Selection of dominant meteorological indices related with heavy rainfall caused by BAIU activity

Koji, Nishiyama
Research associate, Faculty of Engineering, Kyushu University, Fukuoka, Japan

Yoshitaka, I
Master student, Faculty of Engineering, Kyushu University, Fukuoka, Japan

Kenji, Jinno
Professor, Faculty of Engineering, Kyushu University, Fukuoka, Japan

Akira, Kawamura
Associate professor, Faculty of Engineering, Kyushu University, Fukuoka, Japan

ABSTRACT: In this study, paying much attention to notable features obtained from spatial distributions of strongly related indices (precipitable water, convergence of air, convective available potential energy) with precipitation, fatal problems in selecting strongly related indices with observed precipitation in a BAIU season were discussed. These results showed spatial distribution of a predicted index provided alternative and physically consistent interpretation for selecting dominant index for heavy rainfall even if the predicted index did not correlate with observed rainfall at a specific observational point as confirmed by the features of CONV (Convergence) or even if it correlated with observed rainfall as confirmed by those of PW (Precipitable Water). Therefore, dominant meteorological indices of heavy rainfall should be selected according to physically evidenced interpretation on features of spatial distributions of indices, and physically and statistically consistent relationship should be built up.

1. INTRODUCTION

A variety of numerical weather prediction models used in many countries provide useful information for precipitation forecast. However, in spite of the development and improvement of the model, the accuracy of precipitation forecast has been strongly affected by systematic errors originating from relatively coarse resolution and physically complicated precipitation processes in the prediction models. Therefore, instead of direct application of output results of the model to the precipitation forecast, an alternative technique represented by MOS (Model Output Statistics) has been applied. MOS means downscaling of model outputs by relating it to observed data of a specific area using statistical techniques including multiple linear regression and neural network. Therefore, results of MOS provide useful guidance for many varieties of weather predictions. In general, for the construction of a statistically significant relationship between predicted outputs and observed precipitation, predictors are selected from model outputs obtained at a grid point closest to a specific observed point as shown in the methodology of Kurigowski et al. (1998) and Hall et al. (1999). In this case, it would be quite difficult to select strongly related indices with observed precipitation because a spatial distribution of a strongly related index predicted by the model does not shows complete consistency with that of actual precipitation.

Therefore, in this study, correlation maps between observed precipitation and predicted outputs at a specific point are investigated. In addition, spatial distributions of strongly related indices (precipitable water, convergence of air, convective available potential energy) with precipitation are estimated from the GPV explained in the next section, and radar-AMeDAS composite images corresponding to spatial distribution of actual precipitation are compared with those of these indices associated with features of rain-bands appearing in BAIU front. According to these analyses, this paper will provide discussion on desired selection of useful indices related strongly with heavy rainfall system caused by the activity of the BAIU.

2. OUTLINES OF AVAILABLE DATA SETS

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 UTC, 12 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 level. The GPV is available for various purposes as well as an initial condition of the prediction model.

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, 0900 and 2100 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 5 km 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

$$PW=\ \frac{1}{g}\int_{P_T}^{P_0} q\,dp \tag{2}$$

, 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. CORRELATION BETWEEN OBSERVED RAINFALL AND PREDICTED INDICES

The relationships between the above-mentioned three indices and observed rainfall in the BAIU seasons for 4 years (1996-1999) are examined in this section. The estimated indices from the GPV at the specific mesh including Fukuoka in the Northern Kyushu, located in the west of Japan in Fig.1, are compared with observed rainfall at a specific point in Fukuoka city. The rainfall is calculated as total rainfall within twelve hours after the observational time (0900 and 2100 JST) of the GPV from hourly rainfall data of the ground observational network in Japan, AMeDAS (Automated Meteorological Data Acquisition System). The system has the averaging observational scale of 17 km and consists of rainfall, wind, temperature, sunshine duration at the interval of 10 min.

First of all, the relationship between PW and rainfall is shown in Fig.1a. The result shows roughly good agreement between rainfall and PW in some cases of heavy rainfall, although, regardless of large PW, there are many cases representing relatively small amount of rainfall.

