# Improvement of surface process for application of a NWP system

Kun YANG[1], Guangwei HUANG[2] and Nobuyuki TAMAI[3]

[1] Dept. of Civil Engineering, University of Tokyo (Bunkyo-ku, Tokyo 113-8656, Japan)
[2] Member of JSCE, Associate Prof., University of Tokyo (Bunkyo-ku, Tokyo 113-8656, Japan)
[3] Fellow of JSCE, Prof., University of Tokyo, (Bunkyo-ku, Tokyo 113-8656, Japan)

In order to apply a regional NWP (numerical weather prediction) system to Japan, two submodels are developed to refine the interaction between landuse and atmosphere. One is developed to estimate solar radiation using the relative humidity profile in the atmosphere, and the other to deal with the heterogeneity of landuse based on flux-equivalence concept. Some other aspects of this system are also revised for application in Japan. Incorporating the refinement with the NWP system, two numerical experiments are carried out in Tsurumi riverbasin and central Japan, respectively. The idealized storm case in Tsurumi riverbasin indicates the noticeable effect of surface process to rainfall in a small-scale riverbasin, and the case in central Japan shows the prediction performance of this system in mountainous region.

***Key Words*** : *solar radiation, landuse, heterogeneity, surface process, ARPS*

## 1. INTRODUCTION

A global atmospheric model cannot accurately forecast flash floods in small-scale riverbasins, because its horizontal resolution is too coarse to catch the weather features in a small region. However, flash floods occur frequently in Japan so that it is necessary to provide reliable warnings with a few hours lead-time. In recent years, the Center of Analysis and Prediction of Storm (CAPS), University of Oklahoma, has developed a regional prediction system known as the Advanced Regional Prediction System (ARPS) for predicting rapidly growing, storm-scale hazardous weather. This system has been applied in USA[1)] and South Korea[2)]. In order to improve its performance, the abundant dataset available in Japan is believed to be beneficial for refining some aspects of ARPS

In recent years, the effect of surface physical process has been emphasized. Because the air temperature and turbulent fluxes have different intensity over various surfaces, the heterogeneity of landuse may induce local circulation or cumulus convection. Some land cover compositions, such as irrigated-dry land, forestry-urbanized area, are also the potential factors to affect weather patterns[3)]. Emori[4)] carried out an idealized simulation to show how the cumulus convection develops with the heterogeneous distribution of soil moisture. Evidently, it is an important aspect of NWP to study the energy and moisture budget on ground surface. Actually, this physics has been embedded in mesoscale NWP models, such as RAMS, MM5 and ARPS.

This paper at first outlines ARPS and some refined points for application in Japan, then develops models to better estimate solar radiation and to deal with the heterogeneity of landuse, which are two crucial aspects of surface process. Finally, two numerical experiments are carried out to investigate the role of surface process in Tsurumi riverbasin and prediction skill of ARPS in central Japan.

## 2. MODEL DESCRIPTION AND ITS REFINEMENT

ARPS is the first system that is developed with primary emphasis on storm-scale weather prediction. This system includes four packages: atmospheric model, surface process, a radiation package and parameterization of cloud microphysics. The atmospheric model is a three dimensional nonhydrostatic model, which describes the dynamics of air motion. The model is governed by momentum equations, thermodynamic equation, continuity equation, three/six transport equations of water-categories, and sub-grid-scale turbulent kinetic energy (TKE) submodel. These equations are transformed from physical domain to computational domain by the terrain-following coordinate and grid-stretching in vertical. For the surface physical process, five prognostic equations derived from force restoration method (FRM) is used to predict the temperature and moisture in surface layer and deep-soil layer, and the canopy moisture; and Monin-Obukhov similarity is applied to solve the momentum, heat and moisture exchange between soil and air. The cloud microphysics includes the Kessler[5] two-category liquid water scheme and the three-category ice scheme after Lin et al.[6]; also modified Kuo cumulus convection scheme is included[7]. The radiation package includes two options. If only surface process is concerned, the solar radiation and long-wave atmospheric radiation is calculated by simple models; while if considering the directly heating or cooling of radiation, a radiative transfer parameterization is included. So ARPS is a comprehensive physical system.

