Okayama Downbursts on 27 June 1991: Downburst
Identifications and Environmental Conditions

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Abstract

On the afternoon of 27 June 1991, the Okayama area in the western part of Japan was hit by strong
gusty winds and a heavy precipitation of rain and hail associated with severe thunderstorms. The
synoptic condition was that the area was located to the south of the Baiu-front with the northern
edge of the Pacific Subtropical Anticyclone (PSA) prevailing. At one location in the area, a gusty
wind blew down 18 utility poles that were built to withstand winds of 51 m/s.

The present work was derived from this incident. Virtually all available data from various sources
were collected and analyzed. These sources include weather surveillance radars, meteorological ob-
servatories, densely deployed surface anemometers for air pollution monitoring, commercial aircraft,
videotaped imageries and a damage survey. The result of the analysis reveals that at least four wet
downbursts (either microbursts or macrobursts) occurred in the area and that one of them, which was
associated with hail precipitation, blew down the 18 utility poles. Furthermore, the environmental
conditions are found to be similar to those identified as favorable for the development of wet mi-
crobursts in northern Alabama by Atkins and Wakimoto (1991). The potential risk of downburst on
the northern edge of the PSA is also suggested.

1. Introduction

Downbursts are strong downdrafts which cause
damaging divergent winds on or near the ground.
Fujita (1985) subdivided them into macrobursts
and microbursts. The macroburst is a large down-
burst with an outburst wind extending more than
4 km in horizontal dimension. The microburst
is a small downburst with an outburst wind ex-
tending less than 4 km in horizontal dimension.
The damaging wind could be as high as 75 m/s.

Wilson et al. (1984) redefined the microburst with
reference to Doppler radar observations: the differ-
etial Doppler velocity across the divergent center
is greater than 10 m/s and the initial distance be-
tween maximum approaching and receding centers
is shorter than 4 km. This definition allows a sim-
pler quantification of microburst events.

In the US, during the period from 1974 to 1985,
 microburst winds contributed to at least 11 civil
aircraft accidents and incidents involving over 400
fatalities and 145 injuries (Proctor, 1988). To
study microbursts, many field research programs

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have been conducted. Some of them include: the Northern Illinois Meteorological Research on Downburst (NIMROD); the Joint Airport Weather Studies (JAWS); the Classify, Locate and Avoid Wind Shear (CLAWS); the Microburst and Severe Thunderstorm (MIST); the FAA/Lincoln Laboratory Operational Weather Studies (FLOWS); and the Convection Initiation and Downburst Experiment (CINDE).

These studies indicate that microbursts are common phenomena. They showed that microbursts were detected on 60% to 70% of the days during which thunderstorms occurred (Proctor, 1988). The features of the average JAWS microbursts are as
Fig. 12. Arc-shaped rolling up clouds videotaped at RSK around 13:25 JST June 1991 (Courtesy of Radio Sanyo Co.).

Fig. 13. Heavy precipitation approaching the area to be damaged (CUPs). This was videotaped at OHK around 13:25 JST June 1991. Numerals show the horizontal scale (Courtesy of Okayama Broadcasting Co.).
follows: the life cycle is 13 minutes; the maximum low-level reflectivity in the precipitation core ranges from 15 to more than 65 dBZ; and the maximum radial velocity differential is 24 m/s, occurring over a distance of 3.1 km at a height of 80 m AGL (Hjelmfelt, 1988). In the FLOWS and JAWS studies, microburst wind shear was detected with peak differential velocities of up to 50 m/s, with many more weaker ones than stronger ones (Proctor, 1988).

A large number of microbursts occur under two extreme types of atmospheric environments. One is the extremely dry environment in which moist convection is barely possible (dry microburst). The other is the extremely wet environment which can produce microbursts embedded in very heavy rain (wet microburst) (e.g., Caracena et al., 1990). With a temperature lapse rate close to the dry-adiabatic value, even very light precipitation can drive intense downdrafts. As the stability of thermal stratification increases, progressively higher precipitation contents and eventually high precipitation contents in the form of ice are needed to drive intense downdrafts (Srivastava, 1987).

Hjelmfelt et al. (1986) numerically showed that the loading of rain and graupel and the cooling effect of rain evaporation and graupel melting are all important in microburst production. Proctor (1989) demonstrated, through sensitivity experiments, that snow and graupel are most effective in producing microbursts within typical dry microburst environments, while hail is most effective in producing wet microbursts within more stable environments. Wakimoto and Bringi (1988) observed a strong localized downdraft composed of melting hail.

