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Radar and GPV-based consideration on significant indices for detecting heavy rainfall

K. Nishiyama [1], **I. Ishikawa**[1], **K. Jinno**[1], **A. Kawamura**[1], **and K. Wakimizu**[2]

[1]Faculty of Engineering, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan
[2]Faculty of Agriculture, Kyushu University 6-10-1, Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan

Abstract. During a rainy season (BAIU) in Japan, many thunderstorms occur frequently and widely along a BAIU front. In case of heavy rainfall case on 29 June 1999 in Fukuoka, Japan, a squall line with a cold front went southward and led to heavy rainfall and strong gusts, and two weak tornadoes with weak echo region (WER). In this study, it was investigated whether three indices (precipitable water (PW), convergence of air (CONV), convective available potential energy (CAPE)) calculated from the GPV are useful indices for detecting the generation of heavy rainfall caused by the activity of the BAIU through the comparison with radar-AMeDAS composite images. The result showed that PW provides important information on atmospheric instability of a pre-stage of a heavy rainfall event and that CONV plays an important role as an index for the specification of dominant area of heavy rainfall represented by the feature of rain-band appearing in the radar-AMeDAS composite images in comparison with PW. On the other hand, GPV-based CAPE with squall lines in a BAIU front seems to be not so useful index as qualitatively important index for the generation of heavy rainfall.

1 Introduction

During a rainy season (BAIU) in Japan, many thunderstorms occur frequently and widely along a BAIU front, which maintains its strength and becomes stationary with repeating a slight movement along a latitudinal direction in the Japan Islands according to dynamical equilibrium between the ‘warm’ Pacific high pressure system and the ‘cold’ northern high pressure system. Heavy thunderstorms in this season occur as follows. Since supplied abundant warm and humid air continuously into the BAIU front from the south under the influence of Pacific high pressure contributes to the generation and maintenance of strong atmospheric instability as pointed out by Akiyama (1973). Consequently, heavy thunderstorms occur frequently along the BAIU front and cause serious disasters involving intense flood due to heavy rainfall, dangerous tornadoes, wind gusts with a downburst which occasionally contains hailstones, etc.

In this study, based on three indices (precipitable water, convergence of air, convective available potential energy) calculated from the GPV explained in the next section, whether these variables can be useful indices for detecting the generation of heavy rainfall caused by the activity of the BAIU will be investigated through the comparison of radar-AMeDAS composite images corresponding to spatial distribution of actual precipitation with those of these indices associated with features of rain-bands appearing in the mesoscale convective systems (MCS).

2 Outline of available data sets for analysis of heavy rainfall

2.1 Grid Point Value (GPV)

The GPV is three-dimensionally interpolated grid data, based on the sounding data set observed by meteorological balloons twice a day at the same time (00:00 UTC, 12:00 UTC) in the world and the other data sets (ground meteorological data, satellite data, e.g.). The GPV data is constructed by the assimilation of these observed data into three-dimensionally interpolated grid data set through the calibration using the predicted data by the numerical prediction model of Japan Meteorological Agency (JMA). In addition, the GPV is modified for satisfying some physical relationships included in an actual atmosphere represented by the specific mesh size of 20 km, which is taken for the construction of the GPV of the specific area including Japan. The GPV on the basis of the above-mentioned procedures consists of wind (velocity and direction), temperature, dew point depression, geo-potential height with the function of pressure. The structure of the GPV is represented by the horizontal mesh of 20 km and the irregular vertical meshes divided into 21 layers between the ground and 100 hPa. The GPV is available for various purposes as well as an initial condition of the prediction model.

