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An Analysis of Typhoon 9807 (Vicki) Based on Surface Meteorological Records Obtained from Fire Stations

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ABSTRACT

Based on weather observation data collected at fire stations in the Kinki and Chubu districts of Japan, the surface structures of typhoon Vicki were investigated. There were four local, high wind areas in the Kinki district, the instantaneous wind velocity exceeding 50m/s. High winds occurred in two cases; almost simultaneously when minimum atmospheric pressures were reached and about one hour after they were recorded. A comparison of the local high wind areas and combined radar echo charts showed that the latter local high winds occurred around a rain band that formed to the rear of the center of the typhoon. Detailed surface structures of the typhoon concerned with temperature, humidity, precipitation, and atmospheric pressure were obtained. Weather observation data recorded at fire stations were shown to be very useful for analyzing the surface meteorological structures within a typhoon.

1. INTRODUCTION

Typhoon Vicki made landfall on the coastline north of Gobo City, Wakayama Prefecture at about 13:00JST on September 22nd 1998, just after typhoon Waldo which had made landfall at Wakayama Prefecture the previous day. Typhoon Vicki coursed through the Kinki district producing severe damage in many places, especially Nara Prefecture. Because this typhoon passed the central part of the Kinki district, surface weather data was recorded not only at official meteorological stations but at many fire stations, schools, power stations, and other facilities.

In recent years, local governments in Japan have installed weather data acquisition systems for fire fighting. Many fire fighting headquarters have been equipped with automatic weather observation systems to help the prevention of disasters in local areas. There are tens of fire fighting headquarters in each prefecture in the Kinki and Chubu districts, and surface weather data are collected by data acquisition systems in most of them. The weath-

Table 1 Fire station responses

Name of Prefecture	Number of fire stations	Number of responses	Response Rate (%)
Kinki District			
Kyoto	17	10	59
Mie	16	11	69
Shiga	11	7	64
Osaka	33	22	67
Wakayama	21	8	38
Nara	13	11	85
Chubu District			
Aichi	47	38	81
Gifu	24	13	54
Fukui	12	8	67
Total	194	128	66

KEY WORDS: typhoon Vicki, fire station, weather situation, combined radar echo

er observation network that includes these fire fighting headquarters has a denser distribution than that of the JMA (Japan Meteorological Agency) which has only one or two stations per prefecture. The average distance between the AMeDAS (Automated Meteorological Data Acquisition System) observation sites is about 20km whereas the average distance between the fire fighting headquarters is a few kilometers in urban areas. Moreover, indispensable weather elements for the typhoon analysis which are not measured in the AMeDAS, the instantaneous wind velocity, atmospheric pressure, and humidity, are recorded in time series at the fire fighting headquarters. This weather observation network based on fire fighting headquarters has importance for more detailed analyses of surface meteorological structures within a typhoon.

Table 2 Total observation points

Classification of observation points	Number
Fire station	128
Meteorological observatory	27
AMeDAS (four observed elements)	71
Power station	27
Total	253

Uematsu et al. (1999, 2002) published a database for the weather observation network covering Aomori, Akita, Miyagi, Yamagata, and Fukushima prefectures in the Tohoku district. There has been no report, however, that verifies the utility of a weather observation network that collects weather data recorded by weather data acquisition systems that cover an extensive area, because the purpose of these systems seems to be to provide weather information only for local areas.

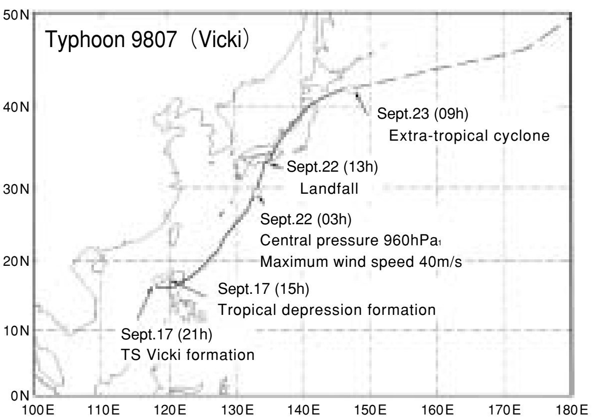


Fig. 1 (a) Path of Typhoon Vicki The times are JST.

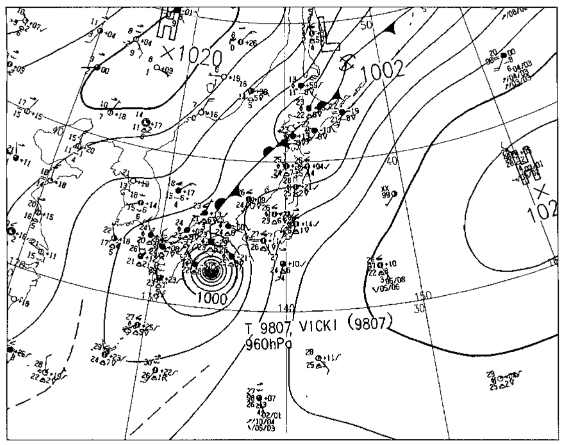


Fig. 1 (b) Weather chart at 9:00JST on September 22nd 1998.