In Japan, during the period from 1981 to 1992, a number of downbursts caused considerable damages on properties (e.g., Iwashita, 1992; Kajikawa, 1988; Kajikawa et al., 1993; Kajikawa and Usuki, 1992; Kobayashi and Kikuchi, 1989; Ohno and Suzuki, 1991; Ohno et al., 1993; Omoto, 1987, 1989), killed at least two people, and also affected the safe operation of aircraft (JAAIC, 1855; Nakayama and Izeki, 1985; Nakayama and Aoyama, 1990). However, reports and studies on downbursts have remained very scarce (see, Appendix). So far, no aircraft crashes have been caused by downbursts and no full-scale field programs directed at studying downburst events have been conducted. Consequently, characteristic features and environmental conditions of downbursts have not been deeply investigated in Japan. For a better understanding of Japanese downbursts and their environments, many case studies on damaging winds are needed.

On the afternoon of 27 June 1991, the Okayama area in the western part of Japan was hit by strong gusty winds and a heavy precipitation of rain and hail associated with severe thunderstorms. At one location in the area, a gusty wind blew down 18 utility poles that were built to withstand winds of 51 m/s (Fig. 1). Since the event occurred in an urban area, various data sources were available. They include surveillance radars, meteorological observatories, densely deployed surface anemometers for air pollution monitoring, commercial aircraft, videotaped imageries, and a damage survey. After compiling the data, we were careful to use all available sources collectively in order to reach a conclusion. The data showed that at least four wet downbursts (either microbursts or macrobursts) occurred in the area, one of which blew down the 18 utility poles. In addition, the data indicated that a preferable environment was achieved in the afternoon.

2. Data used in the analysis

Okayama City is located in the western part of Japan (Fig. 2a). Figure 2b shows the distribution of meteorological facilities in the area, which include three conventional radars, two rawinsonde stations and many AMeDAS1 sites. Figure 2c specifies the Okayama area where meso-analysis is performed and shows the locations of the following various data sources: Okayama Local Meteorological Observatory (LMO), Okayama Airport Office of LMO (AMO), Konan Meteorological Station (KMS), 47 anemometers for air pollution monitoring, six AMeDAS sites, two railway anemometers, two commercial aircraft, VTR imageries of three TV stations, a damage survey in the area of the blown-down 18 utility poles, and two eyewitnesses. No Doppler radars covered the area. Table 1 is the summary of data characteristics.

3. Four events of localized gusty winds

At least four distinct occurrences of gusty winds were identified from the meteorological records and the damage survey data. At AMO, gusty winds were observed at 1241 and 1320 JST (Japan Standard Time) (Fig. 3). These two events will be referred to as Gust-I and Gust-II. At LMO, a gusty wind was observed at 1329 JST and will be referred to as Gust-III (Fig. 4). The gusty wind that blew down the 18 utility poles (Fig. 1) at CUPS will be referred to as Gust-IV. The location and the time of occurrence of the four winds are summarized in Fig. 2c. Detailed features of the four gusty winds will be described in the following sections. Gusty wind patterns on the traces were documented by Sahashi et al. (1993).

4. The synoptic condition

Climatically, the Okayama area is in the pre-
Fig. 2. Data source locations: (a) the geographical location of Okayama City; (b) a total of three conventional radars situated in Hiroshima, Matsue, and Osaka (a data resolution of 2.5 km x 2.5 km); two rawinsonde stations at Yonago and Shiono-misaki; AMeDAS sites indicated by closed circles observe the four elements (temperature, wind vector, precipitation, and sunshine duration); AMeDAS sites indicated by triangles observe only precipitation; and (c) data sources in the Okayama area include LMO (Okayama Local Meteorological Observatory), AMO (Airport Meteorological Office of LMO), KMS (Konan Meteorological Station), NHK (Japan Broadcasting Corporation), RSK (Radio Sanyo Co.), OHK (Okayama Broadcasting Co.), and CUPs (Collapsed Utility Poles). (For data characteristics, see Table 1).
Table 1. Data available in the Okayama area for mesoscale analysis. JMA: Japan Meteorological Agency, L.Gov: Local Government, and WJR: West Japan Railways Co.

<table>
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<tr>
<th>Observing system</th>
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<th>Number deployed</th>
<th>Symbol in Fig. 2c</th>
<th>Measurements</th>
<th>Comments</th>
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<td>●</td>
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<td>Direction of blown-off objects and vegetation falls, identification of hailstorm areas, eyewitness accounts</td>
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Fig. 3. Meteorological traces recorded by AMO from 1100 to 1600 JST 27 June 1991: (a) wind speed; (b) wind direction; (c) temperature and dew-point temperature; (d) pressure; and (e) precipitation rate.

