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Application of Flood Early Warning Using High-Resolution Ensemble Rainfall from Numerical Weather Prediction Model: Case Study of the 2013 Largest Flood Event in Japan

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Synopsis

On mid-September 2013 heavy rainfalls happened over Japan due to the season's 18th typhoon, ‘Man-yi’, which caused large flooding and enormous landslide disasters over Japan's Kinki region. The Japan Meteorological Agency (JMA) issued a “special warning” for three western Japan prefectures of Fukui, Kyoto, and Shiga. This paper investigates the applicability of ensemble forecasts of numerical weather prediction (NWP) model for flood forecasting area and reviews the reasons why ensembles of NWP model are so attractive than deterministic model run. In this study, 10 km resolution ensemble rainfalls forecast and their downscaled forecasts of 2km resolution were used in the hydrologic model as input data for flood forecasting and application of flood early warning. Ensemble data consists of 51 members and 48 hr forecast time. Ensemble outputs are verified spatially whether they can produce suitable rainfall predictions or not during the 2013 Typhoon No. 18, ‘Man-yi’ event. Then flood forecasting driven by ensemble outputs is carried out over the Katusra river basin of the Kinki area, Japan. The results shows flood forecasts driven by ensemble outputs showed that the ensemble flood forecast provides additional information to the deterministic forecast.

Keywords: Ensemble NWP rainfall, Ensemble flood forecasting, Flood early warning

1. INTRODUCTION

On mid-September 2013 heavy rainfalls happened over Japan due to the season's 18th typhoon, ‘Man-yi’, which caused large flooding and enormous landslide disasters over Japan's Kinki region. In Kyoto on September 16, 260,000 people in the city were ordered to evacuate to shelters and were also ordered to evacuate across mainly the west side of Japan. The Japan Meteorological Agency (JMA) issued a “special warning” for three western Japan prefectures of Fukui, Kyoto, and Shiga. Over 70 people were injured and at least one person was killed. Many homes were flooded and about 80,000 were without electricity in western and central Japan.

In these types of extreme events, it is essential to be able to provide as much advance warning as possible. This advance warning requires both quantitative precipitation forecasting (QPF) and quantitative flood forecasting (QFF). Numerical Weather Prediction (NWP) models are now becoming standard for short-range (1~2days) forecasts. NWP models use current weather conditions as input to atmospheric models to predict the evolution of weather systems. These models represent the atmosphere as a dynamic fluid and solve for its behavior through the use of mechanics and thermodynamics. The accuracy of weather forecasts has steadily improved over the years, due to advances in NWP techniques and increased computing power (Buizza et al., 1999; Demeritt et al., 2007).

Recent advances in NWP models have created opportunities to improve streamflow forecasts. The accuracy of weather forecasts has steadily improved over the years, but it has been challenging to integrate quantitative precipitation forecasts (QPF) into flood forecast systems (Cloke and Pappenberger, 2009; Cuo et al., 2011). Using the outputs from a number of forecasts or realizations, the relative frequency of events from the ensemble numerical weather prediction can be used directly to estimate the probability of a given weather or flood event. Ensemble forecasting is a form of Monte Carlo analysis: multiple numerical predictions are conducted using slightly different initial conditions that are all plausible given the past and current set of observations or measurements. Ensemble or probabilistic forecasts are more widely applied to NWP models, with the probabilistic outcome of a number of NWP runs being used to provide the “most likely” scenario for input into a hydrological model of so-called ensemble prediction systems (EPSs).

Several different hydrologic and flood forecasting projects now use EPS operationally or semi-operationally, and many centers may be considering the adoption of such an approach. In 1999, the European Flood Forecasting System (EFFS, 1999 ~ 2003) project was the first European research project based on EPS and addressed early flood warning (De Roo et al., 2003; Kwadijk, 2003; Bartholmes and Todini, 2005). In the light of the EFFS, a European commission created the European Flood Alert System (EFAS). In 2004, the Hydrological Ensemble Prediction Experiment (HEPEX) guided an international initiative to develop cooperative research between the meteorological and hydrological communities (Schaake et al., 2006, 2007; Thielen et al., 2008). Since then, EPS-based research has become a dominant feature of hydrological research and applications on all time scales (Mesoscale Alpine Programme Demonstration of Probabilistic Hydrological and Atmospheric Simulation of Flood Events (MAP D-PHASE) (Zappa et al., 2008), Prevention, Information and Early Warning (PREVIEW) (Bogner and Kalas, 2008), and other research projects on ensemble forecasts (Bartholmes et al., 2009)

In the context of flood management, it is important to integrate NWP model output and flood forecasting. It is possible to incorporate NWP model outputs directly into flood forecasting systems to obtain an extended lead time (Xuan et al., 2009). However, direct application of deterministic NWP model output can propagate uncertainties into the hydrologic domain. For this reason, the development of ensemble hydrological applications started in the late 1990s and is a field of ongoing research (De Roo et al., 2003; Gouweleeuw et al., 2005). Ensemble flood forecasting provides additional information to the deterministic flood forecast in the short forecast range, and provides a signal in terms of pre-warning and exceedance probabilities for threshold values (e.g. critical discharge, levels causing inundation, and so on).

