukuoka. This meant that heavy local rainfall there was not studied. Since 2010, however, heavy local afternoon rainfall on fine summer days was being observed for the first time. It was true that potentially disastrous torrential rainfall occurring on the Fukuoka plain could not be denied. Such torrential rain occurs more locally than on the Kanto plain and lasts 20 to 30 minutes. Accordingly, many such rainfalls could not be confirmed by the Fukuoka District meteorological observatory (FDMO), Hakata AMeDAS or Dazaifu AMeDAS, meaning that detailed conditions could not be grasped. The mechanism behind heavy local rainfall on the Fukuoka plain also seemed to differ from that on the Kanto plain because the precipitation scale was different. This heavy local rain appeared unique to the region because it was influenced by local topography, thus making it necessary to clarify similarities and differences in individual regions. Heavy local rainfall should be forecast as soon as possible because such rainfall could become more common in the near future. We set up high-density rain gauges in urban Fukuoka to clarify the actual situation of the heavy local afternoon rainfall occurring despite fine weather in the morning. We then studied the resulting data.

2. Observation Overview

The north side of the Fukuoka plain is where urban Fukuoka is located by the Genkai Sea. The east and southwest sides contain the Houman-Sangun and Seburi mountain systems, whose peaks ranged from 600 m to 1,000 m in altitude. Our rain gauges were set in ventilated meteorological instrument cases at 14 elementary schools within urban Fukuoka, as shown in **Fig. 1** by black squares 1 to 14. Rain gauges are about 16 km^2 apart and distributed fairly evenly. The time interval for acquiring data was 10 minutes. The triangle indicates the FDMO of the Meteorological Agency, the inverted triangle Hakata AMeDAS and the circle Dazaifu AMeDAS. Analysis was from July 26 to September 18, 2011; from July 14 to September 14, 2012; and from July 2 to August 30, 2013. Criteria for selecting the period to be analyzed was from the day when the daily average temperatures exceed 25°C, continuing for three days to the day before that on which the daily average temperatures fell below 25°C and continued for three days. Line X_1–X_2 is used in cross-sectional analysis.

3. Observation Results

August 27, 2011, data are shown as an example of observation on a day when heavy local rainfall occurred. The general weather situation was mostly fine, no rain

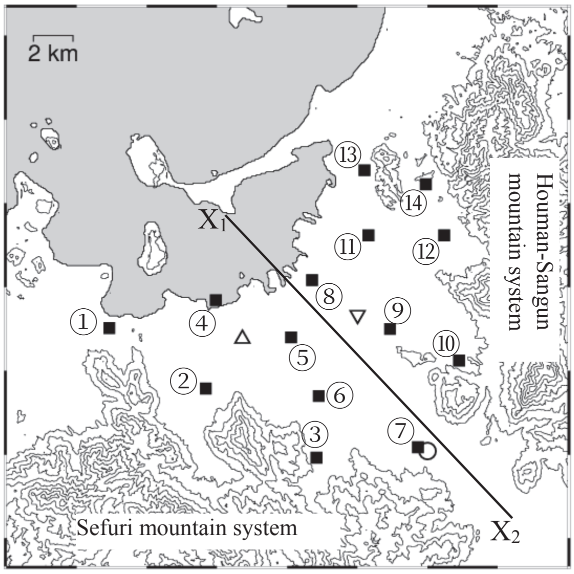

Fig. 1. Urban Fukuoka City topography and observation points. ■: rain gauge; △: Meteorological Agency FDMO; ▽: Hakata AMeDAS; ◯: Dazaifu AMeDAS.