Correspondence to: K. Nishiyama
(nisiyama@civil.kyushu-u.ac.jp)

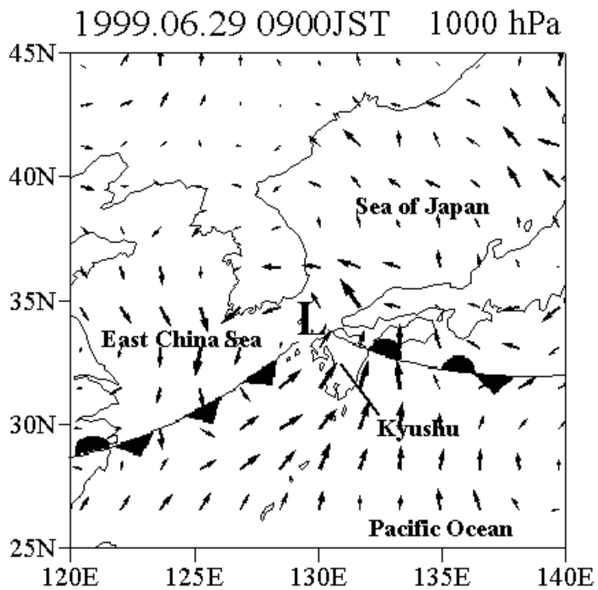

Fig. 1. Small cyclone formed on BAIU front.

However, since the GPV strongly depends on predicted outputs by JMA model as mentioned in the previous paragraph, it is unavailable for the diagnosis of heavy rainfall or squall line if the predicted outputs give inconsistent results with actual observed facts. In addition, the GPV has a drawback that it is unavailable for finding good correspondence of indices with heavy rainfall excepting the designated times, 09:00 and 21:00 JST. Therefore, the GPV should be treated carefully for the analysis of heavy rainfall, paying much attention to the above-mentioned features.

2.2 Radar-AMeDAS composite precipitation

JMA has the observational network consisting of 19 weather radars and the ground observational meso-network in Japan, AMeDAS (Automated Meteorological Data Acquisition System), which has the averaging observational resolution of 17 km and consists of rainfall, wind, temperature, sunshine duration, at the interval of 10 min. The calibration of radar-observed precipitation data with AMeDAS raingauge data precipitation provides radar-AMeDAS composite precipitation, named, the spatial distribution of hourly precipitation with 5km horizontal fine resolution. The radar-AMeDAS composite images are used for comparisons with spatial distributions of indices for the detection of heavy rainfall.

3 Indices of heavy rainfall

The convergence of air into a stationary BAIU front causes the simultaneous accumulation of large amount of water vapor and the continuous supply of the subsequent unstable condition. Here, CONV show the convergence of air. CONV is calculated from wind data at the designated pressure levels of the GPV. The relationship is given as the next equation.

$$CONV = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \tag{1}$$

where u is the western wind component and v southern wind component. The convergence of air containing large amount of water vapor in lower layers provides the chance to cause the generation of heavy rainfall through updraft due to convergence and the simultaneous increase in the instability of atmosphere due to the supply of large amount of water vapor.

Next, Precipitable Water (PW) is calculated by vertical integration of water vapor amount from 1000 hPa (p_0) to 100 hPa (p_T). The equation is given by

$$PW = -\frac{1}{g}\int_{p_0}^{p_T} q\,dp, \tag{2}$$

where g is the gravitational acceleration, and q water vapor mixing ratio, and p atmospheric pressure. PW is an important indicator of atmospheric stability because the instability of atmosphere increases drastically if the supply of water vapor into a specific area is invigorated.

Finally, Convective Available Potential Energy (CAPE) shows the work done by positive buoyant force from Level of Free Convection (LFC) to equilibrium level corresponding to transition level from positive to negative buoyant force. In other words, CAPE is transferred into kinetic energy of convection, which shows the strength of a generated convective cloud. The equation is given by

$$CAPE = -R_d \int_{P_{LFC}}^{P_{CT}} (T_p - T_e)\,d(\ln p) \tag{3}$$

where T_p is the temperature of air parcel lifted from the 1000 hPa (p_0) level and T_e the temperature of ambient atmosphere at the same pressure level as T_p and R_d the gas constant of dry air. P_{CT} and P_{LFC} show the pressure at the cloud top and at Level of Free Convection (LFC), respectively.