This study attempts to deal with ensemble forecast outputs of NWP model for flood forecasting applications with a distributed hydrologic model. In this study, we examined 10km resolution forecasting and its downscaled forecast of 2km resolution. We assess ensemble rainfall from NWP model that whether it can predict the heavy rainfall or not in the Kinki region. Then ensemble outputs are verified temporally and spatially whether they can produce suitable rainfall predictions or not during the Typhoon event. Finally, flood forecasting driven by ensemble outputs is carried out over the Katsura river basin of the Kinki area, Japan.

So the questions in this study are as follows:

1) How much did the downscaled forecast improve the location and magnitude of rainfall?

2) How much did the downscaled NWP improve the reliability of the discharge for the Hiyoshi dam operation?

3) How well did the downscaled NWP predict the water level for flood early warning in the Karsura river basin?

2. Data, a Hydrologic Model and Study Area

2.1 Design of Meteorological Experiment

In Japan, an operational one-week ensemble prediction model from JMA was developed to provide probabilistic information of 51 ensemble members with a horizontal resolution of 60 km, and it used to be applied for hydrological applications (e.g., prior and optimized release discharge for dam operation; Matsubara et al., 2013). However, operational short-term (1–2 day) ensemble prediction with much finer resolution has not yet been developed. For that reason, in this study, 10 km resolution ensemble rainfalls forecast and their downscaled forecasts of 2km resolution were used in the hydrologic model as input data for flood forecasting and application of flood early warning for the 2013 Typhoon No.18 ‘Man-yi’ event.

Both 10 km and 2 km resolution systems used the JMA Non-hydrostatic Model (NHM) as the forecast model (Saito et al., 2006; Saito, 2012). The domain of the two ensemble systems with 10 km and 2 km horizontal resolution are illustrated in Fig. 1. The coarse resolution system of 10 km had a domain of 361×289 grid points with 50 vertical levels and forecasted up to 48 hours in advance. The fine-resolution 2 km system was conducted from the downscale forecast of 10 km resolution systems. This system had a domain of 350×350 grid points with 60 vertical levels and forecasted up to 48 hours in advance. The initial and boundary conditions for each member at 2 km were interpolated from the forecasts on the corresponding member at 10 km resolution.

Ensemble data consists of 51 members and 48 h forecast time. Fig. 2 introduces a design of ensemble forecast with 6 hour interval. In this figure, grey line means actual rainfall period by typhoon man-yi in target basin, and in the time of star mark, heavy rainfall and flood warning was issued in Kyoto prefecture. So we designed the ensemble forecasts to cover the rainfall period by using 48 hr forecast time and 6 hour interval. Finally we constructed 7 forecast periods and analyzed its forecast accuracy from rainfall and discharge verification.

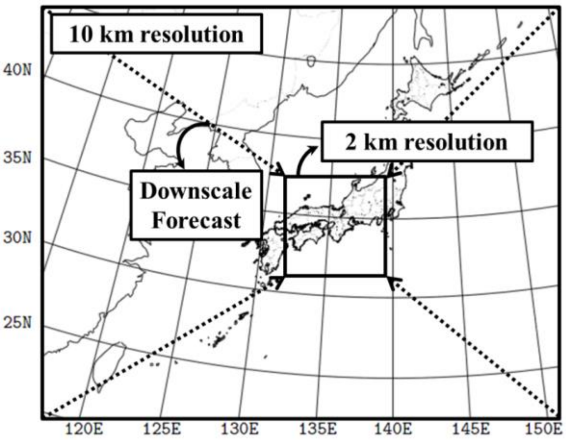


Fig. 1 Forecast domains of 10 km and 2 km horizontal resolution.

