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Using NWP Analysis in Satellite Rainfall Estimation of Heavy Precipitation Events over Complex Terrain

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Using NWP Analysis in Satellite Rainfall Estimation of Heavy Precipitation Events over Complex Terrain

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B.S., Nanjing University of Information Science & Technology, China, 2007

A Thesis

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Using NWP Analysis in Satellite Rainfall Estimation of Heavy Precipitation Events over Complex Terrain

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Abstract

This study investigates the use of Weather Research and Forecasting (WRF) high-resolution storm analysis in satellite rainfall estimation over complex terrains. Rainfall estimation here is based on the NOAA-Climate Prediction Center morphing (CMORPH) product. Specifically, CMORPH rainfall is adjusted by applying a power-law function whose parameter values are obtained from the comparison between WRF and CMORPH hourly rain rates. Results are presented based on the analyses of five storm cases that induced catastrophic floods in southern Europe. The WRF-based adjusted CMORPH rain rates exhibited improved error statistics against independent radar-rainfall estimates. We show that the adjustment reduces the underestimation of high rain rates thus moderating the strong rainfall magnitude dependence of CMORPH bias. The higher Heidke skill scores for all rain rate thresholds indicate that the adjustment procedure meliorates CMORPH rain rates to provide a better estimation. Results also indicate that the missed rain detection of CMORPH rainfall estimates are also identifiable in the WRF-CMORPH comparison, however, the herein adjustment procedure does not incorporate this effect on CMORPH estimates.

Key words: satellite rainfall estimation, numerical weather model, rain rates adjustment, complex terrains.
1 Introduction

The catastrophic precipitation events occurring over complex terrain regions have very high tendency to trigger devastating flash-floods along with subsequent hazards such as landslide or debris flows, and consequently bring substantial impacts on society. Flash-flood forecasting has been a very important topic in hydrologic research. One of the crucial prerequisites for establishing a reliable hydrologic modeling for flash floods is to gather accurate precipitation data for the flood simulation.

Accurate rainfall forcing is needed to enhance the predictive accuracy of flash floods from a distributed hydrologic model. However, there is no perfect precipitation measurement method that can provide accurate rainfall data over extensive areas. Generally, the network of rain gauges furnishes the most accurate observation, but at discrete locations, which cannot represent the rainfall processes over large domains, particularly when this includes complex orography. Radar-derived precipitation is always considered as a reliable data source to obtain the rainfall values over an area. But the area covered by radar is still limited and the radar reflectivity may encounter beam blockage issue due to the topographic effects (Maddox et al. 2002). Satellite-retrieved precipitation data can cover very large region globally but it is still not ideal since the satellite observation is often influenced by the atmospheric or topographic effects and other technical factors (Tang et al. 2012).

There is a broad consensus being demonstrated by many researches that high intensity rainfall rates tend to be underestimated by satellite retrievals. Kidd et al.
(2012) investigated several satellite retrievals over northwest Europe, including the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA); the Climate Prediction Center (CPC) morphing (CMORPH) technique; the CPC merged microwave technique; the Naval Research Laboratory (NRL) blended technique and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) technique. Their results show that the precipitation values are substantially underestimated by most of the satellite techniques over the most complex topography. Prat et al. (2010) evaluated the TRMM precipitation estimates against rain gauge data in the Southern Appalachian mountains and found a -27% overall rain rate bias. It was also shown that TRMM has limited performance of detecting light rainfall events (0.1-1mm/h).

Although the satellite-rainfall exhibit significant uncertainty, it is worth to investigate the feasibility of using these estimates as input rainfall data for hydrologic models since satellite has the coverage advantage particularly over the complex terrain areas where rain gauge networks and radar observations are limited. Nikolopoulos et al. (2010) tested the performance of TRMM 3B42 (resolution: 0.25°-3h), KIDD-4km (4km-1h, Kidd et al. 2003) and KIDD-25km (25km-3h) satellite data on flood simulations for a mountainous region in NE Italy. They concluded that both the satellite data resolution and basin scale have significant influence on the accuracy of satellite rainfall estimation. In all simulations, the high resolution satellite data provided better outputs than the coarser one. In another recent study, Nikolopoulos et al. (2012) applied bias
adjustment on the CMORPH, PERSIANN and 3B52 satellite rainfall datasets using area-average radar data over northern Italy and then forced a distributed hydrologic model with both the original and adjusted satellite datasets. Neither of these satellite datasets could lead the hydrologic simulations to capture the flood events, which indicated that the adjustment procedures need to be meliorated or the satellite rainfall adjustments need to be improved according to the unique topography conditions.