In Japan, not only fine resolution data of terrain and landuse are available, but also various meteorological data can be obtained from observation. In order to take advantage of these data to improve the prediction skill of ARPS for Japan, some aspects of this system have been revised or improved in the following:

(1) A solar radiation model is developed in section 3 to replace that used in ARPS, which doesn't account for cloud effect.
(2) A method is developed to treat the heterogeneity of landuse based on flux-equivalence concept, which will be introduced in section 4
(3) Nesting (or mosaic) approach has been applied to treat subgrid heterogeneity of landuse, which makes ARPS flexible to deal with surface process.
(4) A new land type, concrete, is added. Since in urbanized area, such as Tokyo-Yokohama metropolis, roads and building have a considerable area share, its surface physical effect is never insignificant. The concrete ground is assumed to be able to maintain a critical depth water but impermeable. When the water depth excesses the threshold value, the surplus is taken as runoff.
(5) Terrain dataset with resolution of 30"lat. × 45"lon. has been added for terrain Barnes analysis for Japan. Resolution of terrain data is 1° lat. × 1° lon. for Japan in ARPS, but it is too coarse to identify the existence of some small-scale riversbasins, which are common in Japan.

## 3. SOLAR RADIATION MODEL

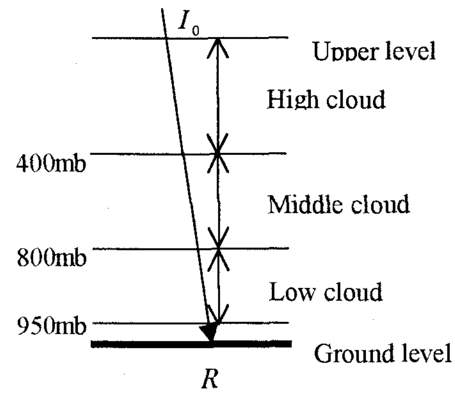

Fig.1 Schematic diagram of cloud layers

The solar radiation is important because it dominates the energy budget of surface physical process. Although ARPS has provided a model to calculate the radiation, it doesn't consider the reflection and absorption of cloud to solar energy, which leads that the radiation is overestimated. So it is necessary to develop a model which can account for the effect of cloud.

As shown in Fig.1, cloud can be divided into low cloud (800mb-950mb), middle cloud (400mb-800mb) and high cloud (<400mb). Although the formation of cloud actually depends on liquid and vapor water, routine observation usually provides water vapor only, so this empirical model scales cloud thickness via relative humidity ($RH$). If $RH$ excesses threshold relative humidity ($RH_{th}$), then cloud may exist in this layer. The cloud depth in each layer is assumed to proportional to

$$d_i = \int_{z_{ib}}^{z_{it}} \max[0.0, (RH - RH_{thi})]dz, \quad (1)$$

where $z_{ib}$ is bottom elevation and $z_{it}$ is top elevation of $i^{th}$ layer. Assuming $k_i$ is the sum of absorptivity and reflectivity of $i^{th}$ layer, the transmittance in this layer can be expressed as

$$\tau_{ci} = \exp(-k_i d_i \sec\theta), \quad (2)$$

where $\theta$ is the zenith angle.

Hence, the total cloud transmittance of three layers is

$$\tau_c = \exp[-(k_l d_l + k_m d_m + k_h d_h)\sec\theta] \quad (3)$$

Subscripts $l$, $m$, $h$ represent low, middle and high cloud layer, respectively. Thus the radiation under cloud conditions is

$$R_s = R_{s0}\tau_c \quad (4)$$

where $R_{s0}$ is the solar radiation under clear sky conditions, which was presented by Atwater and Ball (1981)[8]

$RH_{th}$ for low, middle and high cloud layer is set as 66%, 50% and 40%, respectively[9]. And $k_l = 9.6\times10^{-5}$, $k_m = 1.43\times10^{-5}$, $k_h = 1.43\times10^{-5}$, regressed from observational aerological data in Japan.