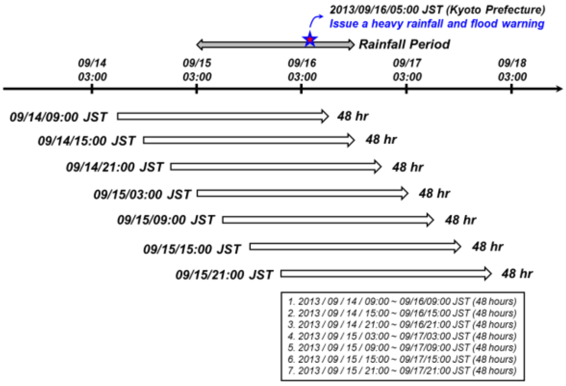


Fig. 2 The design of 48 h ensemble forecast with 6 hour interval.

2.2 Distributed hydrologic model: KWMSS

In this study, we used a spatially-distributed hydrologic model, based on one-dimensional kinematic wave method for subsurface and surface flow (hereafter, KWMSS) with a conceptual stage-discharge relationship, which was introduced by Takasao and Shiiba (1988) and enhanced by Tachikawa et al. (2004).

In this model, the rainfall–runoff modeling system accepts spatially variable information in terms of topographic and meteorological data. The drainage network is represented by sets of hillslope and channel elements from digital elevation model (DEM). In this study, the drainage network was represented by a 250 m × 250 m spatial resolution of DEM. Fig. 3 is a conceptualization of spatial flow movement and flow process in hillslope elements of KWMSS. The rainfall over all hillslope elements flows one-dimensionally into the river nodes and then routes to the catchment outlet. The rainfall-runoff transformation conducted by KWMSS is based on the assumption that each hillslope element is covered with a permeable soil layer, as shown in Fig. 2. This soil layer consists of a capillary layer and a non-capillary layer. In these conceptual soil layers, slow and quick flow are simulated as unsaturated Darcy flow and saturated Darcy flow, respectively, and overland flow occurs if water depth, *h* [m] exceeds soil water capacity.

$$q = \begin{cases} v_c d_c (h/d_c)^{\beta}, & 0 \le h \le d_c \\ v_c d_c + v_a (h - d_c), & d_c \le h \le d_s \\ v_c d_c + v_a (h - d_c) + \alpha (h - d_s)^m, & d_s \le h \end{cases} \tag{1}$$

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(x,t) \tag{2}$$

where $v_c = k_c i$ [m/s], $v_a = k_a i$ [m/s], $k_c = k_a/\beta$ [m/s], $\alpha = i^{1/2}/n$ [$\mathrm{m}^{1/3}\mathrm{s}^{-1}$], $m = 5/3$, i is the slope gradient, kc [m/s] is the hydraulic conductivity of the capillary soil layer, k_a [m/s] is the hydraulic conductivity of the non-capillary soil layer, n [$\mathrm{m}^{-1/3}\mathrm{s}$] is the roughness coefficient, d_s [m] is the water depth corresponding to the water content, and d_c [m] is the water depth corresponding to maximum water content in the capillary pore.

The flow rate of each hillslope element q [m^2/s] is calculated by equation (1), and combined with the continuity equation for channel routing by equation (2).

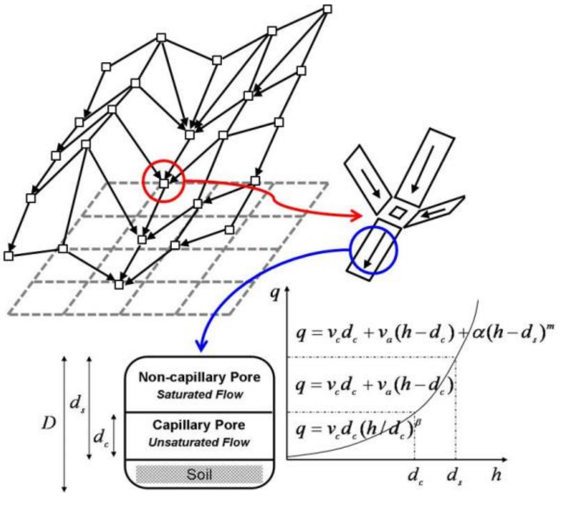


Fig. 3 Conceptualization of spatial flow movement and flow process in hillslope elements.

2.3 Study area

The Katsura river basin was selected as the target area to assess the flood forecast applicability using the ensemble NWP rainfall as illustrated in Fig. 4. The Katsura river basin is located in Kyoto, Japan, and covers an area of 1,100 km^2 (887 km^2 at the Katsura station). Topography in the catchment is characterized by a mountainous upstream in the north and a flatter plain in the south. The elevation in the catchment ranges from 4 to 1,158 m, with an average of about 325 m. The land use consists of forest (76.7%), agricultural area (9.3%), residential area (7.5%), water body (2.0%), public area (2.7%), vacant land (1.2%), and road (0.6%), respectively. The Hiyoshi dam is located upstream. The controlled outflow record from the dam reservoir is given as inflow to the hydrologic model, and the model simulates rainfall-runoff processes for the downstream of the dam.

