KEYNOTE TOPIC 3: TC Precipitation (QPE/QPF) and related inland flood modeling

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KN3.1 Introduction

In recent years, extreme weather events and calamities occurring in both Pacific and Atlantic coastal regions have been generated by LTCs, such as the super typhoons Rananim (2004), Haitang (2005), Saomai (2006) and Morakot (2009) in the Pacific, and the super hurricanes Ivan (2004), Rita (2005) and Katrina (2005) in the Atlantic. Additionally, super cyclonic storm Gonu (2007) in the Arabian sea and super cyclonic storm Nargis (2008) in Bay of Bengal. Consequently, the top priority for scientists working in this field should be the improvement of forecasting techniques and early warning systems for LTCs (Chen et al, 2010).

TC rainfall forecasting techniques are lagging behind those of the track forecast. However, significant progress has been made in recent years due to the advance in remote sensing observations and the improvement of mesoscale models and data assimilation techniques. Until relatively recently, TC rainfall prediction was carried out mainly using empirical speculation and subjective experience on the part of the forecaster. However, advanced techniques for quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF) are currently employed in operational applications in some major forecasting centers, which already have greatly improve the forecasting for LTC-related rainfall. Nevertheless, further improvements in QPF based on a better understanding of TC rainfall mechanisms are still required.
KN3.2 **Progress of QPE/QPF in past four years**

KN3.2.1 **Observation**

Characteristics of the raindrop size distribution in seven tropical cyclones have been studied through impact-type disdrometer measurements at three different sites during the 2004–06 Atlantic hurricane seasons (Tokay et al., 2008). It is found that high concentrations of small and/or midsize drops were observed in the presence or absence of large drops. Even in the presence of large drops, the maximum drop diameter rarely exceeded 4 mm. Chang et al. (2009) analyzed the drop size distribution (DSD) and drop shape relation (DSR) characteristics that were observed by a ground-based 2D video disdrometer and retrieved from a C-band polarimetric radar in the typhoon systems during landfall in the western Pacific, near northern Taiwan. Results also show that the heavy rain is mainly composed by small raindrops, which is mainly due to the colliding, clustering and splitting of cloud droplets in TC rainband. Moreover, a further comparison of the DSRs for different rainfall conditions indicates that raindrops were more spherical when there were high horizontal winds. The DSRs tended to be more oblate (spherical) with the increase in the rainfall rate in typhoon (nontyphoon) systems. The DSRs were primarily influenced by horizontal winds rather than the rainfall rate. Obviously, the rainfall rate and horizontal winds still cannot satisfactorily explain the variation between the DSR in typhoon and nontyphoon systems. Further sophisticated aerodynamics model study is needed to understand these factors.

To determine the extent of the vertical variability of the DSD in tropical systems, several different models of DSD shape are considered and used to estimate the rain-rate and mean-diameter profiles from the measurements made by Jet Propulsion Laboratory’s (JPL’s) airborne second generation precipitation radar (PR-2) (Haddad et al., 2006). It turns out that the vertical structures of the rain profiles retrieved from the same measurements under different DSD assumptions are similar, but the profiles themselves are quantitatively significantly different.

Conventional surface observation, with dense spread rain gauge and automated weather station, is still an important way to provide tropical cyclone (TC) rainfall basic data. An objective technique for estimating the tropical cyclone precipitation from station observations is proposed (REN et al., 2007). Based on a comparison between the Original Objective Method (OOM) and the Expert Subjective Method (ESM), the Objective Synoptic Analysis Technique (OSAT) for partitioning TC precipitation was developed by changing two fixed parameters in OOM, the thresholds for the distance of the absolute TC precipitation (D0) and the TC size (D1), into variable parameters.