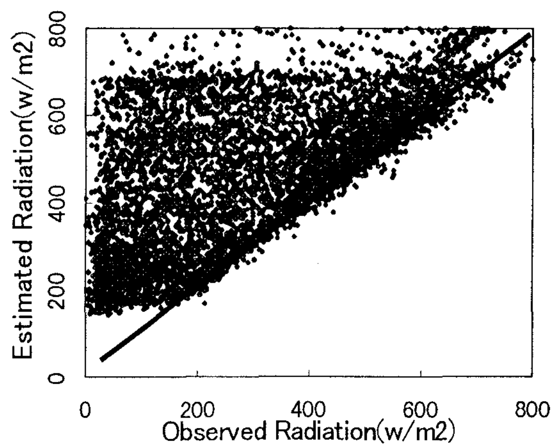


Fig.2-a Comparison of estimation from ARPS model and observation at aerological stations at 9:00 in 1996.

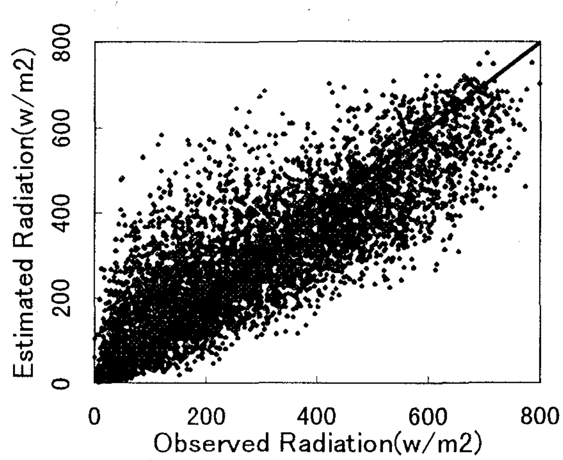


Fig.2-b Comparison of estimation from present model and observation at aerological stations at 9:00 in 1996.

Fig.2 shows the comparison between estimation through radiation model and observation at 18 aerological stations in 1996. These stations are set by Japan Meteorological Agency (JMA). The data of relative humidity is available only at 9:00 and 21:00 JST (Japan standard time) so the comparison is conducted only at 9:00. Estimation in Fig.2-a comes from original solar radiation model of ARPS, which doesn't consider the cloud effect; while radiation in fig.2-b is calculated by present model. Apparently, the present model can give much better estimation to radiation than ARPS can.

## 4.PROCESSING HETEROGENEITY OF LANDUSE

Landuse is another crucial factor determining the ground temperature and intensity of fluxes since surface properties such as roughness, albedo and vegetation fraction depend on landuse. ARPS permits only one type of landuse in one grid box, however, in region like Tokyo metropolis and its surrounding, the treatment to the heterogeneity of landuse is quite important. Hereafter, three ways are applied to study the heterogeneity. The first one characterizes the land surface properties by area-weighted arithmetic average over the grid; the second one is nesting method[10]; and the last one is so-called flux-equivalence method, which is developed in the following.

To explain the method, set $p_i$ is the value of one property of landuse type $i$, $\overline{p}$ is its average in a grid box. The flux of landuse type $i$ has the form

$$flux_i = f(p_i)\,A_i \qquad (5)$$

$f(p_i)$ is the flux per unit area, and $A_i$ is the area of landuse type $i$. Then the total flux in one grid box is

$$flux = \Sigma f(p_i)\,A_i \qquad (6)$$

Again, we assume the average value $\overline{p}$ also satisfies the Eq.(5), i.e.,

$$flux = f(\overline{p})\,\Sigma A_i \qquad (7)$$

Combining Eq.(6) and (7), one can get $\overline{p}$ as follows:

$$\overline{p} = f^{-1}[\Sigma w_i f(p_i)] \qquad (8)$$

where $w_i = A_i / \Sigma A_i$ is area fraction of landuse type $i$. Usually, $f(p_i)$ depends on many factors, such as the atmospheric stability, radiation; in other word, no fixed $\overline{p}$ can satisfy all cases. Herein, we set Eq.(8) holds for some special cases such as neutral stability, then derive the average value $\overline{p}$.