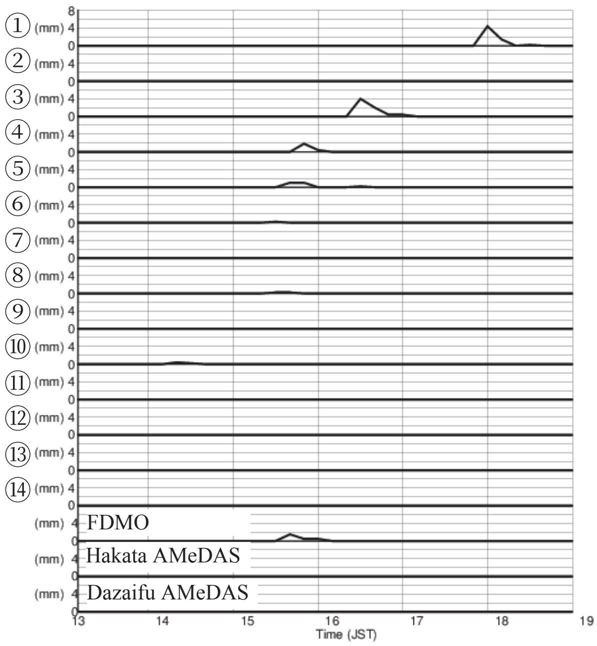

Fig. 2. 10-minute rainfall time change from 13:00 to 19:00. In the figure from top to bottom: rain gauge points 1-14; FDMO; Hakata AMeDAS; Dazaifu AMeDAS.

fell in the morning and according to radar-AMeDAS precipitation analysis, no significant rain clouds were recognized. **Fig. 2** shows the time change in 10-minute rainfall from 13:00 to 19:00. The data of the rain gauge point Nos.1-14, the FDMO, Hakata AMeDAS and Dazaifu AMeDAS are shown. Rainfall from 14:00 was recognized, but it rained at a maximum of 3 observation points. Note how the rain moves over time. **Fig. 3** shows accumulated rainfall distribution for 30 minutes from 14:00 on the day rain began to fall. At left are observation results and at right precipitation analysis data generated by

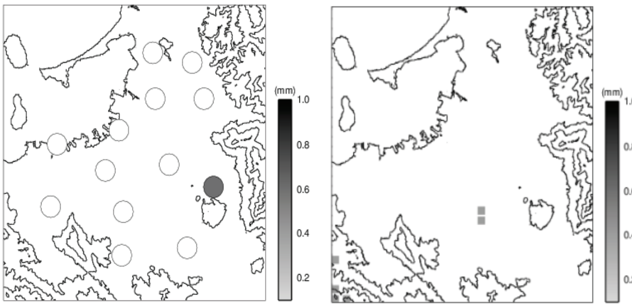

Fig. 3. Rainfall accumulated from 14:00 to 14:30. At left are observation results and at right are precipitation analysis data provided by the Meteorological Agency.

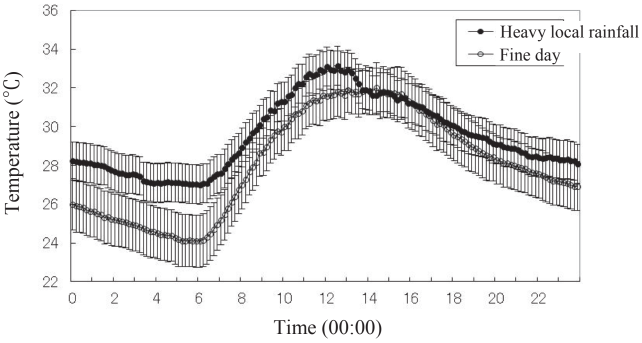

Fig. 4. Time change in surface air temperatures on days of heavy local rainfall and days of fine weather. Data is from the FDMO. Average values are shown for days. The error bar indicates standard deviation.