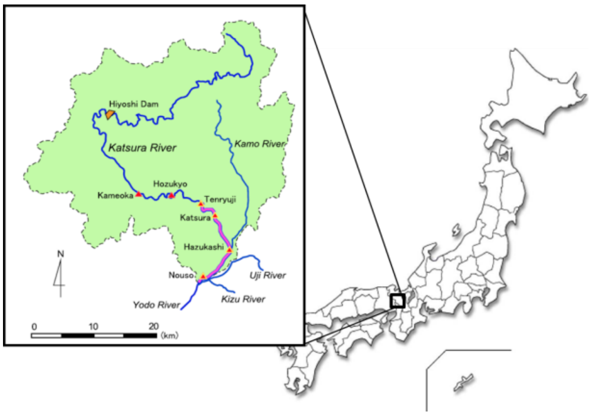


Fig. 4 Katsura river basin, which is target area in Japan.

3. RESULTS AND DISCUSSION

3.1 Spatial Rainfall Verification

The ensemble NWP rainfall forecast in this study have been verified spatially against the MLIT C-band composite radar data with 5 min interval and 1 km resolution, because their high spatial-temporal resolution is suitable to capture the spatial variability of rainfall. The ensemble forecast was expressed as probabilities of exceeding selected rainfall thresholds (1.0 and 5.0 mm/h). A contingency table can be constructed with a spatial comparison, in which each area with more than selected rainfall threshold is defined as "yes," and

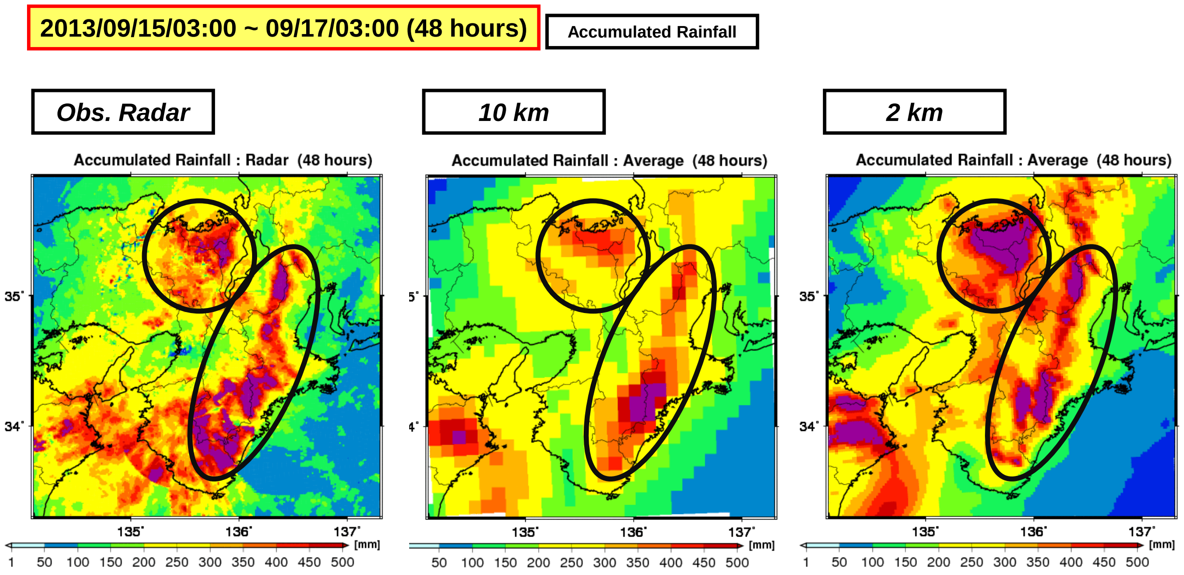


Fig. 5 Ensemble NWP rainfall forecast at 10 km and 2 km horizontal resolution

other areas are defined as "no" for both forecasted and observed rainfall fields. In this study, threat score (TS) are considered for spatial verification of ensemble forecast in the Kinki region and its range is 0 to 1, with a value of 1 indicating a perfect forecast. It takes into account both false alarms and missed events.

$$TS = \frac{hits}{hits + misses + false\,alarms} \tag{3}$$

where *hits* is the number of correct forecasts over the threshold (i.e., when the rainfall that is forecasted is also observed), and *misses* is the number of times rainfall is not forecasted, but is observed. *false alarms* is the number of times rainfall is forecasted, but not observed.