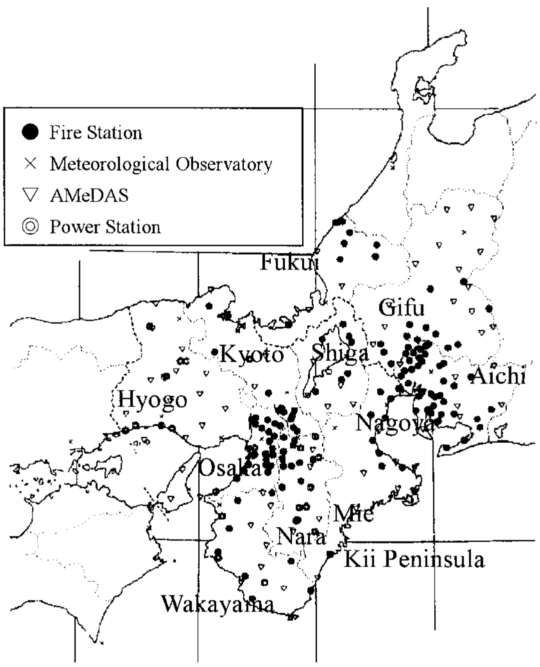


Fig. 2 Locations of fire stations, meteorological observatories, AMeDAS, and power stations

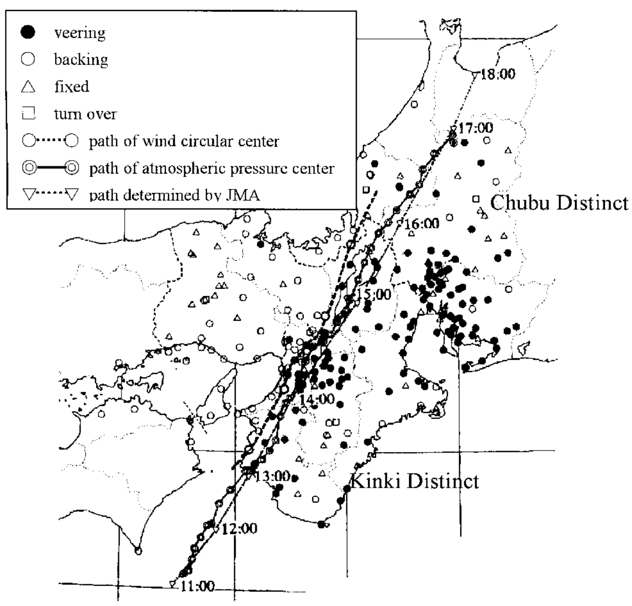


Fig. 3 Path of Typhoon Vicki in the Kinki District
The change in wind direction at observation sites is clockwise at the closed circles, anticlockwise at the open circles.

Okuda et al. (2000a) asked for weather data after typhoon Vicki's attack in order to analyze in detail the surface weather situation during that typhoon. Many responses were received as shown in Table 1. The response rates for Nara and Aichi prefectures, in particular, exceeded 80%. In addition, weather records were obtained from government weather service stations (Japan Meteorological Agency, 1998a) and from power stations in the Kinki district. Totally, data was received from 253 observation sites (Table 2). Okuda et al. (2000a) determined the meteorological characteristics of typhoon Vicki from these observation data. Okuda et al. (2000b) also discussed the high wind generated behind the center of typhoon Vicki. Here, findings on time series changes in the weather elements seen in the typhoon passage charts are discussed and compared with rainfall strength figures from combined radar echo charts. The utility of weather observation networks at the fire stations is verified from the findings.

2. GENERAL FEATURES OF TYPHOON VICKI

The course of typhoon Vicki and weather chart at 9:00JST on September 22nd (Japan Meteorological Agency, 1998b) are shown in Fig.1 (a) and (b), before landfall on the Kii Peninsula. A weak tropical depression, in the western sea off of the Philippines' Luzon Island at 15:00JST on September 17th, developed into typhoon Vicki at 21:00JST the same day. Development was gradual over the course shown in Fig.1 (a), and the typhoon struck the Kii Peninsula of Japan about 13:00JST on September 22nd. The atmospheric pressure at its center was recorded as 960hPa at landfall. Maximum wind velocity was 35m/s in the vicinity of the center. The radius of the severe wind area in which the wind velocity was more than 25m/s was 190km on the southeast and 150km on the northwest sides. The radius of the strong wind area in which the wind velocity was more than 15m/s was 700km on the southeast and 220km on the northwest sides.

After landfall, typhoon Vicki moved northeast over the center of the Kinki district weakening gradually as it approached Toyama Bay. Moreover, it made re-landfall in Yamagata Prefecture before 22:00JST the same day. The central atmospheric pressure at the second landfall was 990hPa, and the maximum wind velocity near the center 25m/s. The radius of the strong wind area with a wind velocity of more than 15m/s was 460km on the southeast and 190km on the northwest sides. It passed through Honshu to the Pacific Ocean, becoming an extra tropical cyclone at 9:00JST on September 23rd. This was not an abnormal typhoon in size or intensity, but it moved very fast and was accompanied by heavy rainfall owing to the front to the rear of the typhoon's center. The speed (Japan Meteorological Agency, 1998b) of this typhoon was about 50-55 km/h immediately before landfall on the Kii Peninsula, thereafter increasing to about 75-85 km/h.

3. SURFACE METEOROLOGICAL DATA

Locations of fire fighting headquarters, government weather service stations, and power stations from which the observation data were obtained, are shown in Fig.2. AMeDAS stations are spatially arranged approximately 17km apart, and there are one or two meteorological observatories per prefecture. In contrast, the fire fighting headquarters observation sites are concentrated in urban centers such as the large cities of Osaka and Nagoya. Few fire fighting headquarter observation sites are located in ravine areas, but there are many power station observation sites in those and coastal areas of the Kinki district. They complement the observation network based on fire stations. In the northern region of Nara Prefecture, where serious damage was caused by the severe winds of typhoon Vicki, there is only one meteorological observatory and three AMeDAS stations, but as the number of fire fighting headquarters is 11, more detailed information on surface meteorological conditions could be obtained. This figure shows that the dense weather observation network based on fire stations that mainly has developed in urban or suburban areas is very useful for understanding severe storm disasters such as this typhoon, in urban areas.

4. METEOROLOGICAL ANALYSIS

4.1 Course of Typhoon Vicki

Fig.3 shows the distributions of veering and backing of the changes in wind direction. The thick lines represent the border between them. This border divides the Kinki district into approximately east and west regions. The line is equivalent to the course of the wind center of the typhoon. As the times when wind direction changed were recorded at some anemograms in some observation sites, the hourly position of the circulation center in the typhoon is shown in Fig.3. The positions of the atmospheric pressure center of the typhoon, determined at 10-minute intervals by objective pressure analysis (Fujii et al., 1999) are shown by double circles. Fujii et al. used atmospheric pressure records from JMA stations. Triangles mark the positions determined by the JMA for intervals of one hour. Each typhoon center course meanders. The courses in the circulation and atmospheric pressure centers closely resemble each other, but the course of the circulation center is about 10 to 20km to the left of that of the atmospheric pressure center.