Besides the precipitation observation methods, there is an alternative approach to obtain precipitation estimates——numerical weather prediction (NWP) quantitative precipitation forecasts, whose simulated precipitation outputs can be employed by a hydrological model for generating flood predictions. Nevertheless, the precipitation estimates or forecasts derived from NWP are also not accurate enough especially in terms of the location and timing of the storm dynamics. Generally, NWP is good at the estimation of synoptically forced rainfall while satellite is good at convective rainfall observation (Ebert et al. 2007).

Since each precipitation data source has its own advantages and shortcomings, it is possible to combine different types of precipitation estimates for the purpose of acquiring data with better accuracy. For example, Papadopoulos et al. (2008) forced an atmospheric mesoscale model with radar rainfall data in order to get better simulation results using improved information on the models land surface processes. Moreover, Huffman et al. (1995) meliorated the rainfall fields by combining multi-satellite field and the rain gauge analysis, then filled the data voids with estimates from the numerical model. Zupanski et al. (2011)
demonstrated use of a cloud-resolving NWP model combined with data assimilation for downscaling satellite rainfall estimates for hydrological applications.

However, the current approaches of rainfall datasets integration are mainly focusing on combining different types of observed datasets or the assimilation of rainfall observations into NWP. The objective of this study is to assess the feasibility of adjusting satellite precipitation estimates over complex terrain for extreme storm cases using NWP simulated precipitation data as reference, and then evaluate the performance against ground-radar rainfall estimates for five flash flood inducing storm cases. High-resolution storm simulations are performed using the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005) while satellite rainfall estimates are from the NOAA-Climate Prediction Center morphing (CMORPH) product technique (Joyce et al. 2004). Description of the study area and data sources is provided in Section 2; followed by the description of WRF setup in section 3. Section 4 contains the methodology of the adjustment procedure. Section 5 discusses the results from the five storm cases. The conclusions are provided in Section 6.

2 Study area and data

2.1 Study area

Three areas (Figure 1) associated with complex topography are selected for this study. These regions are located on the Italian Alps and the Massif mountain range that exhibit frequent heavy precipitation and floods. Recent study (Mehta,
et al., 2008) about the Mediterranean Basin indicates that maximum precipitation has maximum frequency and accumulation over the mountainous regions according to satellite measurements. The areas along the Alpine foothills and the southern flanks of Massif Central mountains are particularly under the influence of extreme rain accumulations because the air from the Mediterranean sea brings sufficient moisture and the mountain windward slope helps the lifting condensation process therefore leading to heavy rains and snow storms (Frei et al. 1998; Nuissier et al. 2008).

Five major storm cases in Northern Italy (three cases) and Southern France (two case) that produced flash floods in three target basins, Fella and Sesia (North Italy) and Gard (Southern France), were selected to evaluate quantitative precipitation estimation by CMORPH and potential improvements gained by adjusting CMORPH estimates using rainfall fields derived from WRF. Evaluation of the rainfall estimates in all three areas is based on high-quality rain gauge-calibrated radar rainfall estimates, which is discussed in the next section.

The Fella area is located at the Friuli-Venezia Giulia region in northeastern Italy adjacent to northwestern Slovenia and southern Austria. The area represents sub-Mediterranean Alpine climate. This type of climate exhibits more humid summer than the typical Mediterranean climate. The Sesia area is located at northwestern Italy. It contains the Sesia river basin and is featured by unique topographies. The bottom-right part of the study area is the Alpine foreland region, while the top-left includes a portion of the central chain of western Alps. This region also belongs to the sub-Mediterranean zone and exhibits a similar climate
type as the Fella. The Gard area, on the other hand, is located in south-central France that is over the southeastern edge of Massif Central mountain ranges. Although the elevation of this area is the highest among the Massif Central mountain ranges, it is still much lower than the main Alps chain. This represents a typical Mediterranean climate featured by hot, dry summers and cool, wet winters. The fall season in the area exhibits the highest rainfall rates and accumulations due to frontal systems and mesoscale convective systems (MCSs) occurring in the area.