Fig. 4. Same as Fig. 3, but for LMO.
summer rainy season in June with the Baiu-front lying between the tropical air mass and the mid-latitude air mass. However, on the morning of 27 June 1991, the Baiu-front temporarily moved northward and the area was covered by the Pacific Sub-tropical Anticyclone (PSA) (Fig. 5a). The Okayama area was exposed to strong insolation. In the early afternoon, the Baiu-front began to move southward and the area was again under the Baiu-front by 2100 JST (Fig. 5b). The southward shift of the PSA is
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The time series of SSI and CAPE during the period from 0900 JST (00 UTC) 26 June to 0900 JST 28 June are shown in Fig. 6a and 6b. They were calculated from averaged profiles of Yonago and Shiono-misaki soundings, since Okayama City is located between these two stations. Also shown are the time series of temperature and dew-point temperature (Fig. 6c), and the amount of hourly precipitation (Fig. 6d).

Prior to the thunderstorm event of 27 June, the SSI was close to 2 and then decreased gradually with time. Meanwhile, the CAPE was increasing from 1000 to 1500 m² s⁻². Thus the stratification over Okayama was destabilized. Generally, a CAPE of 1500 m² s⁻² indicates moderately unstable convective days (Weisman and Klemp, 1986). The surface temperature showed strong diurnal variation with the maximum temperature of 34°C. No precipitation was observed before the event.

On the early afternoon of 27 June 1991, thunderstorms formed in an area northwest of Okayama City (Fig. 7a). The area was located to the south of the Baiu-front covered by the northern edge of the PSA. These thunderstorms developed into large cloud clusters as they moved eastward (Fig. 7b and 7c). During these stages, the SSI decreased rapidly, although the CAPE did not change as much (Fig. 6a and 6b). The surface temperature dropped rapidly with the passage of the thunderstorms.

5. Meso-analysis in the Okayama area

In this section, the result of our meso-analysis will be presented in order to illustrate the meteorological situations in which the four localized gusty winds occurred.

5.1 Radar and surface data analysis

Figure 8 shows the horizontal distributions of radar echoes around the 2-km level and the surface wind from 1228 JST to 1343 JST 27 June. Radar echo data are of 2.5 km x 2.5 km horizontal resolution. The wind discontinuity lines (DLs) are determined as the boundary between the southwesterly and northwesterly wind regimes.

Although a DL (DL-I) is partially identified at the time of Fig. 8b, the anemometer traces in Fig. 3a and 3b during this period showed no wind discontinuity at AMO. DL-I was not yet well organized before its passage at the airport. Moreover, Gust-I at 1241 JST occurred near the central part of Echo-area-I behind DL-I (Fig. 8c). Hence, DL-I is not responsible for Gust-I.

Moving eastward, DL-I passed LMO at 1305 JST (Fig. 8f). At this time, a weak gusty wind of 7 m/s, a wind shift from SW to NW, a temperature drop of 4°C, and a pressure rise of 0.5 hPa were recorded (Fig. 4). However, no precipitation was observed.

Echo-area-II appeared at 1256 JST (Fig. 8e), accompanying another DL (DL-II). With the passage of DL-II at AMO at the time of Fig. 8g, a weak gusty wind of 5 m/s, a wind shift from S to NW, a pressure rise of 1 hPa, little change of temperature and moisture, and heavy precipitation (exceeding 50 mm/hour) were observed for approximately 10 minutes (Fig. 3). After the passage of DL-II at AMO, a southwesterly Gust-II at AMO occurred at 1320 in the northwesterly wind region behind DL-II (Fig. 8h). Gust-II is therefore not related to DL-II.

When DL-II passed over LMO at 1328 JST (Fig. 8i), another DL-II ("a-b" in Fig. 8i) expanded southeastward with a horizontal scale of 10 km. Point "a" was determined as the bend of DL-II, and Point "b" was determined as the northeastern end of the arc-shaped roll clouds observed in central Okayama City (Fig. 12). Gust-III at LMO, defined as a northwesterly wind of 26 m/s, occurred at 1329 JST (Fig. 4). It was associated with a tem-
Fig. 7. GMS IR imageries of 27 June 1991 at (a) 1240 JST, (b) 1340 JST and (c) 1440 JST. Arrows indicate thunderstorm cells which affected Okayama City.
Fig. 8. Radar and surface wind analysis from 1228 JST to 1343 JST 27 June 1991. Areas of precipitation of more than 4 mm/h are enclosed by solid lines. Areas of precipitation of more than 16 mm/h and 32 mm/h are respectively marked by hatching and heavy hatching. Barbs drawn at AMO and LMO are one-minute-mean winds and others are several-minute-mean ones (1 barb: 5 m/s). A cold-front-like line is a wind discontinuity line (DL-I or -II) as a boundary between a southwesterly and a northwesterly wind regime, where a dashed line shows a less evident part of the wind discontinuity line. The dotted line in (f) indicates a flight path of a commercial aircraft. Orography is shown in (z), where the areas higher than 100 m ASL are shaded.
perature drop of 7°C, a pressure jump of 1.5 hPa, and heavy precipitation. Unlike earlier Gust-I and Gust-II, Gust-III occurred almost on DL-II.