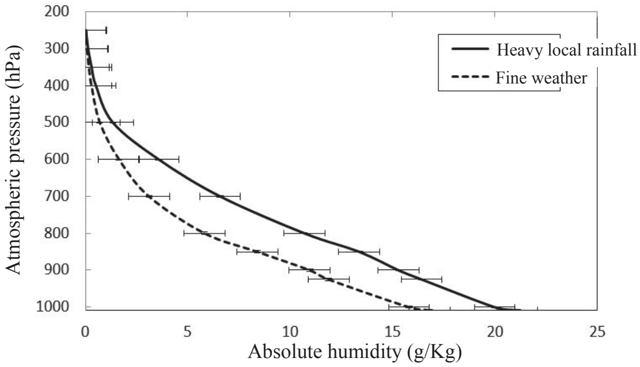

Fig. 5. Absolute humidity in the upper atmosphere on days of heavy local rainfall and on fine days. Data is from the FDMO. Average values for days are shown. The error bar indicates standard deviation.

the Meteorological Agency of Japan. Observation shows rainfall only at point 10. Significantly heavy local rainfall is also observed in precipitation analysis data, although the location of analyzed rainfall has shifted about 5 km westward. At this point, rain had not begun at other observation points. We confirmed that the rain area moved as time passed.

4. Occurrence of Heavy Local Rainfall

Such heavy local rainfall is recognized in 14 days during the period to be analyzed from 2011 to 2013. In this study the heavy local rainfall is defined as follows: (1) the general weather situation in every two hours until 10:00 is either fine or slightly cloudy at the FDMO; (2) according to the weather chart, there is neither front nor typhoon which are considered to cause the rainfall; (3) the FDMO, Hakata AMeDAS, Dazaifu AMeDAS and 14 rain gauges set for the purpose of this study record the rainfall of 0 mm during the period from dawn to 11:00; (4) at least one of the rain gauges referred to in (3) confirms occurrence of heavy local rainfall during the period from 11 to 17:00. And the rainfall which meets all the criteria from (1) to (4) is defined as the heavy local rain in this study. All heavy local rain was smaller than 100 km^2. The duration of rainfall at individual observation points ranged from 10 to 30 minutes. Two patterns are discerned – one in which it rains at only one point and the other in which the rain area gradually moves. The maximum rain area is presumed to be about 64 km^2. This rain area scale is smaller than heavy local rainfall on the Kanto plain. Maximum 10-minute rainfall was 13.8 mm. If rain continues falling several tens of minutes, rain becomes severe, exceeding 50 mm. The maximum accumulated rainfall during the period analyzed in this study was 28.6 mm in 50 minutes. During study observation, rainfall remained at this level, but could conceivably increase because heavy local rainfall is predicted to intensify in the near future.

We define these 14 days as days of heavy local rainfall. To compare with days of heavy local rainfall, we extract a day when the general daytime weather situation every two hours is either fine or slightly cloudy and no rainfall is recorded at any of the 17 rain gauge observation points – resulting in 29 such days, which we refer to as "fine" days. **Fig. 4** shows the time change for the average surface air temperature of a day of heavy local rainfall and for a fine day. Observation data at the FDMO are used as the surface air temperature. A difference of 2–3°C occurred from midnight to 06:00 (dawn between days of heavy local rainfall and fine days. Based on findings from another study 4), wind convergence caused by the rise in surface air temperature promotes cumulonimbus clouds to develop. In this study, although surface air temperature is measured at the FDMO, which differs from that at the site where heavy local rainfall occurred, we confirmed that the temperature of a day on which heavy local rainfall occurred was 2–3°C higher on average than on a fine day, which is regarded as a factor in generating heavy local rainfall.

Figure 5 shows absolute upper atmosphere humidity based on upper atmospheric weather observed at the FDMO. The FDMO provides data on relative humidity, but absolute humidity is found from the relative humidity and temperature. Data on upper atmospheric weather observed at 09:00 are used. The absolute humidity on a day of heavy local rainfall and on a fine day is averaged as shown in **Fig. 4**. The vertical axis represents atmospheric pressure (hPa) corresponding to altitude. **Fig. 4** shows a large difference between days of heavy local rainfall and