2.2 Precipitation data

Table 1 summarizes the basic information of the five storm events used in this study. The durations of these events vary from 12 hours to 4 days and each of the cases encountered extremely heavy precipitation and flooding. The Fella2003 case accumulated max rainfall of 343 mm within 12 hours with ~20% of the hourly rain rates exceeding 10 mm. The impact of this heavy precipitation was enhanced by the complex terrain over Fella basin resulting in a series of subsequent hazards (floods and landslides). The two Sesia cases reached maximum rainfall accumulations of 253 mm and 353 mm, respectively. The largest maximum rainfall accumulation out of the five events (409 mm) occurred in Gard2008 case. This two-day event had only 5% of the hourly rainfall rates being greater than 10 mm. Comparing to the above cases, Gard2007 event was relatively mild occurring over a four-day period and exhibiting 294 mm of maximum rainfall. However, most of the precipitation of Gard2007 was
accumulated during the last 20 hours of the event. The rainfall intensities of this event were also high and triggered a destructive flash-flood.

The precipitation datasets for each storm case consist of three sources: satellite-rainfall from CMORPH, rain gauge-calibrate radar rainfall, and simulated rainfall fields from WRF. Table 2 summarizes the resolutions of each data source. Following is a further description of satellite and radar data. The WRF simulations are discussed in the next section.

The satellite rainfall is from CMORPH technique, which is a global precipitation dataset with 8 km spatial resolution (at the equator) and half-hourly temporal resolution. CMORPH technique is using the passive microwave (PMW) observations obtained from low orbiting satellite platforms whose motion vectors are propagated by the geostationary Infrared (IR) data (Joyce et al. 2004). PMW observations give more accurate precipitation estimates while IR data preforms well at capturing the movement of the precipitation system. CMORPH is a combination scheme exploiting the advantages of both PMW and IR data (Kidd et al. 2012). However, there are certain imperfections in the CMORPH algorithm (Joyce et al. 2004): (i) the current time interpolation process of morphing precipitation features is using a linear method, which may be improved by adding a Kalman filtering technique; (ii) the algorithm misses precipitation that forms and develops over an area between PMW overpasses; (iii) the current snow-screening process gives nonzero rainfall estimates to the snow or ice areas thus causing inauthentic observations over these areas where are usually the mountainous complex terrains, etc. These deficiencies bring uncertainties to the
CMPORPH precipitation estimates and therefore provide even more uncertainties to the flood prediction results if CMPORPH estimates are used as input to a hydrologic model.

The radar-rainfall data of Fella2003 case were obtained from a Doppler, dual-polarized C-band radar after converting the reflectivity scans to rainfall values via a Z-R relationship. Several procedures were applied to correct for ground clutter, partial beam blockage and atmospheric attenuation (Borga et al. 2007). The radar data of the Sesia cases were gathered from the Bric della Croce Doppler weather radar (Sangati et al. 2009). The radar-rainfall for the Gard flood cases were obtained using quantitative rainfall estimation procedures applied to weather radars of the Météo-France ARAMIS network (Delrieu et al. 2004). Although the radar precipitation estimates are not absolutely accurate due to the effects of rainfall drop size distribution, atmospheric attenuation and beam blockage effects, it is still a relatively reliable data source that can be considered as reference to evaluate the CMORPH estimated and WRF-predicted rainfall products.

3 Numerical Weather Prediction model setup

The Weather Research and Forecasting (WRF) modeling system was used to simulate the storm cases presented in the previous section. By forcing the model with both Global Forecast System (GFS) data and Local Analysis and Prediction System (LAPS) reanalysis data, WRF generated better simulations than using GFS data alone to constrain the model. GFS data is commonly used to initialize WRF simulation. The GFS data used in this study is in 1 degree spatial resolution.
and 6-hour temporal resolution. The LAPS reanalysis data were provided every 3 hours in the spatial resolution of 15 km. LAPS reanalysis represents a regional dataset covering a large portion of northern Africa, Europe and major parts of the Atlantic Ocean. The data was generated through the LAPS assimilation system using the available observations from weather stations and buoys, along with the 0.5 degree 6-hourly ECMWF analysis fields.

The WRF simulations have been performed in a two-way interactive mode with 28 vertical levels and a three-domain configuration, in which the coarsest spatial resolution is 18 km and two nested domains have the resolution of 6 km and 2 km, respectively. The domain sizes and locations are accommodated according to the different study regions. Table 3 presents the corresponding grid sizes for each storm case. The major physical parameterizations used in these model simulations are shown in Table 4. These physical parameterizations are consistently implemented in the simulations of all five storm cases. Table 5 gives the WRF running time periods for each case. The model output files were saved for each hour.