4.2 Local High Wind Events

Mean wind velocity distributions for 10 minutes (average 50' to 00' an hour) are shown for the time series from 13:00 to 16:00JST in Fig.4 (a)-(d). At 14:00JST, when the atmospheric pressure center of the typhoon reaches around the border between Osaka and Nara prefectures, a local high wind area, in which the mean wind velocity exceeds 20m/s, appears in the rear region as well as on the right side of the typhoon. At a fire station in Wakayama City, the maximum recorded wind velocity was 32.4m/s at 14:20JST. Thereafter the local high wind area passed Osaka, Nara, and Mie prefectures and reached the western part of Aichi Prefecture and the southwest part of Gifu Prefecture. Mean wind velocities exceeding 30m/s were recorded; maximum wind velocity 31.9m/s at 15:48JST in Kameyama City, Mie Prefecture and 32.7m/s at 15:57JST in Kaitsu Town, Gifu Prefecture. As the wind velocity vector of Fig.4 shows, wind direction mainly was southeast to south in the local high wind area on the right side of the typhoon, whereas it was mainly south to west in the local high wind area within the rear area of the typhoon.

Fig.5 shows the distribution of the daily maximum instantaneous wind velocity at each observation site. The local high wind area, in which the maximum instantaneous wind velocity exceeds

40m/s, spreads from the southern part of the Kinki district to the western part of the Chubu district. The recorded daily maximum instantaneous wind velocities were 51.0m/s at 13:13JST in Tanabe City, 50.0m/s at 14:13JST in Wakayama City, 50.8m/s at 14:07JST in Sumoto City, 59.5m/s at 14:59JST in Shinjo Town, and 56.4m/s at 15:14JST in Ueno City.

Fig.6 shows the difference in the times of the maximum instantaneous wind velocity and minimum atmospheric pressure at each observation sites; Area A, little difference in occurrence times, Area B, a time difference of more than one hour. In Tanabe City the maximum instantaneous wind velocity and minimum atmospheric pressure were recorded at the almost same time,

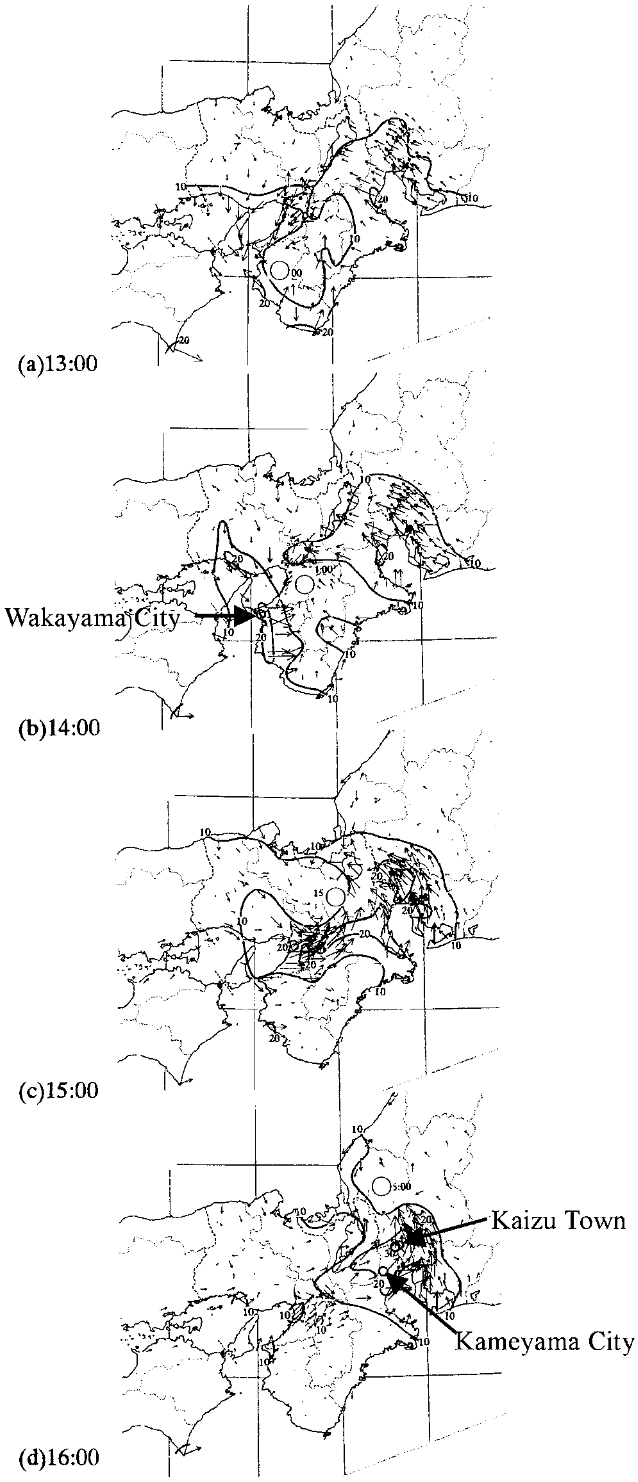


Fig. 4 Mean wind vector distribution (m/s)
Circles show the position of the atmospheric pressure center of the typhoon at each time in an objective pressure analysis (Fujii et al., 1999).