4 Features of heavy rainfall case on June 29, 1999

On 29 June 1999, a small cyclone formed over the prevailing BAIU front in the East China Sea passed through the north side of the Northern Kyushu early in the morning as shown in Fig. 1, developing its strength. A squall line along a cold front extending toward the south-west from the cyclone could be confirmed in radar-AMeDAS precipitation images (see Fig. 2). The squall line with the cold front went southward and led to heavy rainfall more than 70 mm/h at some observational points in Fukuoka and the subsequent urban flood damage including inundation due to internal runoff with strong wind gusts and two weak tornadoes. The squall line was observed by the meteorological radar equipped in Kyushu University, which has the detective extent of 10^4 km^2 in the Northern Kyushu. From the analysis of PPI images detected by Kyushu University radar on this day, some notable features associated closely with serious disasters including tornadoes and wind gust and heavy

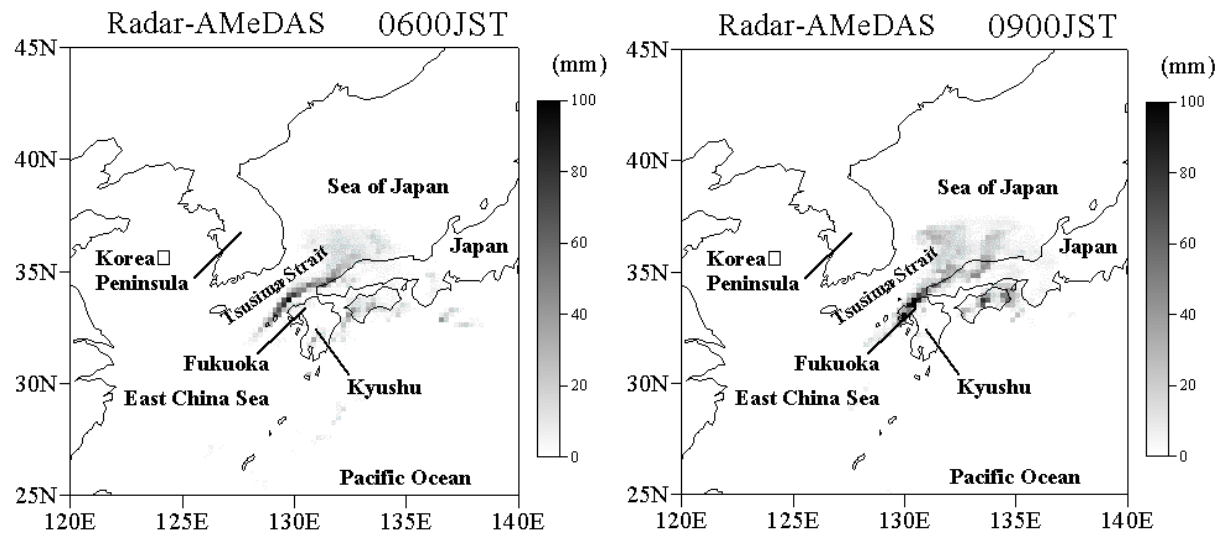

Fig. 2. Squall line confirmed by the Radar-AMeDAS composite rainfall distribution (a) 06:00 JST (b) 09:00 JST.

rainfall could be confirmed as shown in Fig. 3. One of the notable features is to include a weak echo region (WER) or no echo region in the adjacent area to heavy rainfall area and tornado area. In general, the appearance of WER with the formation of a supercell storm as discussed in Browning et al. (1976) shows shortage of time for precipitated particles to grow into enough size to be detected by meteorological radar under considerable strong updraft as noted in Chisholm et al. (1972). Actually, the heavy storm system on the day was quite different from the feature of typical supercell storm system. However, the storm system might have behaved like a supercell in band-like storm system in the squall line, as deduced from the fact that southern wind was observed in the lower layers and western wind was observed in the middle and upper layers, as similar to results analyzed by Maddox (1976).

5 Comparison of GPV-based indices with Radar-AMeDAS images

In this section, the indices estimated from the GPV at 09:00 JST on 29 June are compared with heavy rainfall distribution at the same time. The weather condition leading to heavy rainfall in Fukuoka around 09:00 JST on the day shows the confluence of clockwise and counterclockwise flows that originated from the small cyclone and Pacific high pressure system. Consequently, the flow of large amount of moisture pouring into the small cyclone from southwest or south-southwest direction was formed and caused the increase of water vapor mixing ratio QV and the resultant PW in a confluent strip as shown in Figs. 4 and 5. In general, since the increase of PW occurs in lower layers, it strongly contributes to the development and maintenance of atmospheric instability. Therefore, it is expected that the index of PW provides important information on atmospheric instability of a pre-stage of a heavy rainfall event. However, the spatial distribution of PW doesn't show the locality of heavy rainfall events represented by the feature of rain-band appearing in the radar-AMeDAS composite images of Fig. 2.