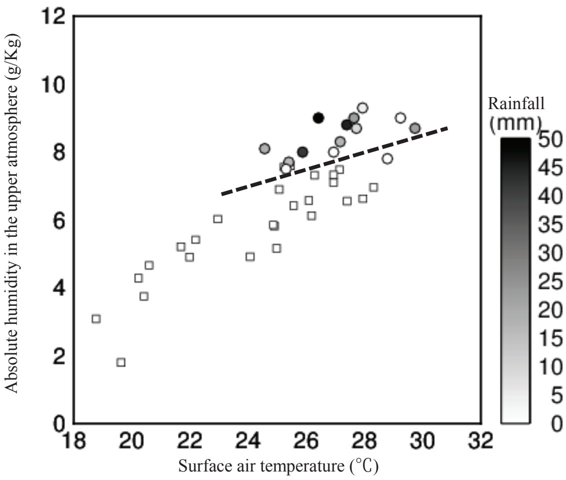

Fig. 6. Relationship between average surface air temperature between 06:00 and 07:00 and average absolute humidity in upper atmosphere between the ground surface and 150 hPa at 09:00. Squares: Fine days. Circles: Day of heavy local rainfall. Light and dark shadowing represent total rainfall.

fine days. On days of heavy local rainfall, more water vapor is contained in the upper atmosphere. Due to a large difference in absolute humidity, we also surmised that the atmosphere becomes more unstable on days of heavy local rainfall.

Figure 6 shows the correlation between surface air temperature and absolute humidity in the upper atmosphere shown in **Figs. 4** and **5** using the average surface air temperature between 06:00 and 07:00. The average absolute humidity in the upper atmosphere between the ground surface and 250 hPa at 09:00 is used. The circle indicates a day of heavy local rainfall and the square a fine day. Color of plot represents total rainfall at 14 observation points. Note that heavy local rainfall occurs above the broken line, meaning that the possibility of heavy local rainfall occurring increases if both the surface air temperature and absolute humidity in the upper atmosphere exceed a certain level. Niimura et al. [11] determined whether rainfall occurred based on the relationship between precipitable water analyzed by using a Global Positioning System (GPS) and the surface air temperature. Although the analysis is conducted year-round and they target an area wider than that in our study, they state that rainfall cannot be clarified within a narrow area in a short time. This threshold should be changed, however, because such a narrow area may be affected by local wind influenced by local topography. It thus seems possible in this study to identify a threshold unique to urban Fukuoka by accumulating data.

Figure 7 shows the relationship between total rainfall and the *KI*, which considers the dew point and the characteristics of the atmosphere in clouds in evaluating the incidence of thunderstorms. The *KI* is calculated as follows:

$$KI = (T850 - T500) + Td850 - (T700 - Td700)$$

T represents temperature (°C), Td the dew point (°C) and the subscript the number height (hPa). At a *KI* of 15°C or less, there is almost no possibility of a thunderstorm, which will occur almost certainly at a *KI* of 40°C or more. The effect restrictive on convection increases as the *KI* decreases. The black plot indicates a day of heavy local rainfall and a white one indicates a fine day. *KI* values exceed 20°C on all days of heavy local rainfall. The distribution of days of heavy local rainfall and of fine days is separated clearly in **Fig. 7**.

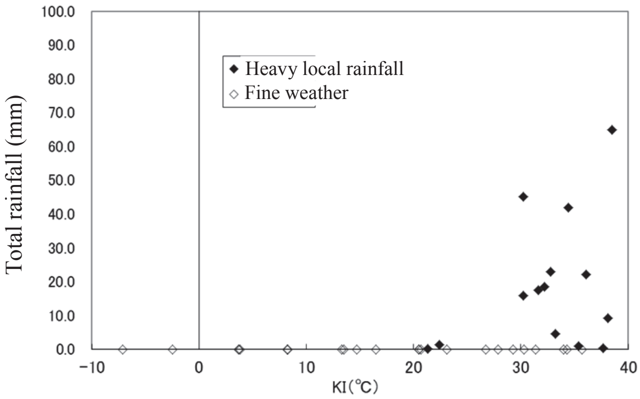

Fig. 7. Relationship between atmosphere stability and total rainfall *KI*.