Gust-IV, which blew down the 18 utility poles, is estimated to have occurred around 1330 JST. The fact on which this estimation is based will be discussed in Section 6.4. The passage of DL-II over CUPS was around 1328 JST (Fig. 8i). Therefore, Gust-IV at CUPS occurred almost on DL-II.

After Gust-IV, no gusty wind was observed in the Okayama area. DL-II and Echo-area-II moved away eastward. The northwesterly winds prevailed over Okayama City (Fig. 8j and 8k).

In Figs. 8b-8k, DLs were always ahead of the radar echoes and were accompanied by gusty winds, although some of them were weak. Hence, DL-I and DL-II seem to be two separate gust fronts respectively induced by the heavy precipitation under

Fig. 8. (Continued)
Echo-areas I and II.

5.2 Aircraft data analysis

Three commercial aircraft provided vertical profiles of wind and temperature between the surface and 3000 m height provided by three commercial aircraft. Closed circles indicate the temperature measured over Takamatsu (40 km south of Okayama). Open circles indicate the temperature measured over Osaka (140 km east of Okayama). Crosses denote the temperature measured along the flight path of “A–B–C–D–E–F” in Fig. 8f. Numerals indicate the time of observation (e.g., 1305: 1305 JST 27 June 1991).

Fig. 9. Vertical profiles of temperature and wind (1 barb: 5 m/s) between the surface and 3000 m height provided by three commercial aircraft. Closed circles indicate the temperature measured over Takamatsu (40 km south of Okayama). Open circles indicate the temperature measured over Osaka (140 km east of Okayama). Crosses denote the temperature measured along the flight path of “A–B–C–D–E–F” in Fig. 8f. Numerals indicate the time of observation (e.g., 1305: 1305 JST 27 June 1991).

(1) Between 3000 m–1800 m (path A–B), the temperature profile is similar to that of the Takamatsu data. This indicates that the air is on the side of the PSA.

(2) Between 1800 m–1000 m (path B–C), the temperature is lower than that over Takamatsu. However, the potential temperature is almost equal to that of the neutral layer below the height of 1100 m over Takamatsu. This fact requires that the air between 1800 m–1000 m has come from a low-level of the PSA, averaging over the frontal surface of DL-I. Hence, the existence of DL-I at the location in Fig. 8f is confirmed.

(3) At about 1000 m (path C–D), there is an inversion layer. The wind direction is northwesterly on the path D–E, which is different from that on the path B–C. These features indicate that the inversion layer of the path C–D is the boundary between the two air masses. Notice in Fig. 8f that the points C and E corresponded to the leading edge of the surface cold outflow from Echo-area-II. The aircraft data thus confirmed the existence of DL-II.

(4) Between 500 m–250 m (path E–F), there is another inversion layer, which shows that AMO was behind DL-I and already covered by a cold layer with 250 m thickness before the arrival of DL-II. Therefore little change in temperature was accounted for with the passage of DL-II, at 1313 JST (Fig. 3c).

6. Downburst identification

6.1 Downburst-I (resulting in Gust-I)

In order to determine whether Gust-I was indeed a downburst, the wind field at 1243 JST was superimposed on the radar echo imageries taken at the same time (Fig. 10). The wind field near the airport was constructed by time-space conversions (e.g., Fujita and Byers, 1977; Fujita and Caracena, 1977; Fujita, 1985) of one-minute-mean wind measured by two anemometers at the airport. The positions of the two anemometers were moved at a speed of 1 km/min in the direction opposite to the echo movement.

The wind field shows the existence of a localized outflow in the strong echo areas behind DL-I, where the asterisk in the figure shows the center of the outflow. This center of outflow can be determined by eye. A localized outflow requires the existence of a concentrated downward motion above the outflow area (Fujita and Byers, 1977).