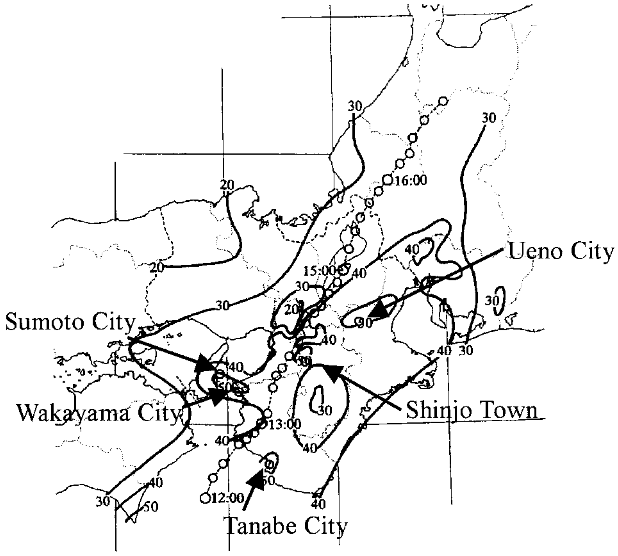


Fig. 5 Daily maximum instantaneous wind velocity distributions (m/s)
Circles show the position of the atmospheric pressure center of the typhoon obtained from an objective pressure analysis (Fujii et al., 1999).

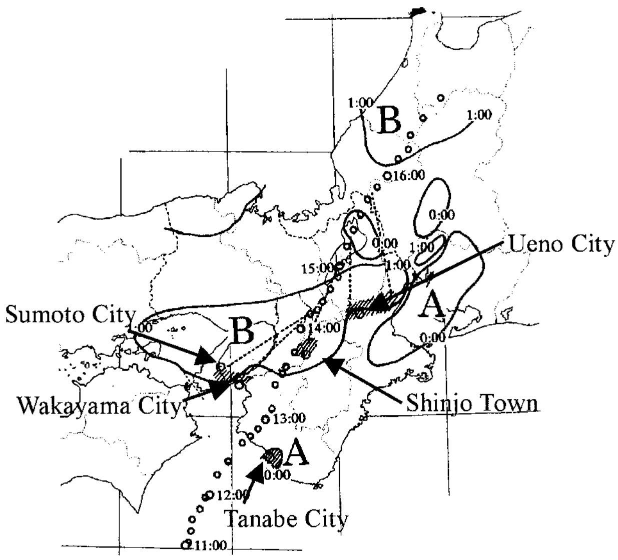


Fig. 6 Difference in hours between the time of the daily maximum instantaneous wind velocity and daily minimum atmospheric pressure
Area A: little difference, Area B: more than one hour
Circles show the position of the atmospheric pressure center of the typhoon obtained from an objective pressure analysis (Fujii et al., 1999).

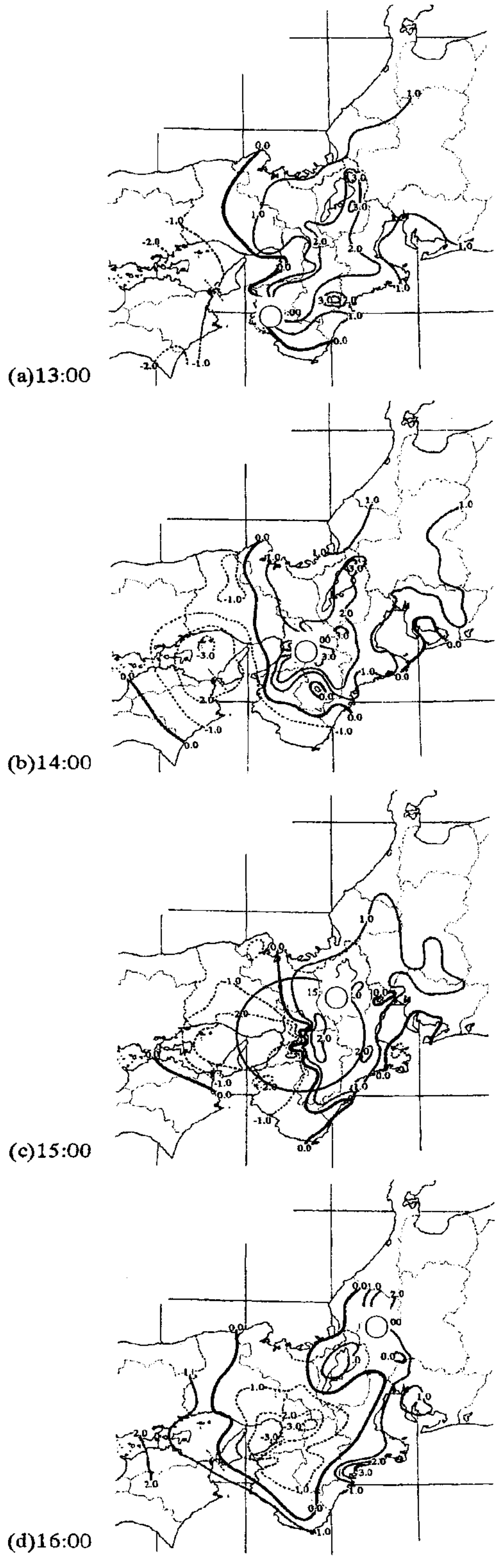


Fig. 7 Distribution of the difference in temperature from the daily mean temperature (℃)
Small circles show the position of the atmospheric pressure center of the typhoon obtained from an objective pressure analysis (Fujii et al., 1999). The large circle in Fig.7 (c) denotes the large temperature gradient region.