KN3.2.2 **Quantitative precipitation estimation**

Radar reflectivities have been widely used to estimate the rainfall rate and distribution of TCs. Some techniques have been developed to find the relationships between radar rainfall and true rainfall (Ji et al., 2008). Rainfall can be calculated from certain algorithms from the relationship between radar reflectivities and observed rainfall, however the algorithms vary with different radar locations and rainfall properties.
Satellite measurements at microwave frequencies are key elements of present and future observing systems. Passive microwave data have been used to estimate TC precipitation. The 10.7-GHz frequency of the NASA Advanced Microwave Precipitation Radiometer (AMPR) has demonstrated high-resolution detection of anomalous surface water and flooding in numerous situations (Buckley et al, 2009). Altimeter dual-frequency measurements have also been shown to provide along-track information related to surface wind speed, wave height, and vertically integrated rain rate at about 6-km resolution. Although limited for operational use by their dimensional sampling, the dual-frequency capability makes altimeters a unique satellite-borne sensor to perform measurements of key surface parameters in a consistent way (Quilfen et al, 2009). The response of the precipitation field for tropical cyclones in relation to the surrounding environmental vertical wind shear has been investigated using 20000 snapshots of passive-microwave satellite rain rates (Wingo et al, 2010). Available for more than 20 years, passive microwave measurements are very valuable but still suffer from insufficient resolution and poor wind vector retrievals in the rainy conditions encountered in and around tropical cyclones.

On the other hand, active sensors data has been used widely to estimate TC rainfall since Tropical Rainfall Measuring Mission (TRMM) satellite with Precipitation Radar on board, launched on Nov. 1997. Chen et al (2006) researched the effects of vertical wind shear and storm motion on TC rainfall asymmetries deduced from TRMM. Study results from Yokoyama et al (2008) show that three-dimensional rain characteristics of tropical cyclones (TCs) are statistically quantified, using TRMM data from December 1997 to December 2003.

Launched in April 2006, the National Aeronautics and Space Administration Earth System Science Pathfinder (ESSP) CloudSat mission began making significant contributions toward broadening the understanding of detailed cloud vertical structures around the earth. The CloudSat’s sensitivity to cloud droplets has proven very useful in profiling TC inner-core cloud and precipitation structure, thus has potential capability to estimate TC rainfall (L’Ecuyer et al, 2007; L’Ecuyer et al, 2008).

To evaluate the abilities of satellite retrievals in reflecting precipitation features related to tropical cyclones (TCs) affecting mainland China, four years of 6- and 24-h precipitation retrievals from three datasets, namely the TRMM satellite algorithm 3B42, version 6 (3B42), Climate Prediction Center morphed (CMORPH) product, and the Geostationary Meteorological Satellite-5 infrared brightness temperature (GMS5-TBB), are compared statistically with direct measurements from surface rain gauges during the periods affected by TCs. The results show that in a general sense, all three satellite-retrieved rainfall datasets give quite reasonable 6- and 24-h rainfall distributions, with skill decreasing with the increase in both latitude and rainfall amount.

However, the vast majority of methods developed for deriving cloud and precipitation information from satellite measurements is highly sensitive to model parameters, which merely reflects the underconstrained nature of the problem and the need for other information in deriving solutions (Stephens and Kummerow, 2007). To mix together data from different sources with certain data processing technique may reduce model error. The combination of active and passive measurements offers
much hope for improving cloud and precipitation retrievals.

TRMM Multisatellite Precipitation Analysis (TMPA) provides a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales (0.25° × 0.25° and 3 hourly) (Huffman et al., 2007). Early validation results show that the TMPA provides reasonable performance at monthly scales. At finer scales the TMPA is successful at approximately reproducing the surface observation–based histogram of precipitation, as well as reasonably detecting large daily events.

Ebert et al. (2007) have been performing daily validation and intercomparisons of several operational satellite rainfall retrieval algorithms over Australia, the United States, and northwestern Europe since late 2002. Short-range quantitative precipitation forecasts from four numerical weather prediction (NWP) models are also included for comparison. Results shows that the satellite-derived estimates of precipitation occurrence, amount, and intensity are most accurate during the warm season and at lower latitudes, where the rainfall is primarily convective in nature. In contrast, the NWP models perform better than the satellite estimates during the cool season when nonconvective precipitation is dominant. An optimal rain-monitoring strategy for remote regions might therefore judiciously combine information from both satellite and NWP models.

