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Research papers

The very short-term rainfall forecasting for a mountainous watershed by means of an ensemble numerical weather prediction system in Taiwan

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ABSTRACT

During typhoons, accurate forecasts of rainfall are always desired for various kinds of disaster warning systems to reduce the impact of rainfall-induced disasters. However, rainfall forecasting, especially the very short-term (hourly) rainfall, is one of the most difficult tasks in hydrology due to the high variability in space and time and the complex physical process. In this study, the purpose is to provide effective forecasts of very short-term rainfall by means of the ensemble numerical weather prediction system in Taiwan. To this end, the ensemble forecasts of hourly rainfall from this ensemble numerical weather prediction system are analyzed to evaluate the performance. Furthermore, a methodology, which is based on the principle of analogue prediction, is proposed to effectively process these ensemble forecasts for improving the performance on very short-term rainfall forecasting. To clearly demonstrate the advantage of the proposed methodology, actual application is conducted on a mountainous watershed to yield 1- to 6-h ahead forecasts during typhoon events. The results indicate that the proposed methodology is better performed and more flexible than the conventional one. Generally, the proposed methodology provides improved performance for very short-term rainfall forecasting, especially for 1- to 2-h ahead forecasting. The improved forecasts provided by the proposed methodology are expected to be useful to support disaster warning systems, such as flash-flood, landslide, and debris flow warning systems, during typhoons.

1. Introduction

Among all natural disasters, tropical cyclones are devastating and ranked second in loss of life according to the World Meteorological Organization studies (De and Joshi, 1998; Bengtsson, 2007). In the whole world, an average of approximately 90 tropical cyclones occur per year. The Northwestern Pacific Ocean is the most active tropical cyclone basin. About 30 tropical cyclones, also called typhoons in this basin, occur each year. Taiwan is situated in one of the main paths of Northwestern Pacific typhoons. Based on the data counted by Central Weather Bureau Taiwan, a total of 360 typhoons invaded Taiwan from 1911 to 2015. That is, on average, three to four typhoons invade Taiwan each year.

During typhoon events, heavy rainfall often causes serious damages, such as floods, inundation, landslides or debris flows, and results in loss of life and property damage. To mitigate disasters due to excessive typhoon rainfall, various kinds of warning systems are developed as a non-structural strategy. By providing early warnings, proper preventive measures, such as the evacuation of people from the most critically threatened areas, can be taken in advance. Consequently, the impact of typhoon rainfall-induced disasters is reduced. Moreover, for giving early warnings with sufficient lead time, precise forecasts of typhoon rainfall are always desired as essential information in these warning systems. Therefore, providing accurate typhoon rainfall forecasts, especially the accurate hourly rainfall forecasts, is always an important task in the work of disaster prevention and mitigation in Taiwan.

In hydrology, the forecasts of hourly rainfall are commonly obtained from radar estimates or by applying various statistically-based techniques, such as time series regression, neural networks, etc. About the use of radar rainfall estimation for forecasting (i.e., radar rainfall nowcasting), it is still limited to very short lead time (Vivoni et al., 2005; Sokol, 2006; Chang et al., 2014). Besides, despite advances in multi-sensor estimation, bias remains a large issue which impairs the use of radar-based quantitative precipitation forecasts for hydrologic applications (Seo et al., 2015). In Taiwan, due to the mountainous terrain and the island nature, the lead time of radar rainfall nowcasting is generally less than 1 h. As regards the use of statistically-based techniques, many studies are available in the literature (e.g., Luk et al., 2000; Lin and Chen, 2005; Lin and Wu, 2009; Wu et al., 2010; Lin et al., 2013; Lin

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and Jhong, 2015). Results of most studies showed that statistically-based techniques yield acceptable forecasts for a lead time of 1- to 2-h only. It is reasonable to speculate that the correlation between desired output and available input decreases with increasing forecast lead time. As a result, those statistically-based techniques usually fail to provide effective forecasts of hourly rainfall for longer lead time.

In recent years, with the development of atmospheric science as well as computer technology, more researches focus on the potential of numerical weather predictions (NWPs) for quantitative rainfall forecasting (e.g., Liguori and Rico-Ramirez, 2012; He et al., 2013; Hsiao et al., 2013; Yu et al., 2015). NWPs are derived from physically- and dynamically-based numerical weather models (NWMs). Based on the physical principles of atmosphere, NWMs are executed to generate 1–3 days ahead weather forecasts according to current weather conditions. Nowadays, NWPs are seen as the most reliable source for atmospheric forecasts with a large spatial coverage and high temporal resolution (Diomede et al., 2008).

In Taiwan, for providing accurate quantitative rainfall forecasts, Taiwan Typhoon and Flood Research Institute of the National Applied Research Laboratories executes a NWP-based quantitative precipitation forecast experiment (Hsiao et al., 2013). This experiment named Taiwan Cooperative Precipitation Ensemble Forecast Experiment (abbreviated as TAPEX hereafter) is an ensemble prediction system (EPS), which means a collection of two or more NWPs for the same location and time. The ensemble prediction system is increasingly used instead of a single deterministic prediction in order to take account of the uncertainties of NWPs. Given the uncertainties in model initial conditions and model physics, EPS can yield multiple weather forecasts to capture the uncertainties of rainfall forecasting (Palmer and Buizza, 2007; Cloke and Pappenberger, 2009) and to provide probabilistic forecasts (Ebert, 2001). Studies related to the use of precipitation forecasts from TAPEX in hydrological modelling have been conducted and confirm the potential of TAPEX to provide valuable information on quantitative precipitation forecasts (Lee et al., 2013; Hsiao et al., 2013; Shih et al., 2014; Yang and Yang, 2014; Yang et al., 2015). This has prompted an investigation into the potential of TAPEX for very short-term (hourly) rainfall forecasting.