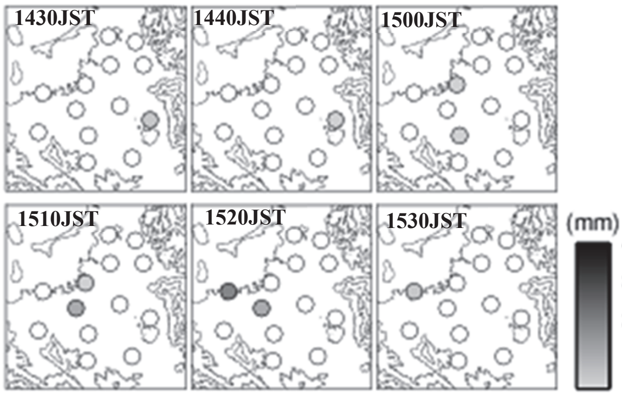

Fig. 8. Time change in 10-minute rainfall on August 27, 2011.

Table 1. Relationship between sea wind direction and east-west rain area movement.

	Wind direction	↘ West-northwest	↘ Northwest	↘ North-northwest	↓ North	↙ North-northeast	↙ Northeast	↙ East-northeast
Rain area	Stay in the east		1	1	1			
	From east to west	1		2				1
	From west to east		1	1			2	
	Stay in the west					1		1

5. Heavy Local Rainfall Rain Area Movement

Figure 8 shows the time change in the horizontal distribution of 10-minute rainfall on August 27, 2011. Times shown are when rainfall was confirmed after 14:30. In this case, the first rainfall was confirmed east of the inland Fukuoka plain area. Later, rainfall moved toward the

Table 2. Calculated WRF model conditions.

Domain number	1	2	3	4
Domain size (km)	931.5	310.5	103.5	34.5
Grid size (km)	13.5	4.5	1.5	0.5
Grid number	69 × 69			
Time step (sec)	54	18	6	2
Land use data	USG 2min	USGS 30sec	National land numerical information 100m	
Topography data	USG 2min	USGS 30sec	Geographical Survey Institute 50m	
Initial and Boundary Condition	NCEP FNL			
Surface Layer scheme	Monin-Obukhov (Janjic Eta) scheme			
Land Surface Model	Noah Land Surface model - Urban Canopy Model			
Planetary Boundary Layer	Melleor - Yamada Nakanishi and Niino Level 2.5 PBL			

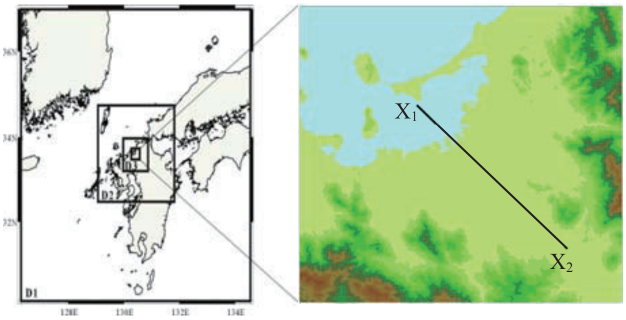

Fig. 9. Calculated domains 1–4, at right is domain 4.