4 Methodology

Figure 2 shows a flow chart explaining the procedures used for determining the adjustment for CMORPH estimates and the validation of those estimates against the in situ radar rainfall estimates. There are three major steps for the data processing.
4.1 Step 1: Rearrange datasets into the same spatio-temporal resolution

The first step is to bring all datasets into a common spatial and temporal resolution grid, which was selected to be 8 km and 1 hour and represents the coarsest resolution among the various datasets. For each storm case, two domains were defined for two distinct purposes: one is the fitting domain, where we determine the CMORPH rainfall adjustment parameters through comparison with WRF rainfall fields; the second is the radar domain (Figure 1), which is used to determine the error statistics.

4.2 Step 2: CMORPH adjustment

The CMORPH adjustment is based on a power-law function:

\[ Y = a \times X^b \quad \ldots \ldots (1) \]

in which ‘X’ and ‘Y’ represent the CMORPH and WRF hourly rain rates, respectively; ‘a’ and ‘b’ are parameters to be estimated over the fitting domain. These two parameters have distinct values for each storm case. The procedure for estimating the parameters is as following:

First, we define the fitting domain for each case. The fitting domains were selected according to two rules: (i) the domain should be small enough to focus on the area of the storm (see Figure 1) and therefore represent the distinctive precipitation features associated with the satellite retrieval; (ii) the domain should be large enough to contain most of the intense rainfall areas and take into account the numerical simulation misplacements. Then, a fixed cumulative distribution function (CDF) bin with cumulative probability values ranging from 5%, 10%, [...], 95% was defined to determine the corresponding WRF and CMORPH
hourly rain rate quantiles. The adjustment function is then employed to fit these WRF and CMORPH hourly rain rate quantiles using Eq. 1 and thus determining the values for parameters ‘a’ and ‘b’. Adjusted CMORPH hourly rain rates were then obtained by applying the adjustment function of Eq. 1 with the determined parameters on the original CMORPH rain rates.

4.3 Step 3: Error analysis

The error analysis in this study is provided over two domains. The analysis over the fitting domain aims to assess how well the WRF-based adjustment ameliorates the CMORPH estimates, while the analysis over the radar domain is used to independently evaluate the improvements obtained by the proposed adjustment using different error statistics.

Two statistical analyses are applied to the fitting domain data: (i) the Q-Q plot of CMORPH and adjusted CMORPH rain rates versus WRF rain rates; (ii) the bias ratio of WRF against CMORPH and adjusted CMORPH rain rates. The bias ratio is defined as the ratio of the amount of occurrences that WRF rain rates exceed a specified threshold versus the respective number from CMORPH or adjusted CMORPH data.

At the radar domain, the comparison is done between each estimator and the reference radar dataset. The estimators are the original CMORPH products, adjusted CMORPH estimates and WRF simulated rainfall. Besides the hourly rainfall time series and the Q-Q plot, two verification scores, which are the bias score (BS) and Heidke skill score (HSS), are implemented to present the performance of the estimators. To calculate these metrics, a set of hourly
precipitation thresholds were created: 1mm, 2mm, 4mm, 8mm and 12mm. Then by considering the following occurrences A, B, C and D,

A: Estimator > threshold and Radar > threshold

B: Estimator > threshold and Radar < threshold

C: Estimator < threshold and Radar > threshold

D: Estimator < threshold and Radar < threshold

BS is defined as the ratio of the number of occurrences that estimated rain rates exceed a specified threshold versus the respective number from the reference rain rates,

\[ BS = \frac{A + B}{A + C} \ldots (2) \]

HSS (Heidke 1926) is defined as the number of correct estimated occurrence minus the number of correct estimated occurrence by chance divided by the total number of estimated occurrences minus the number of correct estimated occurrence by chance,

\[ HSS = \frac{(A + D) - \frac{(A + B)(A + C) + (B + D)(C + D)}{(A + B + C + D)} (A + B + C + D) - \frac{(A + B)(A + C) + (B + D)(C + D)}{(A + B + C + D)}}{(A + B + C + D) - \frac{(A + B)(A + C) + (B + D)(C + D)}{(A + B + C + D)}} \ldots (3) \]

Eq. 3 can be simplified into,

\[ HSS = \frac{2(A \times D - B \times C)}{(A + C)(C + D) + (A + B)(B + D)} \ldots (4) \]

Technically, the range of HSS is -\( \infty \) to 1. A perfect precipitation estimator would obtain the HSS of 1, while the HSS less or equal to zero indicates the estimator gives mostly a random estimation or has less hits than a random estimation. HSS is a widely used score because it is fairly easy to compute and it may explain
more than one effect such as probability of detection, false alarm rate and occurrences by chance.