As an example, surface momentum flux is

$$\tau = U^2\left[\frac{k}{\ln(z/z_0) - \psi_m(z/L, z_0/L)}\right]^2 \qquad (9)$$

where $k = 0.41$ is Karman constant, $U$ is horizontal velocity, $z$ is reference height and $z_0$ is hydraulic roughness length, $L$ is Monin-Obukhov length, $\psi_m$ is a function. We suppose the flux-equivalence holds in neutral stability case, then $\psi_m$ will vanish, and $U$ is approximately equal for each type of landuse. According to Eq.(8), one can get the average value of roughness length as follows.

$$z_0 = z\exp\left\{-\left[\sum \frac{w_i}{[\ln(z/z_{0i})]^2}\right]^{-1/2}\right\} \qquad (10.1)$$

Besides roughness, the parameters involved in estimating various fluxes (Refer to Xue et. al [7]) also include vegetation fraction $veg$, leaf area index $lai$, minimum stomatal resistance $Rs_{\min}$, and threshold solar radiation for plant photosynthesis $R_{GL}$, which can be derived similarly. The final result is

$$veg = w_i veg_i \quad (10.2)$$

$$lai = \frac{1}{veg}\left(\sum \frac{w_i}{(lai_i veg_i)^{2/3}}\right)^{-3/2} \quad (10.3)$$

$$R_{s\min} = \frac{1}{6.13}\left[\left(\sum \frac{w_i}{100 + 6.13 R_{s\min i}}\right)^{-1} - 100\right] \quad (10.4)$$

$$R_{GL} = w_i R_{GLi} \quad (10.5)$$

The average properties are derived based on equivalent flux, so we call the above average as flux-equivalence method. Since the average represents the property in a grid scale, the solution of variables such as surface temperature and humidity represent the equivalent values over grid box and no average techniques are needed for them.

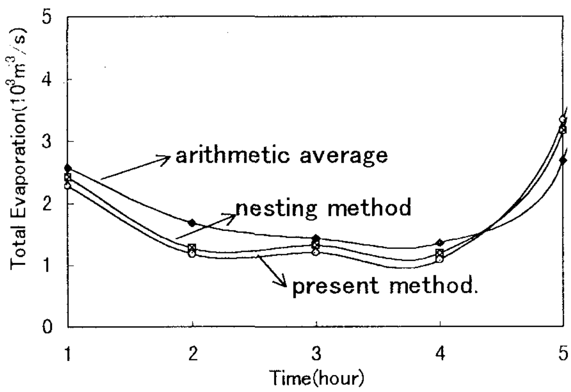


Fig. 3 Comparison of total evaporation in Tsurumi riverbasin calculated by three methods

To compare the performance of this methods, a real case is studied in central Japan using predicted meteorological data of Jul. 8, 1996. All computational conditions such as atmospheric stability and soil properties are the same except the methods to process landuse. Tsurumi riverbasin is selected as the region of this study due to its complex landuse. The computational result is show in Fig. 3. The total evaporation given by present method well agrees with that by nesting method, while the result of arithmetic average method obviously deviates from that of nesting method. Since nesting method is believed to be more accurate than arithmetic average method, the comparison shows flux-equivalence method performs better than arithmetic average method in this study.

## 5. NUMERICAL EXPERIMENTS

Incorporating the above modifications, ARPS is applied to two case studies. The first one investigates the effect of surface process to rainfall in an idealized storm, and the second one shows the prediction skill of ARPS in central Japan.

### 5.1 Experiment 1: Storm case study in Tsurumi riverbasin

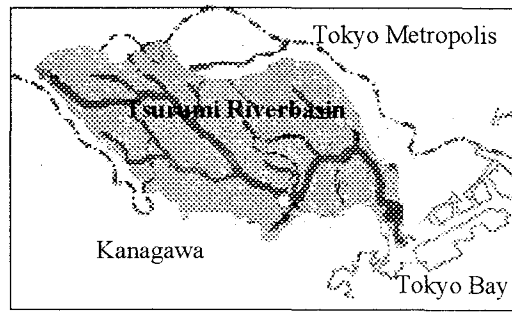


Fig. 4 Composition of Tsurumi riverbasin.