For the calculation of TS value, the ensemble forecasts were expressed as probabilities of exceeding a selected total rainfall threshold (240mm/h), which were used to compare an obvious spatial distribution of observed MLIT radar data with forecasted NWP rainfall. A contingency table can be constructed with a spatial comparison, in which each area with more than 240 mm/h of threshold is defined as "yes," and other areas are defined as "no" for both forecasted and observed rainfall fields. Fig. 5 shows the ensemble NWP rainfall forecast at 10km and 2 km horizontal resolution from 2013/09/15/03:00 to 09/17/03:00 JST (48 hours).

And then we compared the ensemble mean results of 10km and 2km resolution to confirm that how much did the downscaled forecasts improve the location and magnitude of rainfall? 10km and 2km resolution forecasts could well predict the rainfall distribution in Kinki region, but 10 km resolution has coarse distribution. So it has limitation to apply into basin scale. On the other hands, 2km result has more specific distribution than 10 km resolution and more well matched compared with obs. radar rainfall distribution. Fig. 6 is result of threat score with 10 km and 2 km resolution by ensemble mean forecasts to check the accuracy of each resolutions and forecast periods. Horizontal axis means initial time for 7 forecast periods. From this result, we could confirm that 2km forecasts improved the accuracy of rainfall distribution compared with 10 km resolution.

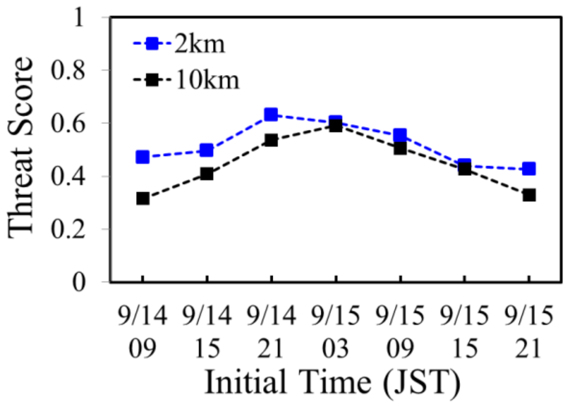


Fig. 6 Threat Score (TS) for 48-h accumulated rainfall forecast of 10 km and 2 km resolution at the 240 mm threshold.

3.2 Ensemble Flood Forecasting

In this study, target basin is katsura river basin, and there is hiyoshi dam in upstream of basin. For the suitable dam operation, the accurate forecast of dam inflow is very important. So we assessed that how much did the downscaled NWP improve the reliability of the discharge for the Hiyoshi dam operation? Fig. 7 is the 2km resolution results of forecasted areal rainfall and discharge in hiyoshi dam during 48 hours period. Red colors mean observed rainfall by radar rainfall and obs. discharge in hiyoshi dam.

From the rainfall forecast result, we could know ensemble mean was under-predicted compared with observed rainfall, but ensemble members covered the observed rainfall. This forecasted ensemble rainfalls were reflected in forecasted discharge result. And then this ensemble forecast is continued with 6 hr interval. And we could also know that accuracy of rainfall and discharge forecast were improved by new forecast term of 6 hour interval. In this forecast period, forecasted ensemble mean value of rainfall and discharge were well matched to obs. value and all of ensemble members covered the obs. value.

But from new forecast after each 6 hr interval, forecasted peak value moved to right side, and has timing error like Fig. 7. So, forecasted discharge also moved to right side. It can be considered by two reasons why it has forecast timing error. First one is the problem of initial condition for new forecast. In this initial time, typhoon has approached the kinki region and caused heavy rainfall in Kyoto prefecture. So, because the atmosphere condition is very unstable and atmosphere is a nonlinear and chaotic system. So, a slight change in the initial condition could result in unpredictable results. Second reason is forecast resolution in basin scale. Hiyoshi dam basin has just 290 km^2. Although 2km is high resolution, it is possible to have location and timing errors in small basin. So, about two reasons why it has forecast timing error, we need research to be more specific.