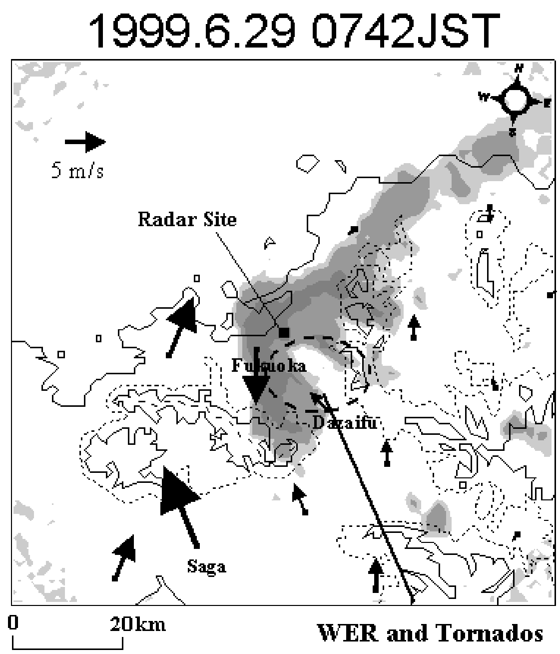

Fig. 3. PPI image with WER of heavy storm causing two tornadoes.

In the next analysis, based on the observed fact that convectively active areas associated with propagating squall lines were located inside mesoscale regions of convergence with the magnitude of convergence reaching approximately $10^{-4}\,s^{-1}$ as shown by Fankhauser (1969, 1974), some fea-

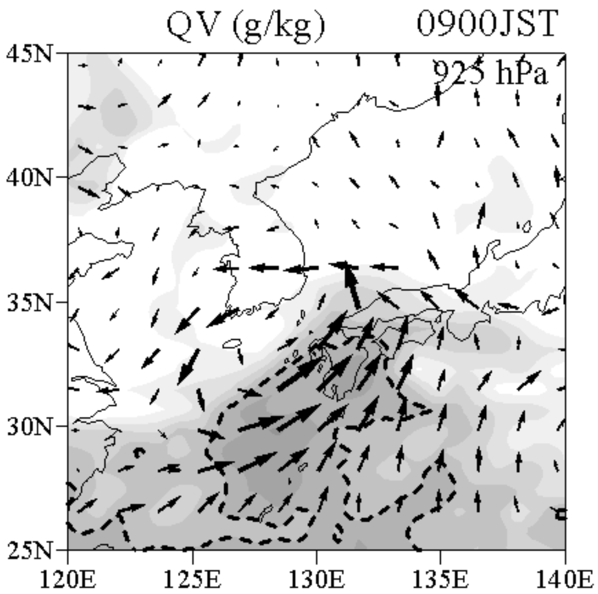

Fig. 4. Spatial distribution of water vapor mixing ratio with the wind component at 925 hPa at 09:00 JST. Broken line indicates the water vapor mixing ratio of 15 g/kg.