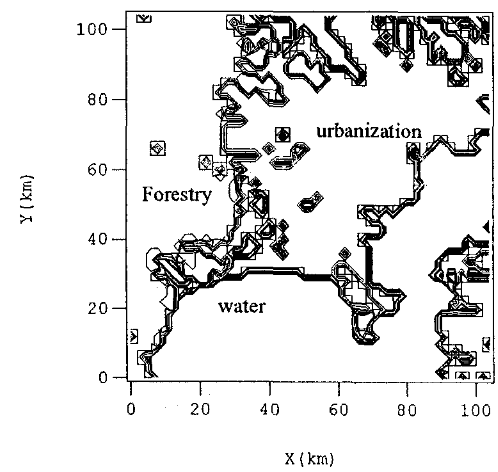


Fig. 5 Domain and landuse for EXP. 1

As shown in Fig. 4, Tsurumi is a small-scale riverbasin with area 235km$^2$. Mountains locate at its west and Tokyo Bay at its east. Its upstream is forestry but downstream is Tokyo-Yokohama metropolis. Landuse consists of forestry, water and urbanized surface etc., as shown in Fig. 5.

To investigate the role of landuse, an idealized storm is studied. As shown in Fig. 5, The domain is 100km × 100km × 16km, centered at (139.5$^0$E, 35.5$^0$ N), horizontal resolution is 2km, average vertical resolution 0.5km. TKE turbulence scheme is included. In order to absorb upward propagating wave disturbance and to eliminate wave reflection at the top boundary, Rayleigh damping layer is set in the upper 4km. Kessler warm rain parameterization is used for cloud microphysics, but cumulus convection parameterization is excluded due to small horizontal resolution. Lateral boundaries are controlled by wave-radiating open conditions, bottom and top boundaries are set as rigid wall. Fields are homogeneously initialized using the sounding of supercell storm in Del City of USA at UTC 9:00, May 20, 1977. The storm is initiated by an isolated thermal bubble centered at $x = 50\text{km}$, $y = 50\text{km}$, $z = 1.5\text{km}$.

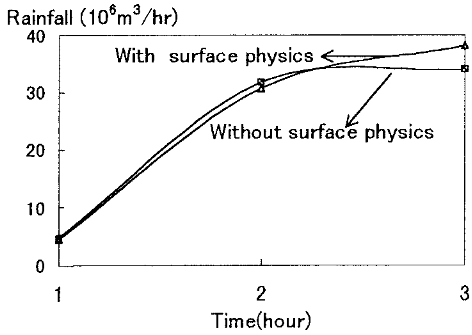


Fig. 6 Comarison of total amount of rainfall in computational domain

Two cases are calculated: case 1 considers the effect of surface process and case 2 excludes it. The predicted total rainfall in the computational domain (100km×100km) is shown in Fig. 6. The comparison of the two cases shows that case 1 predicts 10% more rainfall than case 2 in the third forecasting hour. Obviously, surface process is the unique factor responsible for the precipitation difference. Since the formation of cumulus is closely related to atmospheric boundary layer (Arakawa and Schubert, 1974)[11], which may be changed dramatically in a short time due to surface process (Pleim and Xiu, 1995)[12], it is important to couple this process with atmospheric model for weather forecasting. This study shows that surface process does affect precipitation in a small riverbasin to some extent.

## 5.2 Experiment 2: real case study in central Japan

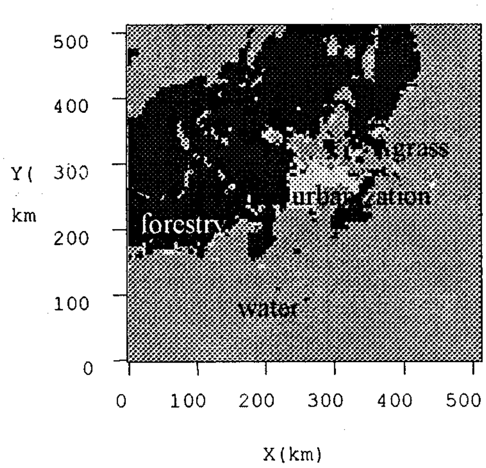


Fig.7 Domain and Landuse types for EXP. 2

As shown in fig. 7, the domain in Central Japan is 500km × 500km × 16km centered at (139.5°E, 35.5° N), the maximum height is 3056m, and landuse includes forestry, grassland, urbanized surface, and water surface. Soil types (not shown)