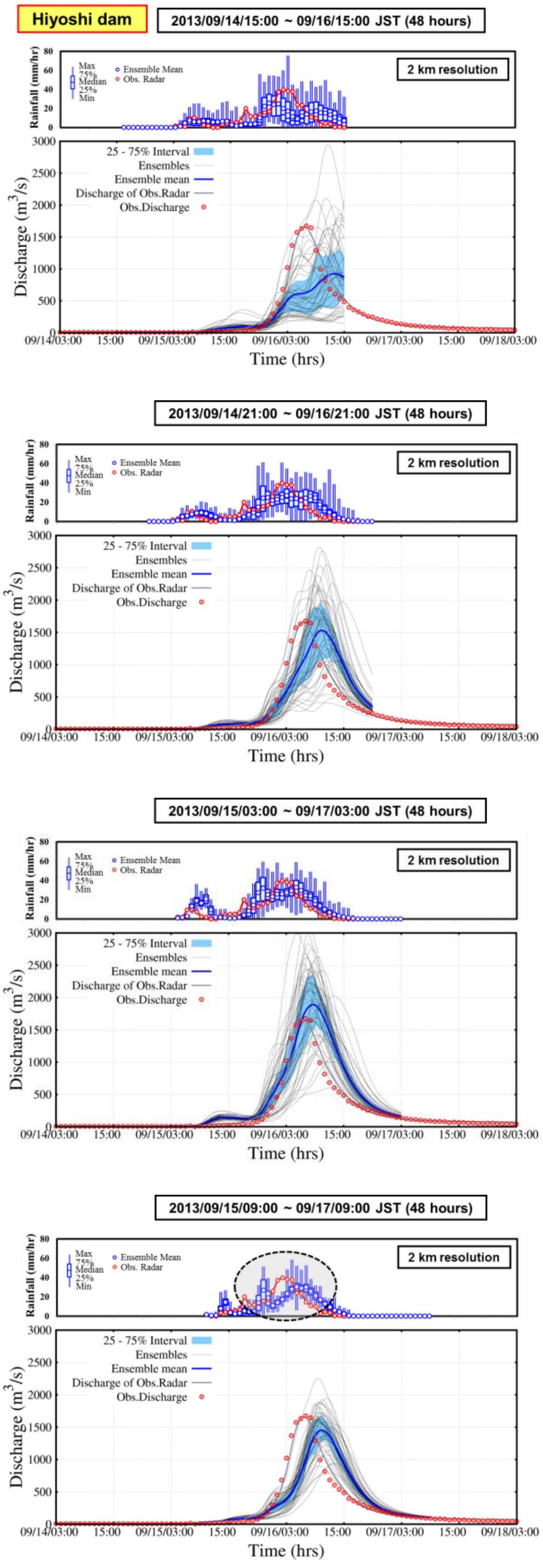
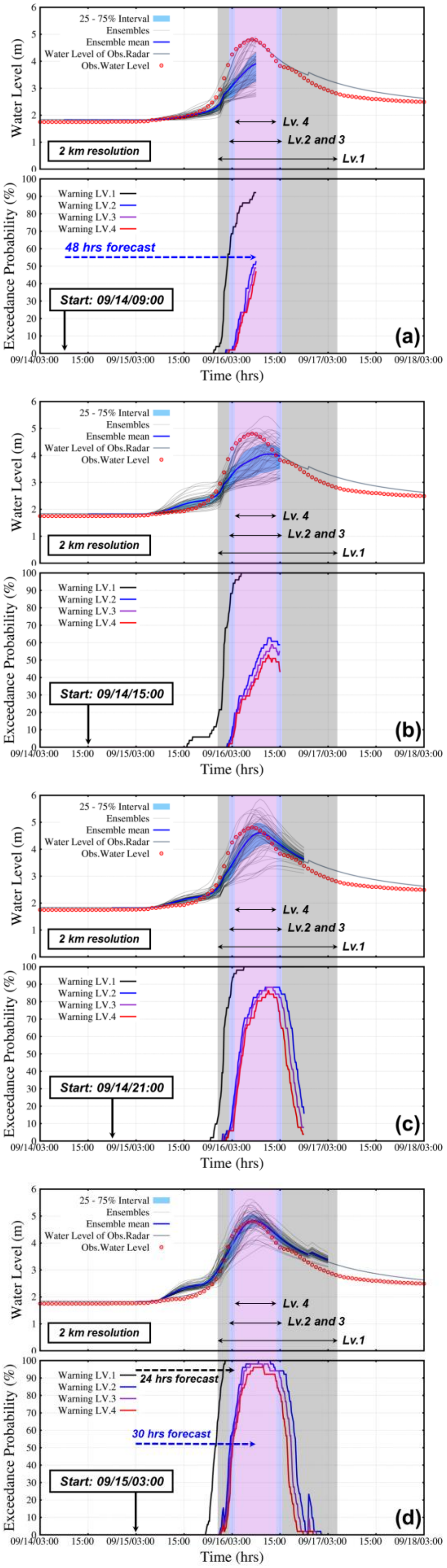


Fig. 7 48 hours Ensemble flood forecast results over the Hiyoshi dam catchment.