Figure 3 shows that Gust-I (250°; max 14 m/s) is associated with a temperature drop of 5°C, a humidity dip, a pressure nose of 1 hPa (for definition of pressure nose, see Byers and Braham, 1949), and a gush of rainfall with a peak rate of 100 mm/h (the radar rainfall rate was 54 mm/h). Byers and Braham (1949) indicated that (1) a humidity dip, which
is a drop of dew-point temperature during a few minutes under very heavy rain, occurs almost exclusively in an area of divergence and (2) the pressure nose should happen before the divergence in the surface layers becomes well established. Gust-I was therefore a divergent wind under heavy rainfall with a maximum wind speed of over 10 m/s (a threshold for downburst identification). It is a wet downburst (Downburst-I) with a strong southwesterly wind that caused Gust-I at the air-

Fig. 10. AMO wind field and radar echoes at 1243 JST 27 June 1991. Areas of precipitation of more than 4 mm/h are enclosed by solid lines. Areas of precipitation of more than 16 mm/h and 32 mm/h are respectively marked by hatching and heavy hatching. Barbs drawn at AMO are one-minute-mean winds and others are several-minute-mean ones (1 barb: 5 m/s). The AMO winds were constructed by time-space conversions. Symbol “*” indicates the center of the localized outflow, as is determined by the eye.

Fig. 11. Same as Fig. 10, but for 1320 JST.
The size of Downburst-I is roughly estimated to be twice the distance between the outflow center and the location of the maximum wind, about 5–10 km.

6.2 Downburst-II (resulting in Gust-II)

The wind field for Gust-II at 1320 JST was also constructed by a time-space conversion of the anemometer traces. Figure 11 shows that Gust-II, occurring under Echo-area-II, is a localized southwesterly wind embedded in the northwesterly flow behind DL-II.

Figure 3 shows that Gust-II (200°; max 14 m/s) was accompanied by a temperature drop of 1°C, a pressure nose of 1 hPa and a rainfall rate of 100 mm/h. No humidity dip was observed in this case. We note that (1) the pressure nose suggests a localized surface divergence, (2) the strong southwesterly wind is different from the flow behind DL-II, and (3) the maximum wind speed exceeding 10 m/s occurred simultaneously with the gush of rainfall. These facts together indicate that it was a wet downburst with a strong southwesterly wind (Downburst-II) that caused Gust-II. The size scale cannot be determined.

In spite of the rain-gauge records of 100 mm/h, the radar rainfall rate remained at only 20 mm/h (Fig. 11). This implies the size of the parent cloud was much smaller than the horizontal resolution of radar data (2.5 km × 2.5 km).

The temperature drop is much smaller in this case (1°C) than in Downburst-I (5°C). The pre-existing cool air layer on the ground (Section 5.2) accounts for this small temperature drop.

6.3 Downburst-III (resulting in Gust-III)

Gust-III (330°; max 26 m/s), which occurred at 1329 JST, was associated with a temperature drop of 7°C, a pressure dome (as defined by Byers and Braham, 1949) of 1.5 hPa, and a gush of rainfall with peak rate of 60 mm/h. There data were recorded at LMO (Fig. 4), where the radar rainfall rate was 38 mm/h (Fig. 8i).

As shown in Section 5.1, a part of DL-II at 1328 JST expanded to the southeast to 10 km in size (line "ab" in Fig. 8i). This indicates a concentrated downward motion followed by a localized outflow over the expansion area. The fact that no expansion was seen before 1320 JST (Fig. 8h) implies that the downward motion had just occurred between 1320 and 1328 JST.

Figure 12 shows a videotape of arc-shaped, rolling-up clouds around 1325 JST at RSK. These clouds approached RSK from a northwesterly direction and passed RSK a few minutes before heavy precipitation occurred. (An RSK cameraman who took this video confirmed that the rolling-up clouds brought only light precipitation.) The arc-shaped
clouds seem to correspond to the expanded DL-II ("ab" in Fig. 8i). The northern end of the clouds is shown in Fig. 12. Such rolling-up clouds are considered to be precipitation rolls which indicate that a downward motion has been occurring from a thunderstorm behind the rolls (Wakimoto 1982).

Considering (1) the existence of a downward motion was indicated by the expansion of the gust front (DL-II) and the arc-shaped rolling-up clouds and (2) the maximum wind speed (26 m/s) over 10 m/s under heavy rainfall, we concluded that it was a wet downburst with strong northwesterly wind at 1329 JST (Downburst-III) which caused Gust-III. Because the extent of the localized outflow was of the order of 10 km, we decided that this downburst was a macroburst. The expanded part of DL-II was a burst front (Fujita, 1981).

6.4 Downburst-IV (resulting in Gust-IV)

The following facts have led us to believe that Gust-IV occurred around 1330 JST.

(1) The blown-down utility poles caused a power failure at 1330 JST.