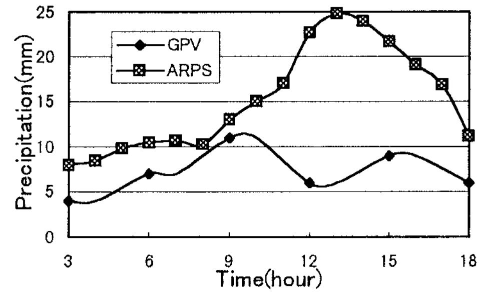


Fig.8 Maximum rainfall in computational domain from GPV and predicted by ARSP

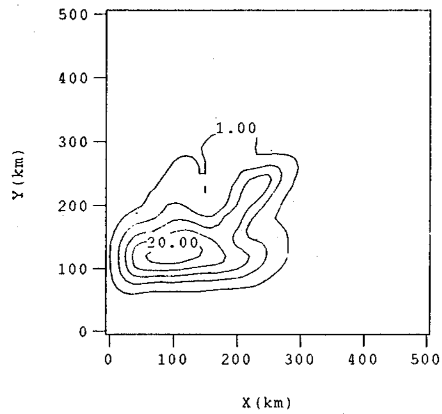


Fig. 9-a Rainfall distribution predicted by ARPS at JST 12:00

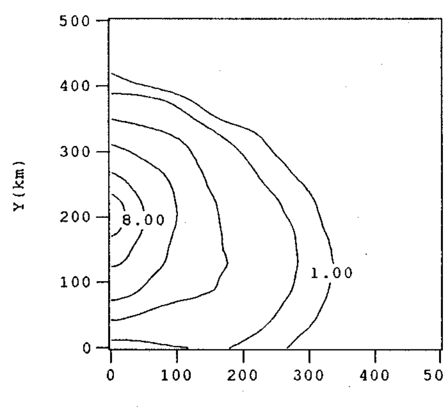


Fig. 9-b Rainfall distribution from GPV at JST 12:00

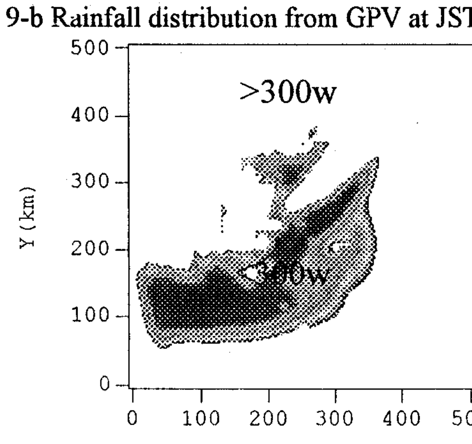


Fig.10, predicted solar radiation by ARPS in computaional domain at JST 12:00

includes loam, clay, sand clay loam, water, concrete. For this application, the horizontal resolution is uniformly 10km, while the vertical resolution varies from 0.14km for the lowest layer to 2km for the upmost. The option of Rayleigh damping, Kessler warm scheme, 1.5 order TKE turbulence model are switched on. Using Barnes analysis, fields are initialized at time 00:00 of Jul. 9, 1996 from GPV dataset, whose resolution is 120km. Lateral boundary conditions are provided by GPV dataset, too.