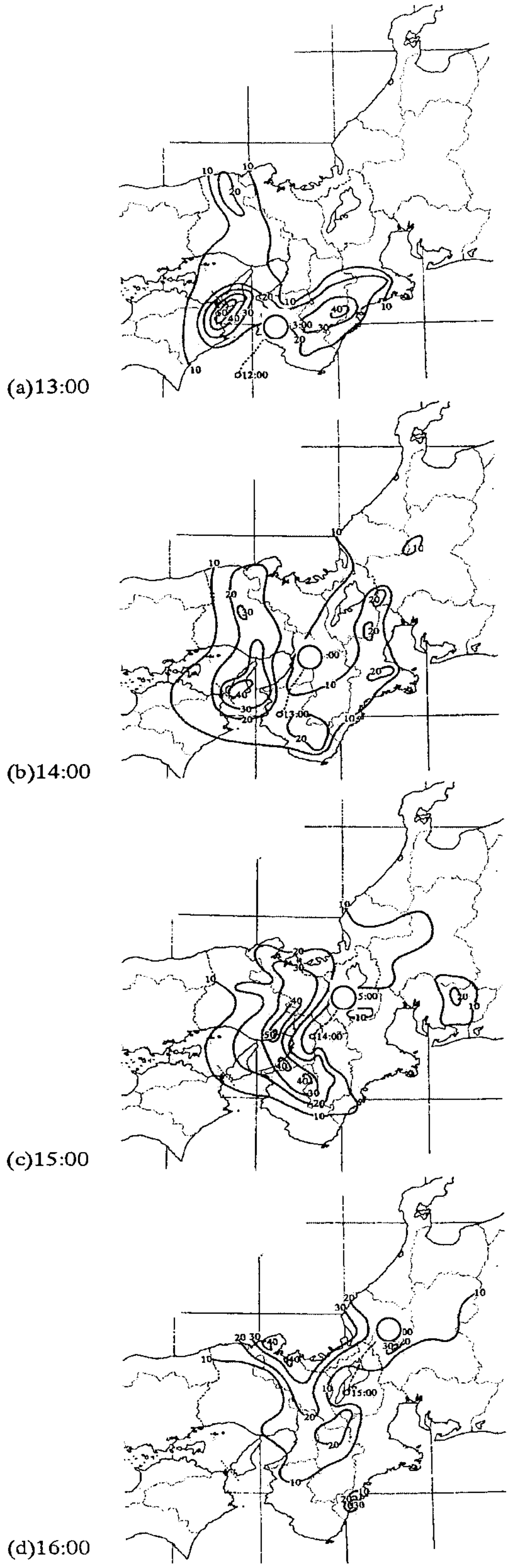


Fig. 8 Distribution of hourly precipitation (mm/h)
The atmospheric pressure center position of the typhoon is the same as in Fig.7.

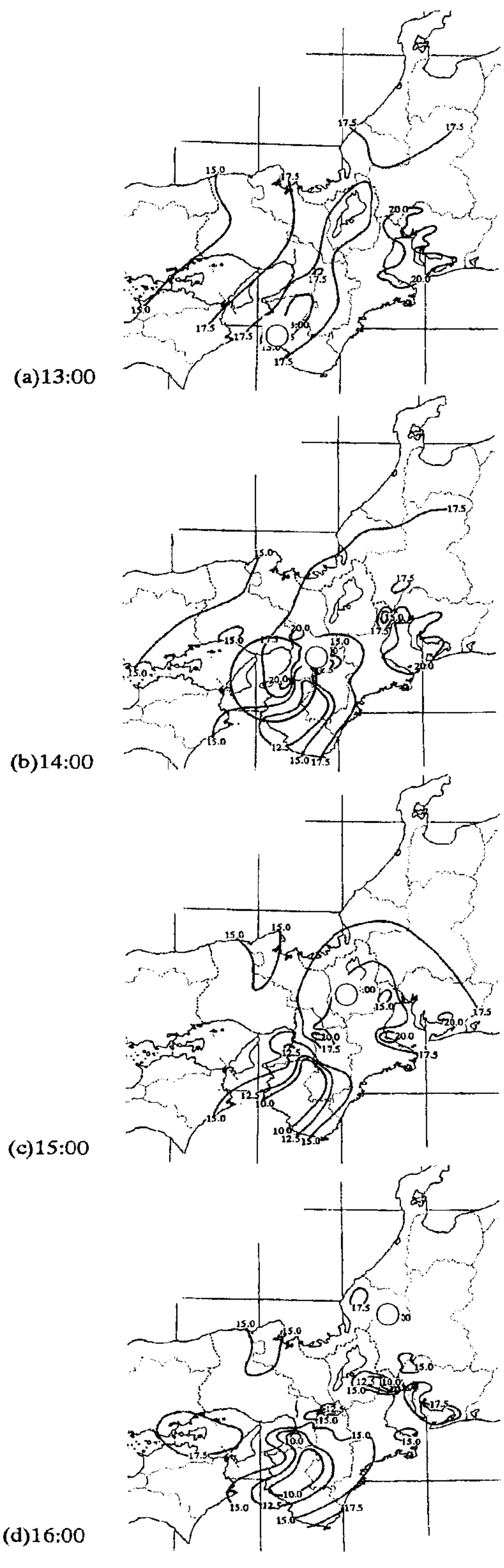


Fig. 9 Distribution of specific humidity (g/kg)
The atmospheric pressure center position of the typhoon is the same as in Fig.7.
The large circle in Fig.9 (b) denotes the high specific humidity region.