(2) Eyewitnesses told the authors that Gust-IV was immediately followed by heavy rainfall and hail. (The appearance of heavy precipitation is shown in Fig. 13).

(3) A radar echo analysis indicates that the time of heavy precipitation in the area (93 mm/h) took place around 1330 JST (Fig. 8i–8j).

Figure 14 is the summary of the damage survey, in which two wind systems can be seen. One wind system is detouring around the small hill denoted by "A", and the other system is localized to the south of the hill as a northwesterly outburst from the point "*" at the west side of the hill. The outburst size is 1 km x 1 km. An eyewitness who was at the open arrow in Fig. 14 said, "A cloud gushed out from the western slope of the hill and advanced toward me in a flash. It looked like a pyroclastic flow seen on a TV news program".

The direction in which she indicated that the cloud was moving, shown by the open arrow, is consistent with the northwesterly localized outburst analyzed in Fig. 14.

2 A pyroclastic flow is a kind of gravity current. The continual volcanic activity of Mt. Unzen was a national concern at that time. Disastrous pyroclastic flows were broadcast everyday on TV. That is why the eyewitness used the term.
Therefore, we conclude that it was a microburst (Downburst-IV) which blew down the 18 utility poles. Although there was no scientific way to estimate the actual wind speed, we know that the wind was strong enough to blow down the utility poles. This microburst was associated with hail precipitation. The cloud that resembled a pyroclastic flow was in fact a burst front. As already shown in Fig. 8i, DL-II was located near the damaged area at 1328 JST. It was therefore diagnosed that the microburst occurred very close to the gust front.

Although Downburst-III and Downburst-IV occurred almost simultaneously, they are judged to be separate downbursts. The strong echo marked as B in Fig. 8i corresponds to the rainshaft in Fig. 13. This echo is definitely separate from the echo-A which caused the macroburst (Downburst-III) in the central area of Okayama City. Figure 15 illustrates these two downbursts. The microburst occurred near the gust front; however, it was the macroburst outflow with the rolling-up clouds that expanded the gust front.

7. Downburst environments

The sounding for Okayama on the afternoon of 27 June 1991 was reconstructed with data from aircraft, two rawinsondes, and surface observations (Fig. 16). The following steps show the reconstructing procedure of the sounding.

(STEP-1) An average of the Yonago and Shionomisaki soundings at 0900 JST was adopted as the initial profile;

(STEP-2) The initial temperature profile below 850 hPa was replaced with the aircraft observation over Takamatsu around 1300 JST (Fig. 9);

(STEP-3) The initial surface dew-point temperature was replaced with the 1300 JST dew-point.

Fig. 17. Vertical profiles of equivalent potential temperature for the previously documented cases. The curve labeled FACE was observed in southern Florida; NIMROD was observed near Chicago, Illinois; and Oklahoma was observed near Edmund, Oklahoma. "July 13" was observed in northern Alabama (after Atkins and Wakimoto 1991). Added are two Okayama profiles, one being obtained from the reconstructed soundings in Fig. 16 represented by open circles and the other from a numerical weather prediction (NWP) output indicated by a dotted line.

Fig. 18. Same as Fig. 6, but for (a) T_{500} and T_{5-5}, (b) \(\theta_e\)-max and \(\theta_e\)-min. (For definitions, see text).
and (STEP-4) The initial dew-point temperature profile in the dry adiabatic layer (below 890 hPa) was replaced by the line of constant mixing ratio through the new surface dew-point temperature.

The reconstructed sounding shows (1) a neutral layer that extends the cloud condensation level, with T-Td of about 10°C at the surface, and (2) an elevated dry layer with T-Td of about 10°C above the neutral layer. This profile is similar to the wet microburst soundings observed in the MIST project that was conducted in northern Alabama (Atkins and Wakimoto, 1991; Tuttle et al., 1989). Compared with FACE wet microbursts in Florida (Caracena and Maier, 1987), this profile is more dry in the neutral layer and more moist in the elevated layer.

This profile is also characterized by the large difference of the equivalent potential temperatures (Δθe > 20 K) between the surface value and the minimum aloft as shown Fig. 17. The large Δθe indicates a preferred downburst environment (Atkins and Wakimoto, 1991).

Fig. 19. Time sequence of 700 hPa relative humidity distribution between 40 N and 25 N along the line through Okayama City (line AA' of Fig. 2) from 0900 JST 15 June to 0900 JST 16 July 1991. Heavily dotted areas represent a relative humidity higher than 70%, while thin dotted areas correspond to less than 40%. 
8. Discussions

8.1 The effect of hail precipitation on downbursts

The wind of Downburst-IV, which was powerful enough to blow down utility poles, was much stronger than the winds of the other three downbursts. This strong wind occurred in the area of heavy hail precipitation (Fig. 14). In contrast, no hail precipitation was reported in other three downburst events. This fact suggests that Downburst-IV was accelerated by the evaporation and melting of hail. Hail is believed to be effective in producing wet microbursts (Srivastava, 1987; Wakimoto and Bringi, 1988; Proctor, 1989).