The predicted maximum rainfall is shown in fig. 8, where GPV and ARPS represents their results, respectively. Due to its fine resolution, ARPS predicts the maximum rainfall much higher than GPV does for all predicting hours. Fig.9-a, b show the rainfall region from GPV and predicted by ARPS at JST 12:00. Although the rainfall location is similar to each other, the region size and rainfall intensity is quite different. GPV gives a larger-domain but lower intense rainfall than ARPS does. Grid resolution is one reason responsible for this difference since finer grid can describe the detail of terrain better and thus simulate topographic effect more realistic. Fig.10 shows the distribution of solar radiation at JST 12:00. Referring to Fig.9-a, the solar radiation is much lower inside the raining area than that outside it, which seems reasonable since cloud reflects and absorbs more radiation in raining region than in rain-free region.

## 6. CONCLUSIONS

Surface physical process is an important component of numerical weather prediction. This paper treats two aspects of surface process. Firstly, one model is developed to consider the cloud effect to solar radiation at ground level. This model calculates the thickness of low, middle and high cloud using the profile of relative humidity, then the cloud transmittance for each layer, and finally gets the radiation. This model was verified by the observation at aerological stations. If the observation of solar radiation and cloud water are available, this empirical model can be further improved by considering the effect of cloud water, which is predicted in ARPS. Secondly, A flux-equivalence method is proposed to treat heterogeneity of landuse. In a case study in Tsurumi riverbasin, this model performances more agreeable to nesting method than arithmetic average method does. Its reliability needs further investigations

Morever, two numerical experiments using ARPS are carried out, respectively, in Tsurumi riverbasin and in central Japan. Tsurumi case shows ignoring surface process may cause 10% difference in rain amount, which suggests that this process may not be neglected for a small-scale riverbasin. Central Japan case shows ARPS has the capacity to predict intense rainfall and the refined solar radiation model can give reasonable estimation. However, for real-time operational prediction, more data from observation or large-scale models are needed for the field initialization since resolution of GPV data is too coarse.

## ACKNOWLEDGMENT

This work was supported by Keihin Work Office, the Ministry of Construction, Japan. Appreciations should be given to the Center for Analysis and Prediction of Storms, University of Okalahoma, U.S.A., for its members' assistance and discussion.

## REFERENCES

1) Xue, M., K. K. Droegemeier and V. Wong, 1995: The advanced regional prediction system and real-time storm-scale weather prediction, International workshop on limited-area and variable resolution models, Beijing, China, October
2) Shin, K. S., S. K. Chung, S. Y. Lee, 1998: Explicit realtime operational prediction of deep convection over Korea During the 1997 summer monsoon season, 16th AMS Conference: Weather analysis and forecasting, Phoenix, Arizona.
3) Chase, T. N., and R. A. Pielke Sr., 1999: Potential impacts on Colorado Rocky Mountain weather due to land use changes on the adjacent Great Plains, *Journal of Geophysical Research*, Vol. 104, No. D14, pp16673-16690.
4) Emori, S., 1998: The interaction of cumulus convection with soil moisture distribution: an idealized simulation. *Journal of Geophysical Research*, Vol. 103, No. D8, pp 8873-8884.
5) Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation, *Meteorological Monographs*, Vol 10, No.32.
6) Lin, Y.L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model, *J. Clim. Appl. Meteor.*, Vol 22, pp1065-1092.
7) Xue, M., K. K. Droegemeter, V. Wang, A. Shapiro, and K. Brewster, 1995: ARPS version 4.0 User's Guide, The university of Oklahoma.
8) Atwater, M. A., and J. T. Ball, 1981: A surface solar radiation model for cloud atmosphere, *Monthly Weather Review*, Vol. 109, pp. 878-888.
9) Krishnamurti, T.N., and L. Bounoua, 1996: An Introduction to Numerical Weather Prediction Technique, pp201-202, Boca Raton, Florida, 1996.
10) Avissar, R., and R. A. Pielke, 1989: A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology. *Monthly Weather Review*, Vol. 117, pp. 2113-2136.
11) Arakawa and Schubert, 1974: Interaction of cumulus cloud ensemble with the large-scale environment, Part I, *Journal of atmospheric science*. Vol. 31, p674-701.
12) Pleim, J. E., and A. Xiu, 1995: Development and testing of a surface flux and planetary boundary layer model for application in mesoscale models, *Journal of Applied Meteorology*, Vol. 34, pp16-32.

**(Received September 30,1999)**