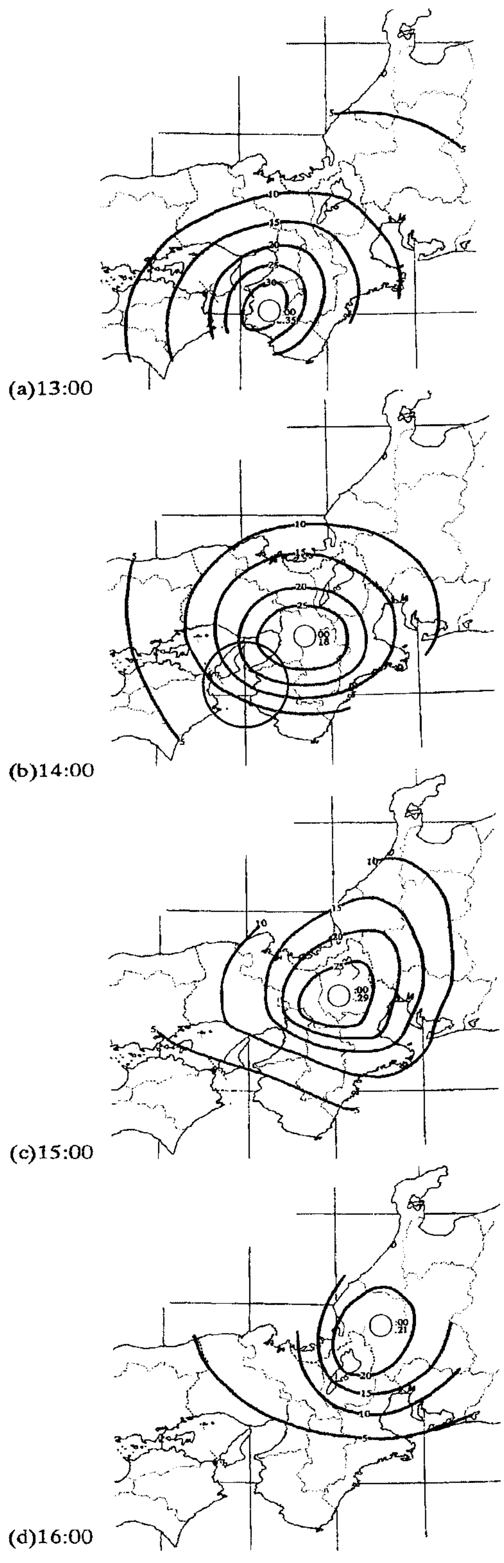


Fig. 10 Distributions of differences from maximum atmospheric pressures before daily minimum atmospheric pressure (-hPa)
The atmospheric pressure center position of the typhoon is the same as in Fig.7.

whereas in Sumoto City, Wakayama City, Shinjo Town, and Ueno City maximum instantaneous wind velocity was recorded about one hour after minimum atmospheric pressure.

4.3 Temperature

The distributions of air temperature from 13:00 to 16:00JST are shown in Fig.7 (a)-(d). The absolute temperature value cannot be compared among the stations because it depends on the altitude of each observation site. The distribution of the temperature difference from the daily mean value at each observation site therefore is shown.

The cold area spreads out on the western side close to the center of the typhoon. From 14:00 to 15:00JST, this cold area is distributed like a hook from west of the center, indicative that cold air entered the center of the typhoon from the northwest. At this time, the isotherm interval became dense from southern Osaka Prefecture to northern Nara Prefecture, and the temperature gradient in space became very large; 0.2℃/km. The cold air invading from the northwest side of the typhoon therefore brought a rapid decrease in temperature across the border of Osaka and Nara prefectures.

4.4 Precipitation and Specific Humidity

Hourly precipitation distributions from 13:00 to 16:00JST are shown in Fig.8 (a)-(d). As typhoon Vicki approached, precipitation in the southern Kinki district rapidly increased. From 14:00 to 15:00JST, the precipitation distributions made a "hook" as the rainfall area from the western side of the typhoon surrounded the center of the typhoon. In contrast, on the east side of the typhoon, rainfall was less than several mm/h, and some sites had none. Thereafter, the rainfall area moved northeast together with the typhoon. The hook-shaped rainfall area became illegible, no rain falling in the Kinki district, except in the north.

Specific humidity distributions from 13:00 to 16:00JST are shown in Fig.9 (a)-(d). While typhoon Vicki was passing through the Kinki district, dry air entering the Kii Peninsula from the southeast met the damp air on of the typhoon's northwest side. As a result, the damp air region was a swirl around the eye of the typhoon from 14:00 to 15:00JST. The high specific humidity, exceeding 20g/kg around the border between Wakayama and Osaka prefectures at 14:00JST seems to have been brought by the rain band that developed on the west side of the typhoon. In contrast, the specific humidity on the east side of the typhoon was reduced to 10-15g/kg by the dry air flowing in from the southwest of the Kinki district.

4.5 Atmospheric Pressure

Fig.10 (a)-(d) shows the atmospheric pressure distributions from 13:00 to 16:00JST. Atmospheric pressure values observed at most of the fire stations were not normalized to the sea level value. Moreover, the accuracy of pressure values recorded at some fire stations were not considered highly confident because they had not been officially approved by the JMA. The pressure difference between the atmospheric pressure at each recording time and the peak pressure before passage of the typhoon therefore are given. The pressure differences are distributed in a rotating elliptical form.

5. THE COMBINED RADAR ECHO AND HIGH WIND AREA RELATIONSHIP IN THE KINKI DISTRICT

The combined radar echo charts together with observations at Murotomisaki and Takayasuyama sites were used in the comparison with maximum wind distribution. Fig.11 (a)-(p) shows the combined radar echo charts for every 7 minutes and 30 seconds from 14:00 to 16:00JST and maximum instantaneous wind velocities are displayed as vectors based on the times when the maximum was recorded. The combined radar echo at 14:45JST lacks an image. In Fig.6, the severe storm area mainly is divided into two areas, in which the minimum atmospheric pressures and maximum instantaneous wind velocities were recorded at the almost same time or maximum instantaneous wind velocities were recorded about one hour after the minimum atmospheric pressures. The first area corresponds to the local high wind area present on the right side of the typhoon, whereas the second is the local high wind area that formed to the rear of the center of the typhoon. Yamamoto et al. (1963) reported severe storms accompanied by a cold front in their study of the 2nd Muroto typhoon. The high wind formed behind typhoon Vicki seems to have the same character as that in the 2nd Muroto typhoon.

The combined radar echo chart at 14:00JST shows a band of strong rainfall on the western side of the typhoon. High winds were recorded mainly inside the rain band. The daily maximum instantaneous west wind around the north of the rain band was recorded in Sumoto City, Hyogo Prefecture at 14:15JST. In the 6 minutes from 14:15 to 14:21JST, a southerly high wind was recorded at Matsuzaka City, Mie Prefecture, but on the right side of the typhoon. A westerly high wind was recorded in Wakayama City. These high winds at Sumoto and Wakayama cities were inside the same rain band indicated as A in Fig.11. Thereafter, the local high wind area moved in the east-northeast direction together with the movement of the rain band. At 14:37JST, the local high wind area had moved from the north of Wakayama Prefecture to the west of Nara Prefecture.