Next, the relationship between CONV and rainfall is shown in Fig.1b. CONV shows the existence of divergent flow when its sign is positive. On the other hand, CONV shows the existence of convergent flow when its sign is negative. In general, the formation of the instability with the accumulation of a large amount of water vapor due to convergence effect in lower layers causes the generation of thunderstorms and the subsequent heavy rainfall. Therefore, observed rainfall should relate strongly to convergence effect. However, the result of Fig.1b shows the generation of heavy rainfall even in divergence cases. In general, the atmosphere in divergence area under the influence of anti-cyclonic high pressure has relatively stable condition. The result is not consistent with the above-mentioned physical relationship. The problems are that the GPV represents instantaneous value (0900 and 2100 JST) per 12 hours, and BAIU front leading to heavy rainfall may pass through a designated location between two designated times. In other words, anticipated results would be that dominant convergence causing heavy rainfall are located in a different area from the observational location, Fukuoka, at the designate time (0900 and 2100 JST) of the GPV. Therefore, the technique for corresponding between CONV and rainfall data at the same location would be unsuitable for constructing physically consistent correlation between them.

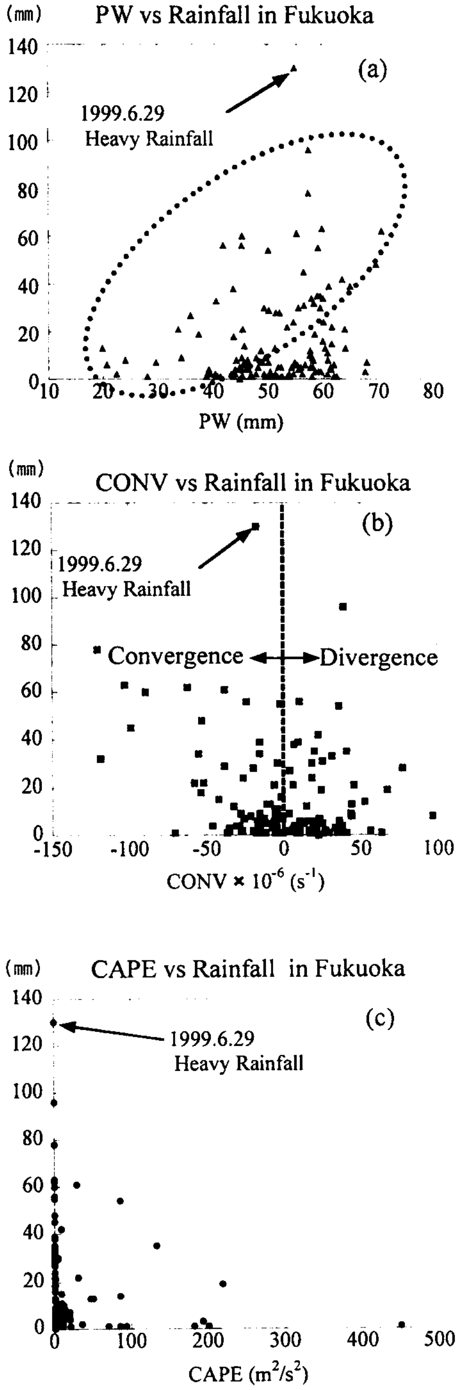

Fig.1. Correlation map between observed rainfall and indices in Fukuoka. (a) Precipitable water (b) Convergence (c) Convective available potential energy

Finally, Fig.1c shows the relationship between CAPE and rainfall in Fukuoka. The result shows that CAPE is zero or relatively small even in case of heavy rainfall. This result is not consistent with remarkable features of the generation of heavy rainfall because the atmosphere causing heavy rainfall requires sufficient instability with large CAPE. The physically inconsistent result would be due to the reason that the generation of atmospheric instability due to large amount of water vapor into the squall line in a BAIU front was in equilibrium with the transformation of atmosphere from unstable condition into stable or neural one through convective activities of embedded thunderstorms in the squall line.

These results are summarized as follows. Estimated CAPE and CONV from the GPV seem to be unsuitable for applying the technique of correspondence between rainfall and the predicted indices at the same location. On the other hand, the relationship of PW with rainfall gives relatively better correspondence for applying the technique in comparison with CAPE and CONV. However, as discussed in section 6, alternative viewpoint based on spatial distributions of the predicted indices and rainfall provides distinct interpretation in selecting dominant indices of heavy rainfall.