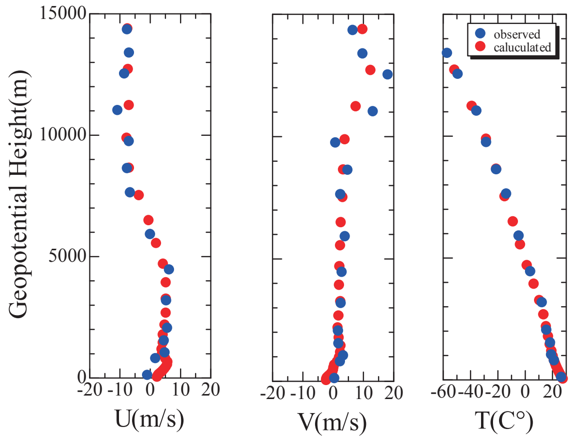

Fig. 10. Comparison of calculation results for reproduction with observation of upper atmospheric weather.

sea coast and the western plain. Rainfall that had moved westward then shifted toward the sea coast. In this way, heavy local rainfall on the Fukuoka plain tends to begin either in the western or eastern inland area and to move later toward the sea coast either the east or west. **Table 1** shows the relationship between the sea wind direction observed at Hakata AMeDAS and rain area movement east-west. (Note that the one case in which the sea wind cannot be confirmed is excluded from the table.) If the sea wind blows from the west, rain often begins on the eastern part of the plain, whereas if the sea wind blows from the east, rain often begins in the western part. We assumed that the west wind coming from the Genkai Sea strikes the Houman-Sangun mountain system at the eastern edge of the plain and generates updrafts and cumulonimbus clouds causing heavy local rainfall. The east sea wind striking the Seburi mountain system at the western edge of the plain triggers the same meteorological phenomenon.

The number of cases in which heavy local rain occurs in the inland area, then moves toward the sea coast, accounts for 75% of all days of heavy local rainfall. We then studied why the rain area moves toward the sea coast, simulating the reproduction of the sea wind using the WRF model for the case of August 27, 2011. **Fig. 9** shows calculated domains and **Table 2** calculated conditions. Calculation starts from 00:00 (midnight) on August 27 following an 8 hour runup. **Fig. 10** compares the upper atmospheric weather observed at the Fukuoka meteorological observatory at 09:00 with numerical simulation results for the horizontal component of wind, U and V, and temperature T to confirm the calculated accuracy. U represents the east-west component of wind and positive values of U are directed west. V represents the north-south component of wind and positive values of V are directed south. Some differences exist in the upper atmosphere for the component of wind, but patterns of wind velocity and temperature were reproduced well based on height.

We next examined the wind structure in the air based on numerical simulation results. **Fig. 11** shows the cross-sectional distribution of horizontal wind velocity on line X_1–X_2. The vertical axis represents height and horizontal axis line X_1–X_2. The solid line represents sea wind from the north and the broken line land wind from the south. Horizontal wind velocity is considered to be the wind velocity of the component toward line X_1–X_2. (a) shows simulation of the situation one hour after the sea wind landed and (b) that when heavy local rain begins falling. In (a), the north wind blows in a section from X_1 point to some kilometers inland. The south wind blows in an area further inland. Note from (a) that the sea wind is moving toward the inland area. In (b), the sea wind has already reached the inland area. Note that the south wind blows as compensation wind above the sea wind in the upper atmosphere. The south wind blows at a height exceeding 700 m. Because cumulonimbus clouds causing the

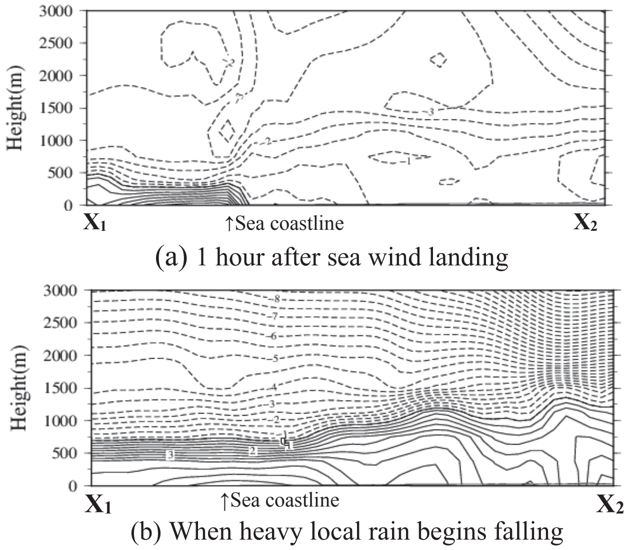

Fig. 11. Distribution of horizontal wind velocity on line X_1–X_2 based on simulated sea wind reproduction using the WRF model. The vertical axis represents height, the solid line north (sea) wind, and the broken line south (land) wind. The horizontal wind velocity is considered a component toward line X_1–X_2.