5 Results

The five storm cases analyzed in this study are distinct in terms of the spatio-temporal rain structures as well as the rainfall intensities providing a good representation of the heavy storm types occurring in complex terrain areas. Overall, WRF and CMORPH rainfall accumulations (Figure 3, Figure 7, Figure 11, Figure 15 and Figure 19) are showing similar patterns for each case. Overall, the precipitation magnitude estimated by CMORPH is generally lower than the rainfall magnitudes simulated by WRF. The Q-Q plots of WRF vs. CMORPH rain rates over the fitting domains (Figure 4, Figure 8, Figure 12, Figure 16 and Figure 20) consistently exhibit the approximate power-law type of relationship, thus the power-law fitting equation (Eq. 1) is selected to adjust CMORPH rainfall estimates. After the adjustments, adjusted CMORPH datasets are showing significant improvements by comparing to the reference radar-rainfall datasets. The results for each storm case are described next.

5.1 Fella2003 case

The Fella2003 case lasted only 12 hours with very intense rainfall mostly concentrated in the afternoon of August 29th, 2003. The CMORPH total precipitation field (Figure 3b) shows a clear rain band that crossed the northeast corner of Italy, while WRF simulation (Figure 3a) provides a similar prediction
but indicates heavier rainfall intensity at slightly shifted location. The CDF plot (not shown here) of the two rainfall estimates also points out to the CMORPH underestimation comparing to WRF.

Since the spatial pattern of WRF has shifted to the south by about 0.1 degree and to the west for about 0.4 degree, the fitting domain, which is the rectangle area encompassed by the black lines in Figure 3, has been defined much larger than the radar domain to include most of the rainfall structures in both CMORPH and WRF rainfall fields. The CMORPH vs. WRF Q-Q based regression suggests parameters $a=0.35$ and $b=1.74$ for the power-law equation.

The adjusted CMORPH rainfall is then calculated by applying the power-law function on the original CMORPH data. Figure 4 shows a significant improvement for the adjusted CMORPH rainfall over the fitting domain. The Q-Q plot (Figure 4a) shows a near-linear relationship between adjusted CMORPH and WRF hourly precipitation. The bias ratios (Figure 4b) between WRF and adjusted CMORPH precipitation are consistently near 1, while the original CMORPH data exhibit a severe rainfall-magnitude dependence with underestimation at the higher rainfall thresholds and overestimation at the low rainfall thresholds, which is consistent to the findings by (Nikolopoulos, Anagnostou, & Borga, in press). The above comparisons using WRF as reference indicate that the adjusted CMORPH data have been meliorated and acting better than the original CMORPH data. For purpose of verifying CMORPH’s actual improvement, we will use the independent radar data as reference and compare all the estimators, including
WRF, CMORPH and adjusted CMORPH dataset, with the radar-derived precipitation.

Figure 5 shows the accumulated rainfall fields based on radar, WRF, CMORPH and adjusted CMORPH data. The radar rainfall magnitude is significantly higher than the WRF and original CMORPH data, which means both WRF and CMORPH did not provide reliable total precipitation. Meanwhile, the adjusted CMORPH data exhibit similar total rainfall magnitude as radar data. Considering a threshold of 0.1 mm/h as the minimum value of CMORPH effective rain rate, it is found that about 1.2% of the radar precipitation was not detected by CMORPH. This high rain detection for this storm indicates that the CMORPH observation indeed captured the main features of the Fella2003 rainfall system, which is why the adjustment procedure gave good results in terms of bias. Figure 6a shows the Q-Q plot of radar rainfall vs. rainfall estimations, which substantiate the claim that the adjusted CMORPH rainfall has the best consistency with the reference radar data among the three estimators. In addition, the bias scores (BS) in Figure 6b and Heidke skill scores (HSS) in Figure 6c are designed to test the details of the CMORPH adjustment at different hourly rainfall thresholds. Both the BS and HSS can test the occurrences of estimators exceeding or failing to reach a certain precipitation threshold, while the HSS also provide combined assessment of the probability of detection and false alarm rate. The BS values of adjusted CMORPH are closest to 1 comparing to the other two estimators, meaning that adjusted CMORPH estimation has more similar occurrences with the radar data, especially when the rainfall threshold is greater.
the 4 mm/h. Moreover, the HSS plot shows the highest values (around 0.4) in the adjusted CMORPH data and lowest values in WRF simulations, which illustrates that the adjusted CMORPH hourly rainfall data performs best not only on rainfall occurrences but also in terms of rainfall detection while WRF gives the least accuracy for the rainfall detection at almost all precipitation thresholds.