5. FEATURES OF SELECTED RAINFALL CASES

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. This study provides some discussion on spatial distributions of strongly related indices with rainfall cases occurring on June 11 and 29, 1999, which are, hereafter, called case 1 and case 2, respectively.

The rainfall of case 1 occurred under active and stationary BAIU front over the western area of the Pacific Ocean, away from the Kyushu. On the other hand, in case of the rainfall of case 2, 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, 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. 2a). 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.

6. COMPARISON OF GPV-BASED INDICES WITH RADAR-AMeDAS IMAGES

In this section, the indices estimated from the GPV at 0900 JST in two rainfall cases are compared with heavy rainfall distribution at the same time. In general, since the indices of PW, CONV, CAPE strongly contributes to the development and maintenance of atmospheric instability, it is expected that these indices provides important information on the generation of heavy rainfall.

First of all, features of PW distributions are examined. The flow of a large amount of moisture along the Pacific high caused the formation of large PW as shown in Figs.2b and 2e and wind field of Figs.2c and 2f.

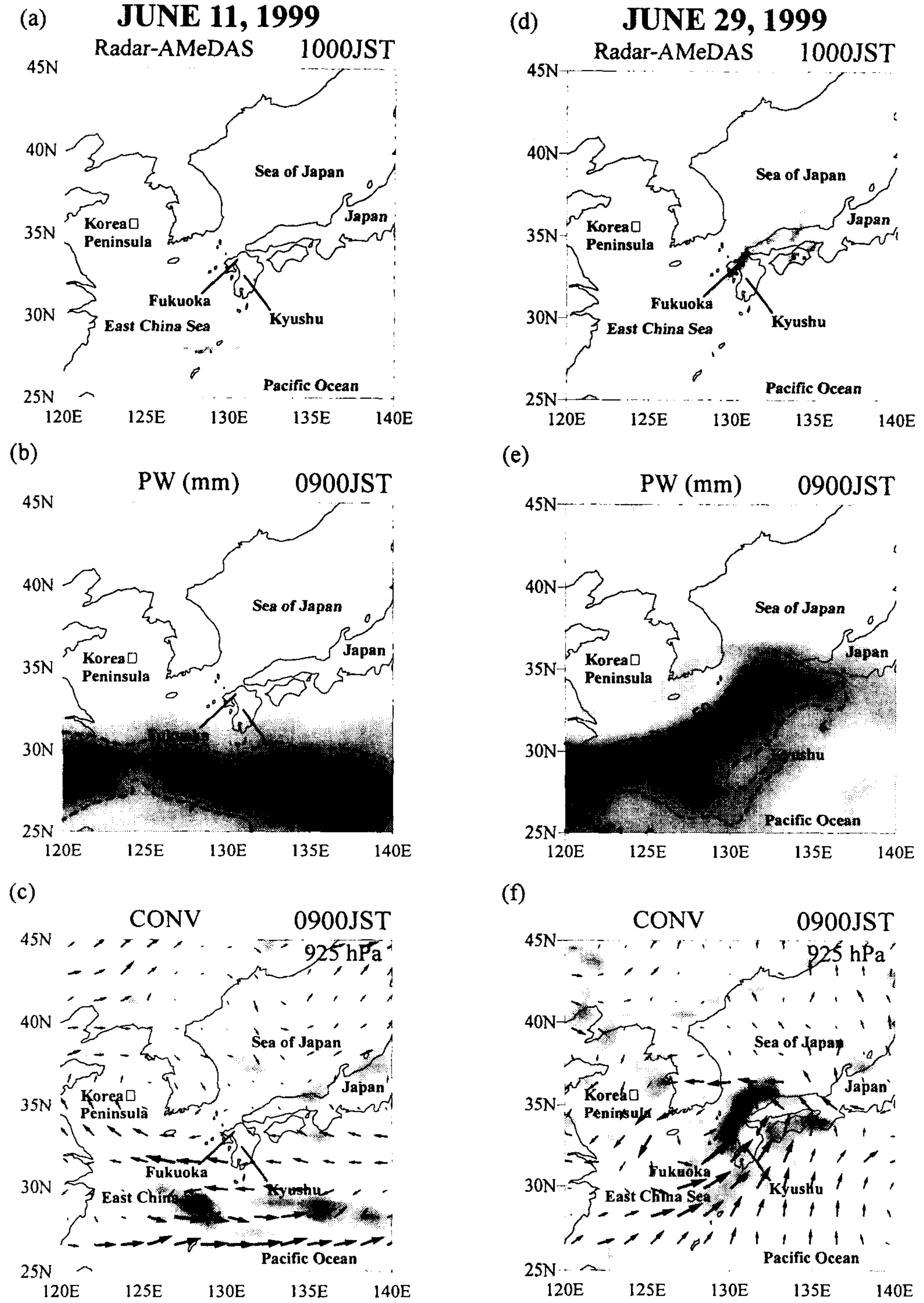

Fig.2. Spatial distributions of Radar-AMeDAS precipitation and the corresponding indices (Precipitable Water Convergence). The left and right figures indicate rainfall cases on June 11 and 29, respectively.

However, remarkable feature of PW distribution is characterized by widely distributed large PW. Therefore, the spatial distributions of PW show no suitability for specifying heavy rainfall area represented by rain-band appearing in the radar-AMeDAS composite images of Figs.2a and 2d, and good correspondence between observed rainfall and PW in section 4 attributes to notable feature of widely distributed large PW.

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 features of spatial distributions (see Figs.2c and 2f) of CONV at the 925 hPa pressure levels are examined here. The area enclosed by dashed lines in the figures corresponds to the convectively dominant area with the magnitude of convergence more than $10^{-4}s^{-1}$. Although the technique for corresponding between CONV and rainfall data at the same location would be unsuitable for constructing physically consistent correlation between them, the dominant convergence areas at the 925 hPa in both cases are approximately consistent with heavy rainfall area or close to rainfall area. These features give an indication for specifying the dominant area of heavy rainfall.

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 (not shown by figure) 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. 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, 0900 JST and 2100 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.

7. DISCUSSION AND CONCLUSION