Hence, the purpose of this study is to provide effective forecasts of very short-term (i.e., 1- to 6-h ahead forecasts herein) rainfall by means of the ensemble NWP system in Taiwan. For this purpose, firstly the performance of ensemble forecasts from TAPEX during typhoons is evaluated. Further, in order to improve the performance on very short-term rainfall forecasting, a methodology is proposed to effectively process and integrate these ensemble forecasts. An application is finally conducted to demonstrate the superiority of the proposed methodology. The remainder of this paper is organized as follows. Section 2 describes the details of the ensemble quantitative precipitation forecast experiment in Taiwan, i.e., TAPEX. Section 3 provides a description of the development of the proposed methodology used for processing the ensemble forecasts of TAPEX. Section 4 contains the study area and typhoon events. Sections 5 and 6 present the results and discussion, and summary and conclusions, respectively.

2. NWP-based ensemble prediction system (TAPEX)

TAPEX which started from 2010 is an ensemble numerical weather prediction system in Taiwan and is a collective effort among several academic institutes and government agencies (Hsiao et al., 2013). In TAPEX, numerical weather prediction models are performed to generate future weather scenarios based on current weather conditions. To date, more than 20 ensemble members, namely different numerical weather prediction models with different model configurations, have been established for weather forecasting. Four numerical weather prediction models, the Weather Research and Forecasting (WRF) Model, the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5), the Cloud Resolving Storm Simulator (CReSS) Model, and the Hurricane Weather Research and Forecasting (HWRF) Model, are used in TAPEX. WRF, HWRF, and MM5 models use three nested domains with 45 km, 15 km, and 5 km horizontal resolutions for the outermost, the middle, and the inner domains, respectively (see Fig. 1). The outermost domain covers most of Asia and the western North Pacific Ocean, and the inner domain covers Taiwan and the neighboring ocean. As for CReSS models, only one domain with 5 km or 2.5 km horizontal resolutions is used. The domain size is similar to the inner domain used in other models. In vertical direction, a total of 45, 43, 35, and 40 vertical levels are used for WRF, HWRF, MM5 and CReSS models, respectively. Detailed model configurations for these ensemble members are given in Table 1.

The perturbations of initial conditions (ICs) mean the variations in the atmospheric first-guess states, i.e., the cold-start or the partial-cycle. Cold-start runs are initialized with large-scale fields that are obtained from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) analyses. Partial-cycle runs include a cold-start run 12-h before the analysis time and then two 6-h data assimilation cycles. Additionally, the three-dimensional variational data assimilation system (3DVAR) with two statistical background error covariance matrices, i.e., CV3 and CV5, and the outer loop (OL) procedure are adopted for initial condition perturbations. The four-dimensional variational data assimilation system (4DVAR) and the no-data-assimilation (NODA) run are also used. Lateral boundary conditions (LBCs) are provided every 6-h from the NCEP GFS, except that the ensemble member M12 uses the LBCs from the Taiwan Central Weather Bureau (CWB) GFS. Variations in cumulus schemes are the use of the Grell-Devenyi (GD), the Grell 3D (G3), the Betts-Miller-Janjic (BMJ), and the Kain-Fritsch (KF) schemes for WRF models. For MM5 and HWRF models, the Grell and the Simplified Arakawa and Schubert (SAS) schemes are used, respectively. These cumulus schemes are used in the outermost and the middle domains. As to CReSS model, there is no need for the cumulus scheme due to the use of only one high-resolution domain. Microphysics schemes, which are used in the domain with horizontal resolution less than 5 km, included the Goddard and WRF Single-Moment 5-class (WSM5) schemes for WRF and MM5 models, the Cold rain scheme for CReSS models, and the Ferrier scheme for HWRF models. Planetary boundary layer schemes included the Yonsei University (YSU) for WRF models, the medium-range forecast (MRF) nonlocal boundary layer schemes for MM5 models, and the Mellor & Yamada (M&Y) scheme for CReSS models. As to HWRF models, the data provided from the NCEP GFS are used. The model configurations are designed based on the preliminary experiments in 2010. For more details about TAPEX, readers can refer to Hsiao et al. (2012 and 2013).

TAPEX operationally provides 72-h typhoon track and precipitation forecasts four times per day (initialized at 0000, 0600, 1200, and 1800 UTC). Fig. 2 shows an example of ensemble forecasts of typhoon track and precipitation issued at 0000 UTC on August 1 during Typhoon Saola in 2012 (the model initial time is 1800 UTC on July 31). Gray lines display the ensemble typhoon track forecasts and the black line is the mean of all ensemble forecasts. The star mark indicates the location of the maximum 24-h typhoon precipitation forecast of each ensemble member. The corresponding value is also provided. Moreover, the ensemble hourly rainfall forecasts of TAPEX for a watershed (the Choshui River watershed located in west-central Taiwan) are shown in Fig. 3. The box-and-whisker plot, which is used to depict the variations of