8.2 The potential risk of downbursts in the northern edge of the PSA

When the downbursts occurred, Okayama had been covered by the PSA airmass. Figure 18a shows (1) the time series of the observed temperature at 500 hPa ($T_{500}$) and (2) the time series of the temperature that a parcel of air at 850 hPa would have if it had been lifted dry-adiabatically to its lifting condensation level and thence moist-adiabatically to 500 hPa ($T_{8-5}$). $T_{500}$ over Okayama decreases by 1°C as the PSA left Okayama, while $T_{8-5}$ remains almost constant. Therefore, a storm potential became higher as the 500 hPa temperature fell in accordance with the southward shift of the PSA.

Figure 18b shows the time series of $\theta_e$-max and $\theta_e$-min, which are located near the surface and at the mid-level, respectively. $\Delta \theta_e$, the difference between $\theta_e$-max and $\theta_e$-min, exceeds 20 K during the period from 2100 JST 26 June to 0900 JST 27 June. Storms in this period have a high risk of downbursts, according to Atkins and Wakimoto (1991).

A small $\theta_e$-min during this period is accounted for in Fig. 19, which shows the time sequence of 700 hPa relative humidity. The wet portion along 30°–35°N indicates the Baiu-front. To the south of the wet portion, there is a dry domain corresponding to the PSA. The mid-level air is less humid during the period of a small $\theta_e$-min than during the preceding and following periods.

The atmosphere along the northern edge of the
PSA is thus characterized by a destabilized atmosphere with an elevated dry layer. This is illustrated by the horizontal distribution of $\Delta \theta_e$ and SSI as shown in Fig. 20. The northern edge of the PSA, which exists along southern coast of Japan, has both a large $\Delta \theta_e$ and a negative SSI. In fact, on the afternoon of 27 June, the temperature profile at Osaka showed a dry adiabatic layer below a height of 1100 m (open circles in Fig. 9). Furthermore, Kobe (located between Okayama and Osaka) was hit by a gusty wind of 21 m/s with heavy rainfall of 80 mm/h, a temperature drop of 5°C and a pressure nose of 2 hPa (Fig. 21). Apparently, another downburst hit Kobe.

Moreover, it is a climatic fact that 60% of downbursts (11 events out of the 18) that occurred in the period from 1981 to 1992, occurred in the northern edge of the PSA (shaded circles in Fig. A.1).

We therefore consider that the northern edge of the PSA has potential risk of downbursts.

8.3 Cloud shading effect

AMeDAS data at 0900 JST showed (1) cloudiness discontinuity (i.e., a cloudy area adjacent to a clear area) to the north of Okayama and (2) wind convergence near the discontinuity (Fig. 22a). Therefore, it is likely that a thermally induced mesoscale circulation between these areas would develop (Purdom, 1982; Segal et al., 1986). GMS visible imageries at 0840 JST and 1340 JST show that the Okayama area was in the clear region just south of the Baiu-front during the early morning of 27 June (Fig. 22b). Then, in the afternoon, the area filled with Cb clusters (Fig. 22c). Therefore, there is a possibility that the cloud shading effect of the Baiu-frontal zone contributed to the initiation of the deep convections.

9. Summary and conclusions

A meso-analysis of the gusty wind events in association with the thunderstorms over the Okayama area on the afternoon of 27 June 1991 identified four wet downbursts. Of all, the most severe one was associated with hail precipitation. The downburst characteristics are summarized in Table 2.

A combined use of the various kinds of data, including the damage survey and the videotaped imageries, was proven to be highly useful in helping us reach our conclusions. Densely deployed anemometers for air pollution monitoring were particularly helpful in discriminating downbursts from gust fronts, even though the anemometers only provided a several-minute-mean wind.
The soundings for Okayama that were reconstructed from the data from the two upper-air stations, the commercial aircraft, and LMO revealed preferable conditions for wet downbursts were achieved on the afternoon of 27 June 1991. These conditions are as follows: (1) A dry adiabatic lapse-rate layer (1100 m deep) below the cloud condensation level and an elevated dry layer; and (2) a large difference in the equivalent potential temperatures (30 K) between the surface value and the mini-

Fig. 22. Cloud shading effect on 27 June 1991. (a) sunshine duration shorter than 10 minutes during a period from 0800 to 0900 JST is indicated by a shaded area; and 10-minute-mean surface winds at 0900 JST are indicated by wind barbs (1 barb: 1 m/s, 1 pennant: 5 m/s). (b) and (c) show GMS visible imageries at 0840 JST and 1340 JST.
Table 2. Characteristics of the Okayama downbursts on 27 June 1991.