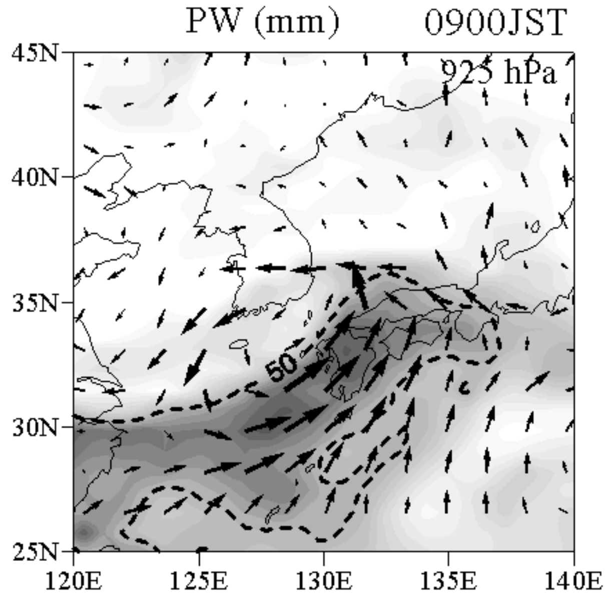

Fig. 5. Spatial distribution of PW with the wind component at 925 hPa at 09:00 JST Broken line indicates the precipitable water of 50 mm.

tures of spatial distributions of CONV at the 850 hPa and 925 hPa pressure levels, shown in Fig. 6, are examined here. The area enclosed by broken lines in the figures corresponds to the convectively dominant area with the magnitude of convergence more than $10^{-4}\,s^{-1}$. The dominant convergence area at the 850 hPa is located in the northeast side of the Kyushu. On the other hand, the dominant convergence area at the 925 hPa is approximately consistent with heavy rainfall area that occurred in the Kyushu. These features give an indication for specifying the dominant area of heavy rainfall. However, dominant pressure level associated with heavy rainfall would be dependent on the relative location of a front with rainfall area.

Finally, CAPE, which shows the strength of convective activity after the generation of thunderstorms, is examined. As shown by Blustein et al. (1985), large CAPE values of 1000 to 4000 m^2/s^2 are required for the formation of categorized severe thunderstorms in Central America. However, regardless of the generation of heavy rainfall in the severe squall line, the values of CAPE in Fig. 7 indicate zero values throughout the squall line, which shows stable or neutral atmospheric condition. The result is quite inconsistent with observed facts characterized by actual heavy rainfall shown in Sect. 4. In general, since heavy rainfall has strong relationship with the formation of hailstone characterized by large buoyant force and the associated updraft, the area of large CAPE should exist somewhere in a squall line with heavy rainfall. However, since most of observed sounding data during a BAIU season indicates relatively small or zero values of CAPE (not shown by figure), it would be quite difficult to detect large CAPE with the movement of a squall line only at two times, 09:00 JST and 21:00 JST. Similarly, spatial distribution of CAPE by the GPV indicates zero values of CAPE along a squall line in a BAIU front because atmosphere in a BAIU front indicates moist neutral condition as shown in Ninomiya (2000). This means that actual features of sub-grid scale, which are represented by cumulus or cumulonimbus convection, cannot be resolved in the spatial distribution of CAPE obtained from the GPV, which has the horizontal resolution of 20 km. Therefore, GPV-based CAPE is unavailable for getting useful information of heavy rainfall.

6 Conclusion

During a rainy season (BAIU) in Japan, many thunderstorms occur frequently and widely along a BAIU front. In case of heavy rainfall case on 29 June 1999 in Fukuoka, Japan, a squall line with a cold front went southward and led to heavy rainfall more than 70 mm/h and strong gusts, and two weak tornadoes with weak echo region (WER), confirmed by the meteorological radar equipped in Kyushu University. In this study, it was investigated whether three indices (precipitable water (PW), convergence of air (CONV), convective available potential energy (CAPE)) calculated from the GPV are useful indices for detecting the generation of heavy rainfall caused by the activity of the BAIU through the comparison with radar-AMeDAS composite images.

As a result, it is expected that PW provides important information on atmospheric instability of a pre-stage of a heavy rainfall event. On the other hand, it is expected that CONV plays an important role as an index for the specification of dominant area of heavy rainfall represented by the feature of rain-band appearing in the radar-AMeDAS composite im-