The conclusion about rainfall detection is confirmed in Figure 6d, the hourly rainfall time series plot. It is clear that the radar rainfall peak is not captured correctly by the WRF simulated estimation. WRF generates the peak time 3-hours earlier and shows very low value at the actual peak time. The CMOPRH peak is only 1-hour later than the radar peak and follows a similar trend as the radar data. Furthermore, it is important to note that the CMORPH adjustment does not provide enough increase for the relative low rainfall values, while the improvement is significant for the high rainfall values such as rainfall at the peak time. Overall, in Fella2003 event, the adjusted CMORPH estimation is better than either the original CMORPH or WRF data. The adjustment improved the estimator’s performance.

5.2 Sesia2005 case

The Sesia 2005 event lasted for 24 hours with moderate rainfall rate. The WRF rainfall field (Figure 7a) shows a prominent rain band over the boundary of north Italy. Meanwhile, WRF develops another rainfall concentrated area in the northwestern corner of Italy where the Sesia river basin is located. The total rainfall occurred in Sesia river basin is much lower than the prominent rain band
mentioned above. CMORPH exhibits a similar rainfall pattern (Figure 7b) as WRF. But the precipitation magnitude of CMORPH was significantly underestimated.

The fitting domain is a larger area than the Fella2003 in order to include all the major rain bands shown on CMORPH rainfall map. The determined parameters for the power-law equation are a=0.78 and b=1.51. Figure 7c shows the adjusted CMORPH accumulated rainfall map demonstrating a better estimation in terms of total precipitation magnitude. The Q-Q plot (Figure 8a) illustrates a near-linear relationship between adjusted CMORPH and WRF data while the original CMORPH data show apparent underestimation. Additionally, a consistent result is shown in the bias ratio plot of WRF versus CMORPH at different rain rate thresholds (Figure 8b). The ratios between WRF and adjusted CMORPH are close to 1 and display a mildly increasing trend; the ratios between WRF and original CMORPH are also around 1 at low rain rate thresholds but dramatically increase to high values (>20) at higher rain rate thresholds. Clearly, the accuracy of the original CMORPH estimation depends heavily on the intensity of rain rates for this storm case. The magnitude dependence was effectively removed by the WRF-based adjustment.

Figure 9 shows the accumulated rainfall fields over the radar domain. The radar rainfall was mostly concentrated on the left side of the domain. WRF shows a similar rainfall distribution, while CMORPH did not show any significant rainfall on the left side of radar domain. A possible reason causing the misplacement is the CMORPH snow-screening process which gives zero value to
the snow-covered high elevation mountainous areas (Joyce, Janowiak, Arkin, & Xie, 2004). Considering the left side of the radar domain is a portion of the central chain of western Alps with high elevations, part of this area might be covered by snow thus given constant zero rainfall values.

The apparent difference of rainfall distribution between radar and CMORPH can also be reflected in the efficiency of CMORPH rainfall detection. There was only 32% of radar rainfall detected by the original CMORPH estimates. The adjusted CMORPH performs even worse in terms of rainfall detection because the power-law adjustment tends to reduce the low rain rate (less than 1.6 mm/h). However, the overall rainfall magnitude of the adjusted CMORPH (Figure 9c) is improved.

The Q-Q plot over the radar domain (Figure 10a) illustrates that the adjusted CMORPH performs best among the three estimators. There is a near-linear relationship between adjusted CMORPH and reference data for relatively low hourly rain rates (less than 6 mm/h). However, the adjustment for higher rain rates shows an overestimation relative to reference rainfall.