A variety of numerical weather prediction models used in many countries provide useful information for precipitation forecast. However, the accuracy of the prediction has not reached practical level of quantitative prediction due to relatively coarse resolution and physically complicated precipitation processes in the prediction models. Therefore, the present weather prediction for providing useful precipitation guidance in many countries adopts an alternative technique represented by MOS (Model Output Statistics), which means downscaling method of prediction model outputs by relating it to observed data of a specific area using statistical techniques including multiple linear regression and neural network. In general, for the construction of a statistically significant relationship between predicted outputs and observed precipitation, predictors are selected from model outputs obtained at a grid point closest to a specific observed point. However, the MOS seems to contain some fatal problems in selecting strongly related indices with observed precipitation. Therefore, in this study, paying much attention to notable features obtained from spatial distributions of strongly related indices (precipitable water, convergence of air, convective available potential energy) with precipitation, fatal problems in selecting strongly related indices with observed precipitation in a BAIU season were pointed out.

The relationship between PW and rainfall at a specific point (Fukuoka) showed roughly good agreement between them in some cases of heavy rainfall excepting many cases representing relatively small amount of rainfall regardless of large PW. However, PW was found to be unsuitable indicator for specifying heavy rainfall because of remarkable feature characterized by widely distributed large PW. Therefore, PW provides a requirement for the generation of heavy rainfall and, however, does not provide sufficient information for specifying the area of heavy rainfall. On the other hand, the relationship between CONV and rainfall at the specific point showed that CONV would be unsuitable for constructing physically consistent correlation between them, and, however, these features of CONV spatial distributions provide an indication for specifying the dominant area of heavy rainfall. Finally, CAPE would provide no indication for constructing physically consistent correlation as shown from the features of CONV spatial distributions as well as those of the relationship between CAPE and rainfall at the specific point 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, which has the horizontal resolution of 20 km.

From these results, spatial distribution of a predicted index provide alternative and physically consistent interpretation for selecting dominant index for heavy rainfall even if the predicted index does not correlate with observed rainfall at a specific observational point as confirmed by the features of CONV or even if it correlates with observed rainfall as confirmed by those of PW. Therefore, dominant meteorological indices of heavy rainfall should be selected according to physically evidenced interpretation on features of spatial distributions of indices, and physically and statistically consistent relationship should be built up.

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