Very high winds blew in the south of the Nara basin and the west-southwest area along the Yoshino River. The inflow angle across the isobars was large along the Yoshino River, whereas it was small in the south of the Nara basin. There were high winds from the south across Mt. Kongo on the border between Osaka and Nara prefectures. The maximum wind velocity was 59.5m/s in Shinjo Town, Nara Prefecture at 15:00JST. Only the wind direction recorded at Shinjo Town was south-southeast. At 15:07JST, westerly high winds were recorded around the rain band from the southern Osaka Prefecture to northern Nara Prefecture. Within just 15 minutes, from 14:52 to 15:07JST, the wind direction across Mt. Kongo had changed from west to south and again from south to west. Our field study in Nara Prefecture turned up many first-hand testimonies: at first a southerly wind blew then it shifted to a westerly one, and there was much evidence of the damage done to houses and trees by the westerly wind, as well as by the southerly one. It therefore is believed that the rain band that had a rapid change in the wind direction had passed through.

From an analysis of the Doppler radar echo obtained at Kansai International Airport at 15:30JST, Sakakibara et al. (1999) showed that a converging shear line existed near the rain band over Nara

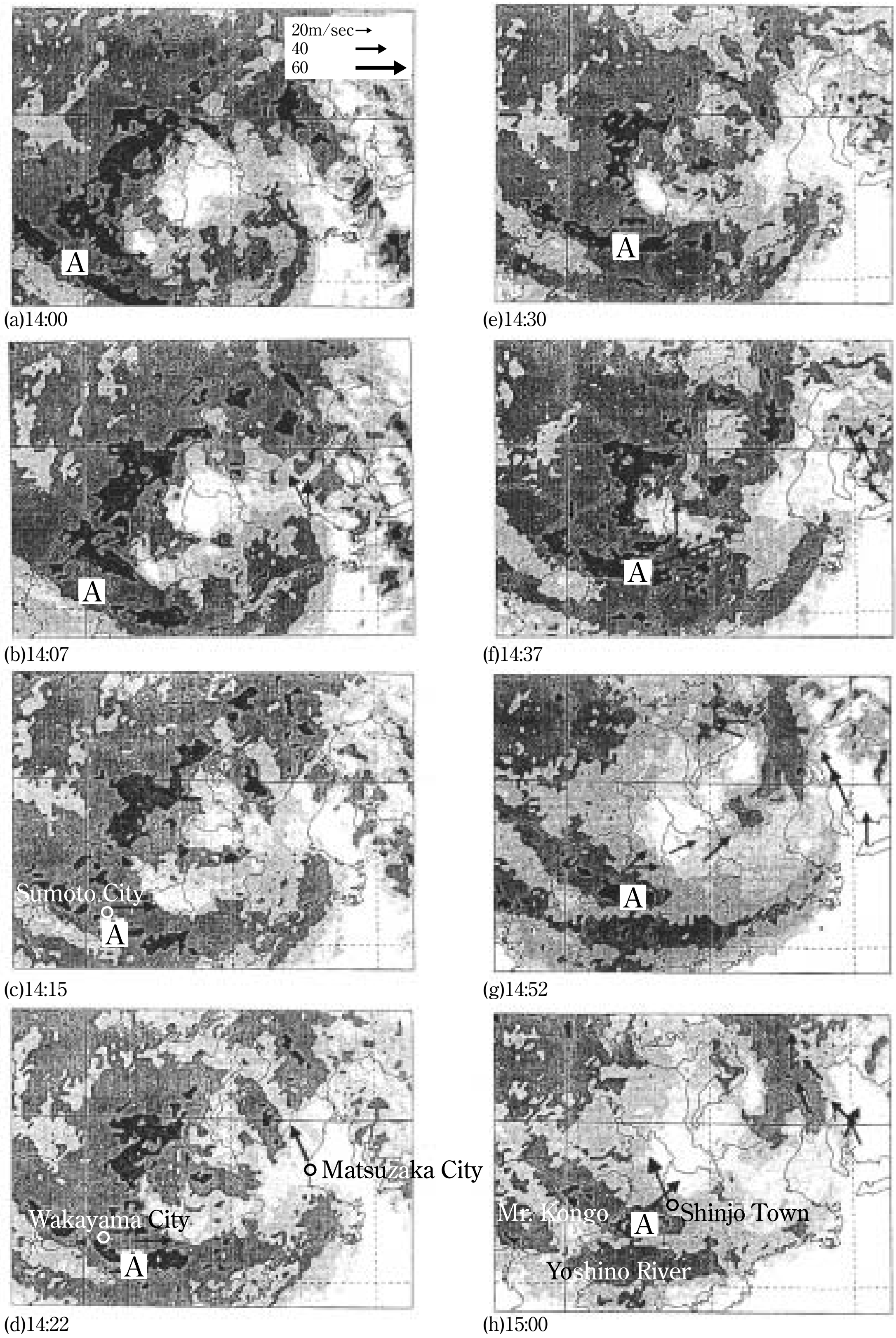
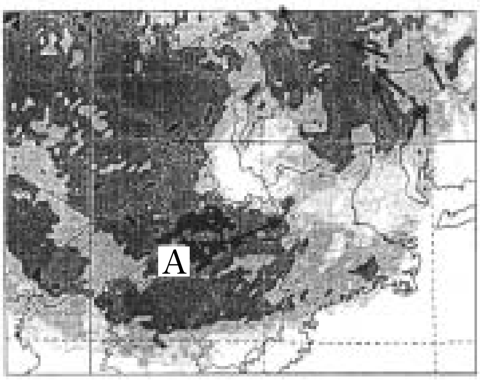
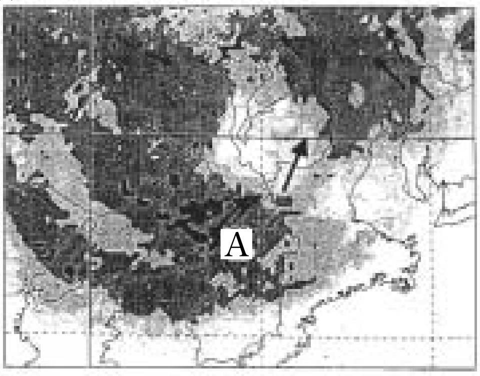


Fig. 11 Combined radar echo and daily maximum instantaneous wind vectors
The rain band formed behind the typhoon center is shown as a boxed A.