3.3 Application to Flood Early Warning

The use of probabilistic flood forecasting for risk assessment and risk-based decision-making in flood warning is still one of the greatest challenges for the scientific community. And the use of meteorological ensembles to produce sets of hydrological predictions increased the capability to issue flood warnings. General literature agreement is that EPS flood forecasting is a useful activity and has the potential to inform early flood warning.

In Katsura river basin, there are 4 warning level for information to local people. Using these warning level information, we assessed that how well did the downscaled NWP predict the water level for flood early warning in the Karsura river basin? Fig. 8 shows predicted water level by ensemble data and the percentages of ensemble members exceeding each warning level. The colors in this figure mean actually happened warning levels in Katsura river basin. Fig. 8 (a) means flood probabilities from ensemble rainfall from 48 hrs before, show up to about 90% probability to exceed warning level 1 and show up to about 50% probability to excceed warning levels 2, 3 and 4. And from the new forecast by 6 hr interval, the probabilities increase considerably. And the forecast on Fig. 8 (d), probabilities show up to about 100% probability to exceed warning level 1 before 24 hours and provide the information of probabilities to exceed the warning levels 2,3 and 4 about 100% before 30 hours. The accurate probability exceeding warning level is important for flood early warning, but these information like this probability figure is more important for local people to prepare the flood and evacuate. After 6 hour interval, predicted water level was under-predicted compared with observed water level, so that reason, predicted exceedance probability has also limitation. But as you know, in real time forecasting, we do not know these forecasting is accurate or not, so these probability information is still important. Therefore, further research for the use of all of forecast information at the same time is very important for local people.



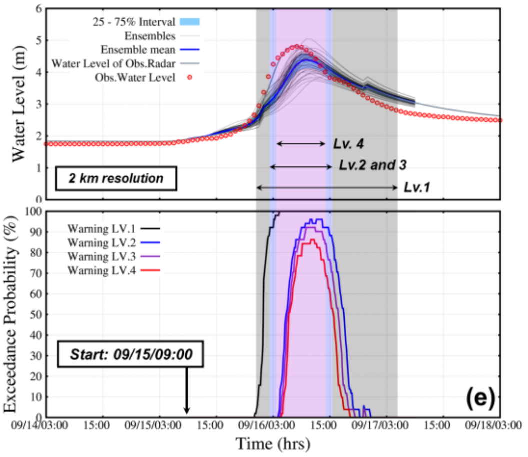


Fig. 8 predicted water level by ensemble data and the percentages of ensemble members exceeding each warning level.

4. CONCLUSION

Given the current issue with application of ensemble NWP to flood forecasting, this study conducted rainfall and flood forecast to overcome an insufficiency of the deterministic flood forecast using ensemble outputs with 48-hr forecast time and 2km high-resolution and to explore an accuracy improvement of the flood forecasting using ensemble NWP rainfall forecast.

Therefore, we assess the latest ensemble NWP outputs with 51 ensemble members, 48-hr forecast time and 2km horizontal resolution whether they can produce suitable rainfall predictions or not during the Typhoon No. 18 ‘Man-yi’ 2013 event, and we also assess the performance of ensemble flood forecasting for application of flood early warning based on the latest ensemble NWP rainfall forecast over the Katsura river basin. In this study, it is important that the ensemble flood forecast with 51 ensemble members, 48-hr forecast time and 2km high-resolution has not been carried out in previous researches for the flood early warning field.

The results of this study lead to the following conclusions:

1) Downscaled NWP result had more specific distribution than 10 km resolution and was more well matched compared with obs. radar rainfall distribution.

2) Downscaled NWP improved the reliability of the discharge for the Hiyoshi dam operation.

3) NWP predicted well the water level for flood early warning in the Katsura river basin.

We expect it to be used in hydrological applications operationally, such as in real-time flood forecasting for warning systems and optimized release discharge for dam operations.

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References

Bartholmes, J. and Todini, E. (2005) Coupling meteorological and hydrological models for flood forecasting. Hydrology and Earth System Sciences, Vol. 9, pp. 333-346.

Bartholmes, J., Thielen, J., Ramos, M. and Gentilini, S. (2009) The European Flood Alert System EFAS – Part 2: Statistical skill assessment of probabilistic and deterministic operational forecasts. Hydrology and Earth System Sciences, Vol. 13, pp. 141-153.

Bogner, K. and Kalas, M. (2008) Error correction methods and evaluation of an ensemble based hydrological forecasting system for the Upper Danube catchment. Atmospheric Science Letters, Vol. 9, pp. 95-102.