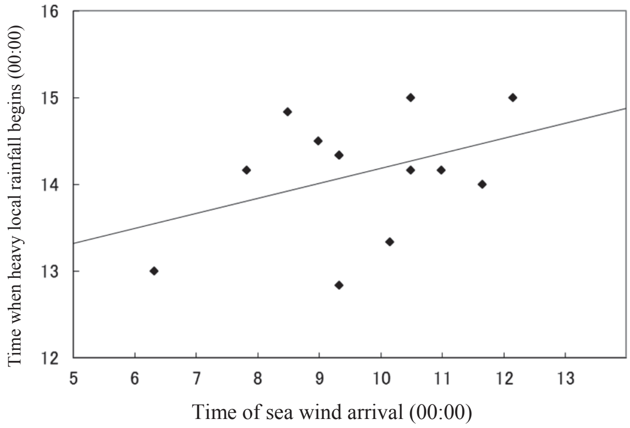

Fig. 12. Relationship between sea wind arrival time and time when heavy local rainfall begins.

rainfall form at a height of 800 m–1,000 m, we concluded that cumulonimbus clouds were moved north by this south wind and that the rain area of heavy local rainfall moved correspondingly toward the sea coast. **Fig. 12** shows the relationship between the time the sea wind arrived and that when heavy local rainfall begin falling. Note that days on which the arrival of the sea wind could not be confirmed are excluded from the figure, and that two days have the same time of sea wind arrival and the same time for when heavy local rainfall began, so there are seemingly only 12 plots in the figure. We recognize a general correlation between the sea wind arrival time and the time when heavy local rainfall began falling. According to Nakanishi et al. [9] the convergence of the sea wind is strengthened before rainfall in the case of heavy local rainfall in the metropolitan area. On the urban Fukuoka plain, the sea wind comes from one direction and is believed to strengthen updrafts when it strikes the mountain system.

6. Conclusions

We set up rain gauges at a high density in urban Fukuoka to determine actual conditions for heavy local rain and to clarify the characteristics of its occurrence. The observation and analysis period was during summer from 2011 to 2013. Based on data analysis of days when heavy local rainfall occurred and when it was either fine or slightly cloudy, we obtained the following findings:

1) Maximum heavy local rainfall area observed on the Fukuoka plain is about 64 km^2. Rainfall lasts from 10 to 30 minutes at each observation point. Maximum 10-minute rainfall is 13.8 mm.

2) A comparison of average days of heavy local rainfall to that of fine or slightly cloudy days showed a difference of 2–3°C in surface air temperature. A comparison of upper atmospheric weather showed large differences in humidity distribution. It is thus clear that heavy local rainfall tends to occur if both surface air temperature and humidity in upper atmospheric weather exceed a certain level.

3) In a comparison in *KI*, the index indicating atmosphere stability, some differences existed between days of heavy local rainfall and fine days. We confirmed that atmosphere conditions are more unstable on days of heavy local rainfall than on fine days.

4) Heavy local rainfall begins either in the eastern or western part of the inland Fukuoka plain. In many cases, the rain area moves toward the sea coast. Based on reproduction simulation using the mesoscale meteorological WRF model, we found that the south wind blows above the sea wind, so cumulonimbus clouds move toward the sea coast and the rain area moves correspondingly. Heavy local rainfall often occurs in the eastern inland area if the sea wind blows from the west. Such rainfall also occurs often in the western inland area if the sea wind blows from the east.

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