(i)15:07



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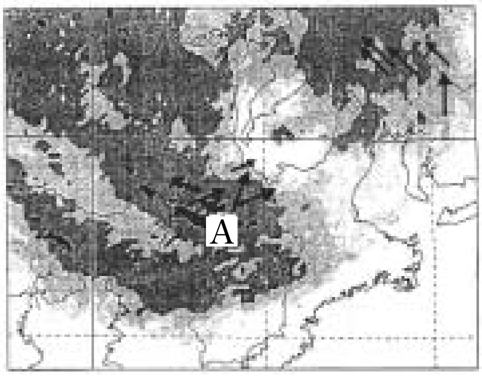
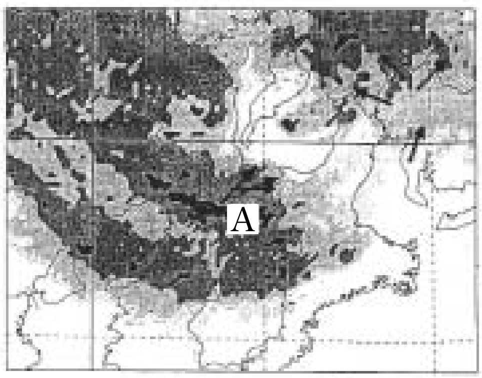
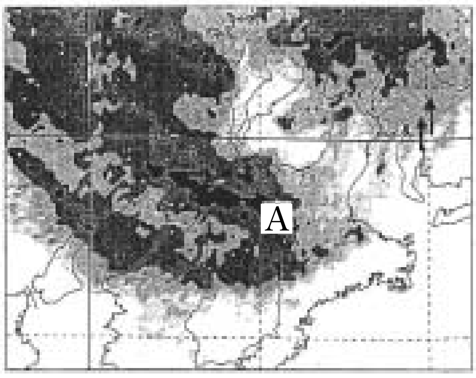


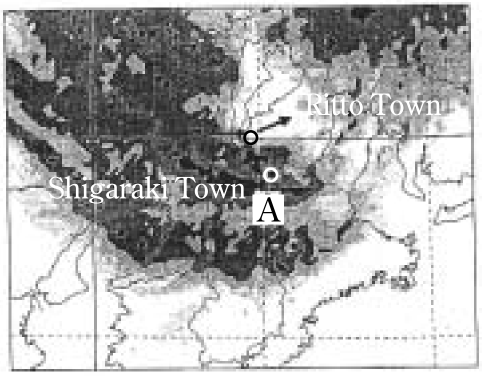
(k)15:22



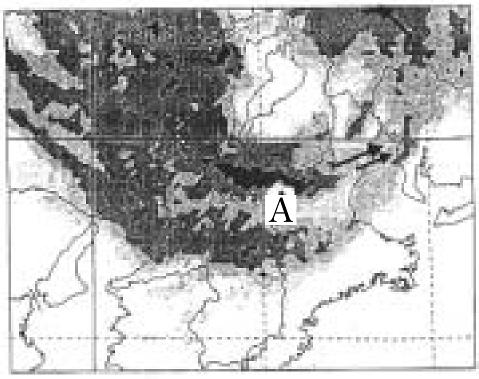
(l)15:30



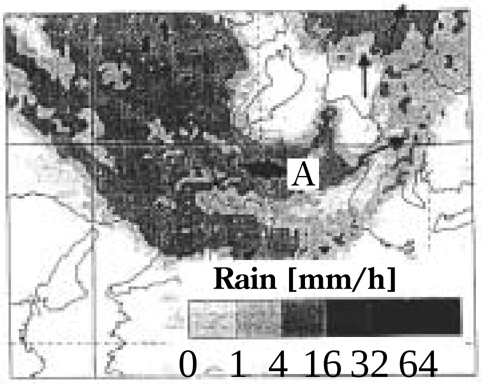
(m)15:37



(n)15:45



(o)15:52



(p)16:00

Fig. 11 (continued)

City. They reported that this converging shear line caused the high wind on the ground. Kawano et al. (1999) observed 3 components of wind velocity in typhoon Vicki based on MU radar system data from Shigaraki Town, Shiga Prefecture. At 15:53JST, observation was stopped by a blackout, but they recorded a strong down draft of 4-5m/s, at height of 2-3 km above Shigaraki Town. At that time, the rain band seen on the combined radar echo charts approached Shigaraki Town. Maximum instantaneous wind velocities were 36.4m/s at 15:45JST in Ritto Town and 41.6m/s at 16:16JST in Yokaichi City, both in Shiga Prefecture. The converging shear line, down draft, and local high wind on the ground are considered to have been related.

6. CONCLUSIONS

Based mainly on weather observation data obtained at fire stations, we analyzed the surface structures of typhoon Vicki:

1) The weather observation networks of fire stations were extremely useful for the analysis because they were much denser than the observation networks of the JMA.
2) Three courses shown for this typhoon in the Kinki district were meandering ones. The meanderings of the wind circulation and atmospheric pressure centers, in particular, were well correlated.
3) The local high wind area in the typhoon was divided into two parts, one formed on the right side of the typhoon, the other in its rear area as shown by the typhoon tracking. The first local high wind area occurred in Wakayama and Aichi prefectures, the second, in the central of Kinki district, causing widespread damage.
4) The temperature distribution showed that cold air intruded the center from the typhoon's northwest side. The temperature gradient became very large across the border between Osaka and Nara prefectures at 15:00JST.
5) The hourly precipitation distribution of showed a hook-shaped rainfall area within the typhoon.
6) The specific humidity distribution showed that dry air from the southwest and damp air from the northeast flew in the center of the typhoon at 15:00JST.
7) The isobar distribution in the typhoon often had a rotating elliptical form.

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