**KN3.2.3 Quantitative precipitation forecast**

(1) Statistical models of TC QPFs

a. R-CLIPER and PHRaM

In the R-CLIPER model, a climatological rainfall rate is determined and then integrated along the storm track. The sample including nearly all U.S. landfalling tropical storms and hurricanes from 1948 to 2000 was used to construct the model. Based on the relationship, an accurate estimate of the storm rainfall rate can be considered a function of radius from the storm center and of the time from when the storm center moved inland (Tuleya et al., 2007). Additionally, to include the tendency for higher rain rates for stronger storms (e.g., Lonfat et al. 2004), a comprehensive satellite climatology of tropical cyclone rainfall rates determined from the Tropical Rainfall Measuring Mission (TRMM) was used.

It is noted that, compared with the GFDL model, the R-CLIPER model does not take into account the influences of topography, nor landmasses, and assumes storms are symmetric. These limit the QPF ability of the model. To further improve the model, particularly to represent hurricane rainfall asymmetries, Lonfat et al. (2007) developed a Parametric Hurricane Rainfall Model (PHRaM) which builds on the original R-CLIPER algorithm and includes parametric representations of the shear and topography effects.

Comparisons of the three model (R-CLIPER, PHRaM only with wind shear effects, and PHRaM) outputs with observations for 2004 U.S. landfalling storms show that both the shear and the shear plus topography models improve upon the operational
Accounting for shear alone minimally increases the prediction skill, while modeling the shear and topography effect leads to significant improvement in many cases, doubling the skill for some metrics. However, the enhancement of rainfall due to flow convergence along the coasts, the cross-track shift in the rainfall distribution during extratropical transition, and extreme accumulations of rainfall in rainband echoes over specific regions a few hundred kilometers from the storm center are need to further address in the model.

b. The Climatology Model for Typhoon Rainfall in Taiwan

Since most of the disasters caused by typhoons in Taiwan were due to the torrential rain that caused floods, landslides or debris flows, a climatology model for QPF during typhoon periods was developed by Lee et al. (2006).

The basic consideration in developing the climatology model was that the terrain slope lifting of the typhoon circulation played one major role in determining the rainfall amount besides the rainfall variations with radius. The model comprises of a set of rainfall climatology maps, one for each rainfall station. To construct the rainfall climatology map for a rainfall station, all the hourly rainfall data (including no rain) at a given station when typhoon centers were within a 0.5° latitude × 0.5° longitude grid box were averaged and shown at that grid box. After the rainfall climatology map for a station had been constructed, the hourly rainfall amount at that station could be estimated for a given typhoon center. During the typhoon period, the hourly rainfall at the station can be computed for every hourly center position along the forecasted typhoon track. The cumulative rainfall at each station, especially where it is vulnerable to debris flow, during the whole typhoon period can then be computed. The distribution of cumulative rainfall around the whole island during typhoon period thus can be produced from computed data at the 371 rainfall stations. Besides the rainfall stations, the rainfall climatology maps for 32 river basins were also developed.

Verification indicated that this climatology model could provide reasonable cumulative rainfall estimate for each river basin and around the whole Taiwan, if a well forecasted typhoon track was given. However, it was noted that the climatology model could only give the average condition, thus any deviations from the average condition inherent in the individual cases would appear as errors when the climatology model was applied during real-time operation. Recently, several improvements were conducted for this model, including an increase in the grid spacing, and using different rainfall thresholds on each grid based on distinctive characteristics of TCs.

c. The TC QPF based on a Dynamic Similarity Scheme

Zhong et al. (2009) developed a dynamic similarity scheme for TC QPFs. This model statistically considered the dynamic evolution of TC features and associated environmental fields, particularly taking account for the corresponding similarity after forecast time. The 6-12 h change of TC parameters before the forecast time, and the numerically predicted environmental fields at 12, 24, 36, and 48 h after the forecast time are chosen to conduct the QPF.

A group of TC parameters related tightly to TC precipitation is selected to estimate the
dynamic similarity, such as the initial location, intensity, and movement of TCs, sea level pressure, temperature, and so on. Another group of environmental fields is also introduced in the scheme, such as lower and upper winds, mid-level steering flow, low-level humidity, vertical velocity, etc. As a result, the sum of 15 parameters is considered to produce 28 criteria of similarity, which are then used to form a similarity parameter. This similarity parameter corresponds to a uniform standard utilized to determine the similarity of a variety of criteria. It is noted that, through the similarity parameter, samples with more similarity are given high weights, while those less similar samples are of reduced weights, suggestive of the isolation of the similarity degree of the historical samples.