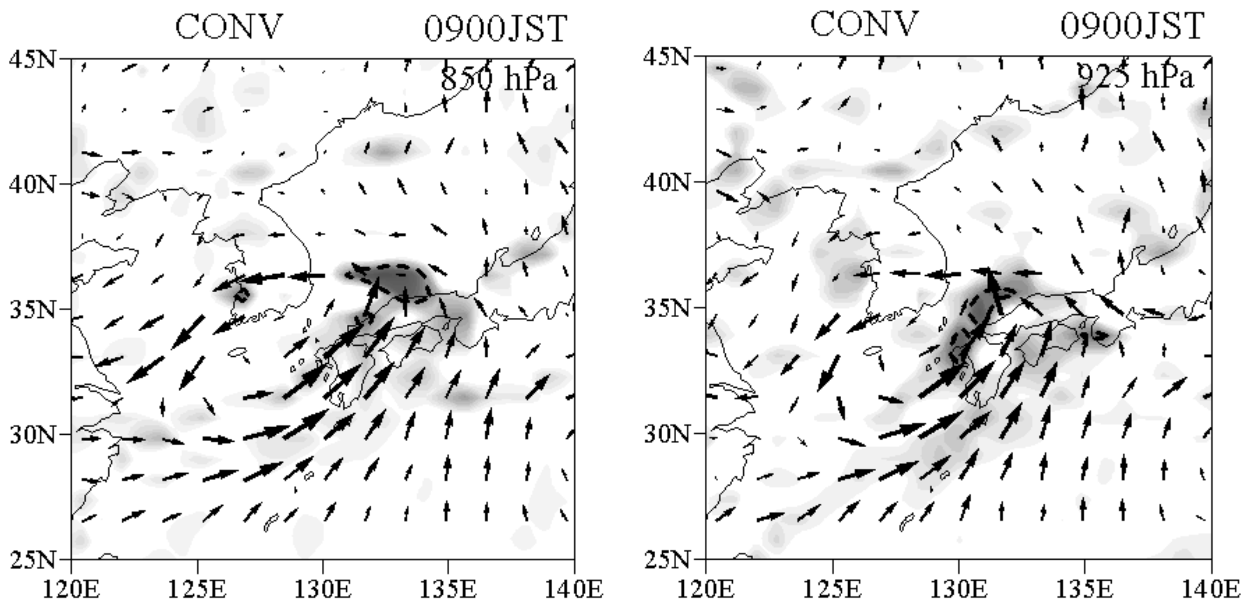

Fig. 6. Spatial distributions of CONV at 09:00 JST at (a) 850 hPa and (b) 925 hPa with each wind component at 09:00 JST. The area enclosed by broken lines in the figures corresponds to the convectively dominant area with the magnitude of convergence more than 10^{-4} s^{-1}.

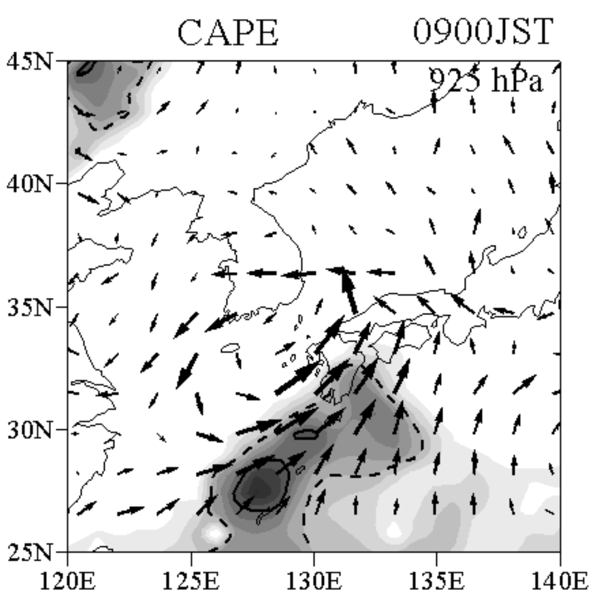

Fig. 7. Spatial distribution of CAPE with the wind component at 925 hPa at 09:00 JST. Contour lines are depicted every 250 m^2/s^2 from the minimum of 250 m^2/s^2. Broken and solid line indicate 1000 m^2/s^2 and 2000 m^2/s^2, respectively.

ages in comparison with PW. In case of CAPE as qualitatively important index for the generation of heavy rainfall, GPV-based CAPE with squall lines in a BAIU front is not useful index because actual features of sub-grid scale, which are represented by cumulus or cumulonimbus convection, cannot be resolved in the spatial distribution of CAPE obtained from the GPV.

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