<table>
<thead>
<tr>
<th>Downburst</th>
<th>Location</th>
<th>Time of occurrence (JST)</th>
<th>Size-scale (km)</th>
<th>Maximum intensity (m/s)</th>
<th>Maximum wind direction</th>
<th>Cloud cluster movement</th>
<th>Downburst location in the cloud cluster</th>
<th>Temperature drop (°C)</th>
<th>Humidity dip (°C)</th>
<th>Pressure rise (hPa)</th>
<th>Rainfall rate (mm/h)</th>
<th>Rain gauge</th>
<th>Hail</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Airport</td>
<td>1241</td>
<td>5–10</td>
<td>14</td>
<td>SW</td>
<td>E</td>
<td>Near central</td>
<td>5</td>
<td>1–2</td>
<td>1 (nose)</td>
<td>54</td>
<td>100</td>
<td>Non</td>
</tr>
<tr>
<td>II</td>
<td>Airport</td>
<td>1320</td>
<td>—</td>
<td>14</td>
<td>SW</td>
<td>E</td>
<td>Near central</td>
<td>1</td>
<td>Non</td>
<td>1 (nose)</td>
<td>20</td>
<td>100</td>
<td>Non</td>
</tr>
<tr>
<td>III</td>
<td>City-central</td>
<td>1328</td>
<td>10</td>
<td>26</td>
<td>NW</td>
<td>E</td>
<td>Front side</td>
<td>7</td>
<td>Non</td>
<td>2 (dome)</td>
<td>38</td>
<td>60</td>
<td>Non</td>
</tr>
<tr>
<td>IV</td>
<td>City-NE</td>
<td>1330</td>
<td>1</td>
<td>Severe</td>
<td>NW</td>
<td>E</td>
<td>Front side</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>93</td>
<td>—</td>
<td>Yes</td>
</tr>
</tbody>
</table>
mum aloft. The vertical profiles of temperature and moisture were similar to the MIST wet microburst soundings.

It is probable that the cloud shading effect of the Baiu-frontal zone was a contributing factor in initiating the deep convection of the day.

The analysis of the SSI and $\theta_e$ was performed based on (1) the time series of the reconstructed sounding for Okayama and on (2) the NWP output for the afternoon of 27 June. This analysis led to the suggestion that the northern edge of the Pacific Subtropical Anticyclone has a potential risk of downbursts. This suggestion was supported by the climatology on Japanese downbursts during the period from 1981 to 1992.

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Appendix


Based on information, currently available to the authors, there have been at least 18 downburst events reported or investigated from 1981 to 1992. Figure A.1 shows their monthly geographical distributions. The 18 events are listed according to the month in which they occurred.

(2) May 15, 1989, 1540 JST, Kyowa-machi, Akita Prefecture (Kajikawa et al., 1993).
As one can see from the upper graph in Fig. A.2, downbursts are much more frequent in Japan during the months from June to September than during any other time of the year. The lower graph shows the most probable time of the day for a downburst to occur (1200–1800 JST).

References


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岡山ダウンバースト 1991 年 6 月 27 日
- ダウンバーストの特定と環境条件 -

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太平洋高気圧の北辺に位置する岡山地方で 1991 年 6 月 27 日午後発生した雷雨帯は同地方に激しい雨や雷および強い突風をもたらした。中でも岡山市北東部で発生した突風は特に強く、単体では 51 m/s の風に耐えるコンクリート製電柱 18 本を倒壊させた。

この研究は、電柱の倒壊をもたらした突風の原因を調べるために始められた。利用可能なすべてのデータが集められ、解析された。データ源は、通常レーダー、気象庁のシステム、密に展開された自治体の大気汚染監視用風向風速計、民間航空機、テレビ局のビデオ画像、被害調査結果等と多岐にわたった。これらを複合利用してメソ解析を行った結果、少なくとも 4 つのダウンバースト（マイクロバーストとマクロ
バーストの両方）の発生が明らかになった。電柱を倒壊させたのはそのうちの1つで、雷を伴っていた。当時大気構築は、湿マイクロバーストを発生させるのに適したもので、Atkins and Wakimoto (1991) が報告した米国北アラバマの事例と類似していた。また、ダウンバースト発生の潜在的危険性が太平洋高気圧の北辺にあるとの指摘がなされた。