The QPF for two typhoons using this model revealed that the 6-h rainfall forecast prior to 36 h was significantly better than the results from the most similar sample, but it became worse after 36 h. This suggests that the forecast errors increase with the increasing forecast time, resulting possibly from very huge differences existing in some samples with the increasing forecast time, and the prediction from several extreme samples being damped.

(2) TC QPFs based on satellite and radar detection

a. eTRaP

To address the need for cyclone-related heavy rainfall, the National Oceanic and Atmospheric Administration’s (NOAA) Satellite Data and Information Service (NESDIS) has been producing operational areal Tropical Rainfall Potential (TRaP) forecasts for landfalling tropical cyclones since the early 2000’s. TRaP forecasts (called TRaPs herein) are essentially 24h extrapolation forecasts of satellite-estimated rain rates that give the expected location and intensity of the rain maximum as well as the spatial rainfall pattern (Kidder et al. 2005). Results from both validation studies (Ferraro et al. 2005; Ebert et al. 2005) suggest that the errors in TRaP forecasts are more likely to be related to errors in satellite rain rates and the assumption of steady state rainfall than to errors in operational track predictions. One way to reduce the random error is to average several forecasts together in an ensemble. In principle an ensemble TRaP (abbreviated eTRaP) can be made up of forecasts using observations from several microwave sensors, initialized at several observation times, using several different track forecasts.

Kusselson et al. (2010) further improved the eTRaP, mainly including new sensor weights of 1.0 for AMSU and TRMM, and new weights for forecast latency. Kusselson et al. (2010) also pointed out that many improvements could still be made to eTRaP. One enhancement was to include additional types of rainfall forecasts in the ensemble, such as R-CLIPER and/or NWP results. Other improvements to eTRaP would involve modifications to the TRaP forecasts themselves. Topographic enhancement of TRaP land-based rainfall estimates could be included to increase rainfall in upslope flow and reduce it in downslope flow. The existing TRaP scheme does not include storm rotation; this would be a valuable improvement to increase the physical realism of the forecasts. Liu et al (2008) included estimates of storm rotation from geostationary cloud drift winds in past TRaP extrapolation forecasts and found that this one enhancement alone reduced the mean absolute errors by 40%
compared to original TRaP forecasts for tropical cyclone rainfall over Taiwan.

b. SWIRLS

The Hong Kong Observatory developed a rainstorm nowcasting system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) to monitor and predict local rainfall distribution trends within the next couple of hours.

In SWIRLS, the motion vectors of rain echoes between successive radar reflectivity images at 6-min interval are determined by the TREC (Tracking Radar Echoes by Correlations) technique (Tuttle and Foote 1990). At the same time, echo intensity is calibrated dynamically in real time against surface rainfall as measured by a dense network of raingauges in Hong Kong. Armed with the latest information on rain movement and intensity, QPF in the coming hours is obtained by advecting the radar echoes forward in time. To reduce pattern deformation during the integration period, a modified semi-Lagrangian advection scheme has been introduced in SWIRLS. The scheme is based on Robert’s 3-step iterative, bi-cubic interpolation integration algorithm (Robert 1982) with flux limiters employed (Bermejo and Staniforth 1992).

(3) TC QPFs based on numerical weather prediction models

a. Data assimilation

Initial conditions significantly affect the prediction by numerical models. In particular, a poor representation of a TC in the initial condition can lead to poor or even unsuccessful forecasts of the TC structure, and thus false QPFs for the TC. More recently, many studies focused on radar data assimilation used for TC QPFs.

Xiao et al. (2006) introduced a radar reflectivity data assimilation scheme within the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) three-dimensional variational data assimilation (3DVAR) system. The model total water mixing ratio was used as a control variable. A warm-rain process, its linear, and its adjoint were incorporated into the system to partition the moisture and hydrometeor increments. The observation operator for radar reflectivity was developed and incorporated into the 3DVAR. The results revealed that assimilation of Doppler reflectivity data improved the inland short-range QPF skill. The positive impact appeared mainly in the first 3-h forecast. A noticeable positive impact on the rainfall forecast was observed for up to 12 h when both radial velocity and reflectivity data from onshore Doppler radar were assimilated into the typhoon’s initial conditions.