Buizza, R., Miller, M., and Palmer, T. (1999) Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System, Quart. J. Roy. Meteor. Soc., Vol.125, pp.2887–2908.

Cloke, H.L. and Pappenberger, F. (2009) Ensemble flood forecasting: a review. Journal of Hydrology, Vol.375, pp.613-626.

Cuo, L., Pagano, T.C. and Wang, Q.J. (2011) A review of quantitative precipitation forecasts and their use in short- to medium-range streamflow forecasting. Journal of Hydrometeorology, Vol.12, pp.713-728.

Demeritt, D., Cloke, H., Pappenberger, F., Thielen, J., Bartholmes, J., and Ramos, M. (2007) Ensemble predictions and perceptions of risk, uncertainty, and error in flood forecasting, Environ. Hazards, Vol.7, pp.115–127.

De Roo, A., Bartholmes, J., Bates, P.D., Beven, K., Bongioannini-Cerlini, B., Gouweleeuw, B., Heise, E., Hils, M., Hollingsworth, M., Holst, B., Horritt, M., Hunter, N., Kwadijk, J., Pappenburger, F., Reggiani, P., Rivin, G., Sattler, K., Sprokkereef, E., Thielen, J., Todini, E., Van Dijk, M. (2003) Development of a European flood forecasting system. International Journal of River Basin Management, Vol. 1, No. 1, pp. 49-59.

Gouweleeuw, B., Thielen, J., Franchello, G., de Roo, A. and Buizza, R. (2005) Flood forecasting using medium-range probabilistic weather prediction. Hydrology and Earth System Sciences, Vol. 9, No. 4, pp. 365-380.

Kwadijk, J. (2003) EFFS – European Flood Forecasting System. Final report of Contract EVG1-CT-1999-00011 (http://effs.wldelft.nl).

Matsubara, T., Kasahara, S., Shimada, Y., Nakakita, E., Tsuchida, K., and Takada, N. (2013) Study on applicability of information of typhoons and GSM for dam operation, Ann. J. Hydraul. Eng, JSCE, Vol.69, No.4, pp.367-372 (in Japanese with English abstract).

Saito, K., Fujita, T., Yamada, Y., Ishida, J., Kumagai, Y., Aranami, K., Ohmori, S., Nagasawa, R., Kumagai, S., Muroi, C., Kato, T., Eito, H. and Yamazaki, Y. (2006) The operational JMA nonhydrostatic meso-scale model. Monthly Weather Review, Vol.134, pp.1266-1298.

Saito, K. (2012) The JMA nonhydrostatic model and its application to operation and research. In: Yucel, I. (Eds.), Atmospheric Model Applications, InTech, pp.85-110.

Schaake, J., Franz, K., Bradley, A. and Buizza, R. (2006) The hydrologic ensemble prediction experiment (HEPEX). Hydrology and Earth System Sciences Discussions, Vol. 3, pp. 3321-3332.

Schaake, J., Hamill, T.H., Buizza, R. and Clark, M. (2007) HEPEX: the hydrological ensemble prediction experiment. Bulletin of the American Meteorological Society, Vol. 88, No. 10, pp. 1541-1547.

Tachikawa, Y., Nagatani, G. and Takara, K. (2004) Development of stage-discharge relationship equation incorporating saturated–unsaturated flow mechanism. Ann. J. Hydraul. Eng, JSCE, Vol.48, pp.7-12 (in Japanese with English abstract).

Takasao, T. and Shiiba, M. (1988) Incorporation of the effect of concentration of flow into the kinematic wave equations and its applications to runoff system lumping. Journal of Hydrology, Vol.102, pp. 301-322.

Thielen, J., Schaake, J., Hartman, R. and Buizza, R. (2008) Aims, challenges and progress of the Hydrological Ensemble Prediction Experiment (HEPEX) following the third HEPEX workshop held in Stresa 27 to 29 June 2007. Atmospheric Science Letters, Vol. 9, pp. 29-35.

Xuan, Y., Cluckie, I. and Wang, Y. (2009) Uncertainty analysis of hydrological ensemble forecasts in a distributed model utilizing short-range rainfall prediction. Hydrol. Earth Syst. Sci., Vol.13, pp.293-303.

Zappa, M., Rotach, M.W., Arpagaus, M., Dorninger, M., Hegg, C., Montani, A., Ranzi, R., Ament, F., Germann, U., Grossi, G., Jaum, S., Rossi, A., Vogt, S., Walser, A., Wehrhand, J. and Wunram, C. (2008) MAP D-PHASE; real-time demonstration of hydrological ensemble prediction systems. Atmospheric Science Letters, Vol. 9, pp. 80-87.

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