Zhao and Jin (2008) also investigated the role of radar data assimilation in the QPF for hurricane Isabel (2003). Radar observations of reflectivity and Doppler radial velocity from five WSR-88D radars in the landfall area during the hurricane landfall period were collected and assimilated into COAMPS using a variational approach. This largest improvement in precipitation forecasts mainly occurs along the path of the inner-core region during the hurricane landfall, where significant improvements in hurricane dynamical structures by radar data assimilation have been observed. Zhao and Xue (2009) assimilated the Z and Vr data from two coastal operational WSR-88D
radars to investigate the QPF for the landfalling Hurricane Ike (2008), using the ARPS 3DVAR and cloud analysis package through 30-min assimilation cycles. The prediction with both the Z and Vr data assimilated also represented highest equitable threat scores of rainfall in the first 10 h.

Additionally, airborne Doppler radar data were also used in assimilation to improve TC QPFs. Pu et al. (2009) used airborne Doppler radar data collected during the NASA Tropical Cloud Systems and Processes (TCSP) field experiment in July 2005 to examine the impact of airborne radar observations on the short-range numerical simulation of hurricane track, intensity changes, as well as rainfall. Both radar reflectivity and radial velocity–derived wind fields were assimilated into the Weather Research and Forecasting (WRF) model with its three-dimensional variational data assimilation (3DVAR) system. When both reflectivity and wind data are assimilated, the model produces the rainfall amount that is much closer to the TRMM observation. Larger impact on the precipitation forecasts from the assimilation of wind data might be caused by the improved vortex inner convergence and divergence and modified convection conditions in the initial.

b. Wet Q vector interpretation technique (WQVIT)

Yue et al. (2007) developed a new WQVIT for TC QPFs. In the method, the vertical motion $\omega_1$ can be obtained by solving the omega equation whose forcing term is the dry ageostrophic Q vector divergence based on the successive relaxation method. The wet Q vector divergence can then be calculated. Then vertical motion $\omega_2$ can be obtained by solving the omega equation whose forcing term is the wet Q vector divergence also based on the successive relaxation method. Finally, precipitable water is calculated on the basis of the calculated $\omega_2$ and vapor. This technique was applied to the results derived from the Eastern China regional numerical prediction model which is based on the MM5 model. It was indicated that the WQVIT was superior to the MM5 model in predicting 24-h rainfall with magnitude > 10 mm through investigating QPFs of a TC case. Furthermore, analysis showed that the test scores and forecast accuracy of the wet Q vector interpretation forecast were obviously higher than the counterpart of MM5. Meanwhile, the false alarm and miss rates of the wet Q vector interpretation forecast were much lower than those of the MM5.

(4) Superensemble QPFs for TCs

Application of the superensemble technique to regional precipitation forecasts has shown the ability to generate more accurate forecasts pinpointing the exact locations and intensities of strong precipitation systems. Cartwright and Krishnamurti (2007) introduced a regional superensemble consisting of 12–60-h daily quantitative precipitation forecasts from six models. The computation of the superensemble forecast required a training and a forecast phase with all member models and observations available. The superensemble utilized approximately 360 different 60-h forecasts from the multimodel forecasts. Using the 360 multimodel forecasts, which include the selected numerical weather prediction models for 60 forecast days, and the best estimate of the respective observed rainfall estimations, a simple linear multiple regression was computed to determine the statistical weights. Each of these weights described the model biases at each geographical location for each
participating model. The superensemble technique used a regular multiple regression method to obtain the regression coefficients for each ensemble forecast at each grid point for each forecast time.

A comparison of the QPFs of Tropical Storm Bill (2003) from the superensemble and all six member models suggested that the superensemble tended toward improving the member model forecasts by reducing the overestimation of light rain and adding a significant rain forecast that most of the member models miss. The average ETS for the 12- and 24-h forecasts illustrated that the ETSs for the superensemble were highest at the lightest and also at the heaviest rainfall thresholds. The superensemble seemingly pinpointed the locations of the most intense precipitation, which improved the ETS values.

(5) Forecasters technique for diagnosing areas of extreme rainfall

The turning of winds with height, mostly between the 850hPa and 500hPa levels, has been used by forecasters for decades to diagnose likely regions of thermal advection and thus ascent and descent, but due to its roots in geostrophic theory, the diagnostic is generally not applied in the tropics. An exception is staff at the Severe Weather Section in the Brisbane office of the Australian Bureau of Meteorology. After more than ten years of use, they have found the anti-cyclonic turning of winds with height to be an important indicator for extreme tropical and sub-tropical rainfall (Bonell and Callaghan 2008; Bonell et al. 2005; Callaghan and Bonell 2005; see also the numerous rainfall event reports at, http://www.bom.gov.au/hydro/flood/qld/fld_reports/reports.shtml).

Kevin Tory from the Centre for Australian Weather and Climate Research has demonstrated that the turning winds with height diagnosis of thermal advection and associated ascent and descent behaviour are equally valid for winds in near gradient balance, which includes most tropical rain bearing systems. An explanation for such facts is given in Topic 2.3. A more detailed description of the diagnostics displayed here is presented in Topic 1.1.

The diagnostic technique have been used to investigated several extreme rainfall events associated with tropical cyclones around the globe such as typhoon Bilis (2006), Hurricane Mitch (1998), and Tropical Storm Chataan (2002) etc. Results show that the heavy rainfall area was associated with warm air advection at 700hPa.

KN3.2.4 Hydrological Perspective on QPE/QPF

The basic structure of a hydrological service system involves data inputs, model’s response and product outputs. For the outputs aiming to the especial purposes, the requirements to the data inputs may be variable on the spatial and temporal scale as mentioned above.

Precipitation inputs, including real time observation and whether forecasting, are used in hydrologic runoff and snow-melt models to generate estimates of rates and stages of streamflow or used in flash flood prediction models to issue early warning of rainfall-triggered sediment disasters. Therefore, hydrometeorological inputs,
generally, and precipitation inputs, specifically, strongly influence real-time hydrologic forecasts. Hydrometeorological inputs consist of quantitative precipitation estimations (QPEs), satellite-based precipitation measurements, and quantitative precipitation forecasts (QPFs). The accuracy of hydrologic products is largely dependent on the accuracy of QPE and the skill of QPF.

Historically, precipitation analysis operations in hydrological models/methods have been based on interpolation of gage observations to mean areal precipitation (MAP) within individual hydrologic basins. Nowadays, with an abroad application of weather radars and satellite images, the radar-based precipitation processing system and satellite-based precipitation processing system are developed and applied. Accordingly, the finer spatial and temporal scales precipitation products (QPE/QPF) would be available and applicable for better hydrological service.

As hydrological traditional model, the lumped modeling are commonly used as main approaches in the real time operational flood forecasting, in which where the catchment behaviour is described by catchment scale parameters as a unit. The spatial resolution is linked to the schematization of the basin, which can be considered as a single element or an ensemble of sub-basins. In order to get the appropriate model's parameters, a large river basin is usually divided into several or decades forecasting catchments based on the feature of topographic and geographic, type of soil, vegetation, the distribution of rainfall and hydrological observation stations, and the river system in the basin. The magnitude of the catchment area is usually variable from $10^2$ to $10^3$ km$^2$. At present, the lumped models are dominative in hydrological service.

As a new approach of hydrological modeling developed with development of Digital Earth, the distributed modeling describes the hydrologic processes at small scale and then adding these up and routing the flows through the landscape by taking an explicit account of spatial variability of processes, input, boundary conditions, land use and watershed characteristics provided by Digital Elevation Models (DEM). The scale of model grid can vary from $10^1$m x $10^1$m up to $10^3$ m x $10^3$m with the catchment area and the purpose of modeling. Considering the limitation of DEM and the computing speed, the solution of 1km x 1km ~ 4km x 4km is usually adopted in the real-time operational use.

Model resolution has been at the center of a debate in the hydrologic community about the advantages/disadvantages of lumped versus distributed models. One side of the debate notes that lumped models create coarse but accurate results, even though they do not effectively represent spatial variability of hydrologic processes, or intra-basin differences in elevation or terrain. Distributed models are designed to work at spatial and temporal scales finer than lumped models.

The other side of the debate, the argument in favor of distributed models, posits that because distributed models can account for differences in site specific characteristics, including basin size, topography, land cover. It has not been popularly used in hydrological service yet because the precipitation inputs (QPE/QPF) do not meet the needs of spatial and temporal resolution of hydrologic models.
For catchment hydrological forecasting, the basic meteorological inputs are rainfall and potential evapotranspiration (optional). The requirements on QPE and QPF for catchment hydrological forecasting may be described as following: (a) As input of the hydrological lumped modeling, the 6 hourly QPEs/QPFs with the lead-time of 1-3 days are required to be downscaled to the desired catchment-scale ($10^1$-$10^3$ km$^2$). (b) As input of the hydrological distributed modeling, the hourly QPEs/QPFs with the lead-time of 1-3 days are required to be downscaled to the desired grid (less than $10^1$ km x $10^1$ km). The rainfall in the period of the lead-time of flood forecasting will become the most important factor for the decision-making at the emergency moment, even though only several millimeters. Therefore, the accuracy of QPF is judged crazily sometimes.

For sediment disaster forecasting and warning, QPE, nowcasting and QPF with short time-interval (normally 10-minute, 30-minute, 1-hour rainfall, etc) are expected. Even though minutes lead-time (nowcasting products) would play very important role in sediment disaster reduction, especially mortality risk reduction.

For flash flood forecasting and warning, it is expected that the precipitation analyses in a “basin world”, which means all calculations are done over the areas of small basins. The spatial scale of QPE/QPF is expected to be at 1km x 1km grid resolution. This gridded precipitation is then converted to Mean Area Precipitation (MAP) for a predefined set of watershed boundaries. The requirements on QPE/QPF for flash flood prediction could be described as (1) improved accurate high-resolution seamless hourly QPE; (2) hourly nowcasting; (3) hourly high quality seamless QPF.

For dam operation, hourly or 6-hourly QPE and QPF are essential and vital for the purpose of flood regulation, daily QPE and QPF would be enough for water resources regulation. One-day lead-time might be sufficient for small-scale reservoirs. However, 1-3 days, even one-week lead-time would be required for medium- and large-scale reservoirs which have to take charge of the objective of flood control for its downstream.

KN3.2.5 QPF/QPE operational development

(1) QPF/QPE systems

Based on FY2C stationary satellite data, TBB gradient, offset of cloud body and its moving speed etc. are selected to build regression equation to estimate TC rainfall in China. Blending the estimated rainfall rate and rain gauges, TC rainfall distribution products at 0.1º x 0.1º resolution over China are made in 1 hr, 3 hr and 24 hr intervals. Besides, a Multimodel Ensemble QPF System has been developed to estimate TC rainfall by Chinese Meteorological Center. Similar disparity parameter and gradual classification method are used to analyze the outputs from different operational models such as T639, EC, JMA and NCEP etc, provide QPF products of TC rainfall within 24 hr.

In USA, Tropical Rainfall Potential (TRaP) system takes the latest microwave rain rate data from DMSP, SSM/I, AMSU, or TRMM/TMI and performs an extrapolation of the rain rate values based on the latest forecast track and speed of the storm.
Ensemble Tropical Rainfall Potential Product (eTRaP) is a simple ensemble of 6-hourly TRaP, in which a satellite “member” is included when its path passes over the TC, and “members” are weighted according to age of pass and past performance of sensor. It provides products 4 times a day at 0315, 0915, 1515, and 2115 UTC. Besides, R-CLIPER (Rainfall Climatology and Persistence Model), which is a statistical model developed from TRMM TMI data and rain gauges, creates a rainfall swath at $0.25^\circ \times 0.25^\circ$ resolution with hourly output dependent on storm track, speed, intensity, and size. Recently, R-CLIPER is improved including shear and topographic effects.

JMA Ensemble Prediction System (EPS) includes Weekly EPS and Typhoon EPS, and the main differences between the two are singular vector (SV) target area and operational form. The initial conditions of ensemble member are defined by adding (subtracting) initial perturbation, which is generated by SVs to the control analysis field.

Hong Kong Observatory develops a nowcasting rainstorm forecasting system called RAPIDS (Rainstorm Analysis & Prediction Integrated Data-processing System) to blend or merge the SWIRLS with NWP. SWIRLS makes use of raingauge data over Hong Kong to calibrate radar reflectivity in real time, however, it becomes less skillful with time when the rainstorm motion is erratic or when echoes develop or dissipate rapidly. On the other hand, NWP models usually suffer from the intrinsic ‘spin-up’ problem, hence hindering reliability of numerical prognoses in the first couple of hours. RAPIDS incorporates the best features of SWIRLS and NWP forecasts to generate an optimal QPF for operational guidance in rainstorm situations.

Microwave provides good estimates of rain rate but poor sampling (a few times a day), while geostationary IR provides great sampling but poor rain rate estimates. QMORPH merges the two by using IR cloud motion vector to transport microwave precipitation features for increased temporal resolution.

(2) Verification for TC QPFs

It is generally accepted that QPSs must first be validated against observations to identify model limitations and biases and possible areas for improvement in the forecasts. Standard QPF validation techniques, such as bias and equitable threat scores (ETSs), can be used to assess some aspects of TC QPFs. However, an additional set of QPF validation techniques specific to TCs is needed in order to evaluate the ability of the models to predict rainfall attributes unique to TCs, such as the extreme rain amounts so often responsible for the death and damage accompanying landfall (Marchok et al. 2007).

Marchok et al. (2007) developed and tested a QPF validation scheme specifically designed to objectively evaluate model rainfall forecasts for landfalling TCs. It consisted of pattern matching, mean rain and distribution of rain flux, and extreme rain amounts. These skill indices were utilized to validate model ability to match the large-scale rainfall pattern, to match the mean rainfall and the distribution of rain volume, and produce the extreme amounts often observed in TCs. For each skill index, the associated algorithm will assign a value ranging from 0 for no skill to 1 for
the most skill.

Using the QPF skill indices, validation of TC QPFs for the storms in the 1998–2004 samples was conducted. It suggests that, for the pattern matching, the GFS had the highest skill, although all of the numerical models (GFS, GFDL, NAM) had skill relative to R-CLIPER. The GFDL had the lowest skill among the dynamical models for pattern matching. The NAM model scored better than the GFDL in this metric due to the higher mean correlation coefficient for the NAM model described above. For the mean rainfall and distributions of rain flux, the skill indices for all of the dynamical models were very similar, but the GFS had a slight edge. All of the models have skill relative to the R-CLIPER. For the extreme rain amounts, the GFS has the highest skill. The GFDL produces too much of the heaviest rain, but both the GFDL and GFS have skill relative to R-CLIPER. The NAM has no skill relative to R-CLIPER, due mainly to its inability to produce the extreme rain amounts observed in the core.

KN3.3 Recommendations

To meet the needs of TC-related disaster mitigation, observational and forecasting techniques relating to heavy rainfall caused by LTCs still require urgent improvements and significant development.

Heavy rainfall and flooding caused by LTCs are recognized as extreme weather events, but the science behind the behaviors of LTC rainfall is not currently understood to a great enough extent.

For numerical modeling, differences in the resolution and microphysical parameterization likely cause distinct QPFs. Further improvements in microphysical and boundary layer parameterization are required to obtain successful TC QPFs.

For data assimilation, more realistic microphysics scheme needs to be included in the radar data assimilation.

One of the major reasons for the slow pace of improvement in TC QPFs may be deficiencies in the collection and assimilation of real-time inner core data into numerical weather prediction models. Due to cloud and rain effect, satellite retrieved products usually have large uncertainties under cloudy and precipitating areas, thus most of the cloudy and rain-effected data are rejected during the quality control procedures in data assimilation.

The QPE and QPF could be strengthen through an end-to-end evaluation that assesses QPE/QPF quality and impacts on flood and streamflow products for basins of diverse size and topography. Hydrologists could be encouraged to work with QPE/QPF groups to ensure the hydrologic requirements for precipitation can be considered.

Coupled hydrological–meteorological models should be constructed in a manner that permits prediction of the time and space distribution of both the rainfall and the resultant flooding.
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