The bias score (Figure 10b) further proves the significant improvement of the adjusted CMOPRH data, which exhibit better consistency with radar rainfall than either WRF or the original CMORPH estimates, especially for the high rain rate thresholds. Nevertheless, the HSS (Figure 10c) of CMORPH and adjusted CMORPH data are around zero, which means that both CMORPH estimators give mostly a random estimation. This points out that the CMORPH detection problem
dominated the estimation problem for this storm. The WRF HSS is also low for this storm case (around 0.04 to 0.12), but greater than CMORPH estimates.

Furthermore, a plot of hourly rainfall time series (Figure 10d) exposes that WRF simulated rainfall tends to develop the rain peak earlier than the actual peak time. On the other hand, CMORPH and adjusted CMORPH rainfall follow the reference time series better since they observed several rainfall peaks at the same time as the radar data. However, the original CMORPH data are too low to provide a reasonable estimation and the adjusted CMORPH data did not obtain enough improvements for the low rain rates while they were increased too much for the higher rain rates.

5.3 **Sesia2006 case**

The Sesia2006 storm event started at the midnight of September 14th, 2006 and persisted for 2 days. The WRF and CMORPH rainfall fields are shown in Figure 11a and Figure 11b, respectively. WRF simulations developed an intense rainfall area over northwestern Italy; CMORPH observation also exhibits a clear rainfall pattern over the similar area but with lower intensity than WRF.

The fitting domain contains a large area since WRF and CMORPH rainfall spread over the entire northwestern Italy. The estimated parameters for the power-law equation are a=1.24 and b=1.26. The substantial improvement of CMORPH accumulated rainfall is apparent in Figure 11c and leads to a near-linear relationship in the Q-Q plot between WRF and adjusted CMORPH rain rates (Figure 12a). The bias ratios (Figure 12b) between WRF and adjusted CMORPH
rain rates are consistently close to 1 meaning that the magnitude dependence of CMORPH estimates has been removed by the adjustment.

Figure 13 shows the rainfall maps focusing only on radar domain. There is an intense rain band across this area through the southwest-northeast direction on radar rainfall map. The rain band is located right on the windward slope of western Alps. WRF rainfall map also depicts a rain band over the same area. However, CMORPH and adjusted CMORPH rainfall are mostly concentrated over the eastern part of radar domain. This fact, which also happened in Sesia2005 case, may result from the CMORPH snow-screening process over high elevation complex terrains.

Error analyses over the radar domain are provided in Figure 14. In the Q-Q plot (Figure 14a), adjusted CMORPH estimates shows good result for the high rain rates, while lower rain rates (less than 8 mm/h) do not increase enough to reach the reference values. Figure 14b shows that the BS of the adjusted CMORPH data is consistently close 1. The adjustment reduced the dependency of CMORPH bias on rain magnitude. In addition, the BS of adjusted CMORPH data provides particularly good estimation for the larger rain rate thresholds, but it performs less accurately than WRF for the lower thresholds. Moreover, CMORPH adjustment can only increase the rain rates magnitude, but does not help the problem of misplacement. Since HSS is influenced not only by the number of the rainfall occurrence but also the rainfall location detection, the HSS plot (Figure 14c) does not show apparent improvement for the adjusted CMORPH data. The hourly rainfall time-series (Figure 14d) on the other hand demonstrate
that the adjusted CMORPH rainfall has significant improvement and its magnitude is closer to the reference data. Meanwhile, CMORPH estimates are exhibiting better correlation with radar data capturing the radar observed trends in the rainfall dynamics. Only one peak in the middle of the rainfall period is missed by CMORPH data, while WRF analysis could only capture one peak correctly.

5.4 Gard2007 case

Gard 2007 event has the longest-lived precipitation of the five storm cases. This event lasted almost four days. The extreme storm though did not occur until the last 20 hours. The storm event is located at the windward slope of the Massif Central mountain ranges. WRF model has considered this topographic factor and consequently simulated the rainfall distribution map (Figure 15a) with a very clear boundary between the precipitation concentrated area and the mountain leeward. However, the rainfall estimates by CMORPH (Figure 15b) shift a bit to the east compared to WRF and radar and do not show a clear rain band as in the WRF analysis.

The fitting domain, which is shown as the black-line rectangle in Figure 15, is defined to include both the rain band of WRF and the rainfall area of CMORPH. The power-law function parameters fitted in the domain are a=1.39 and b=0.96. As in previous cases the adjusted CMORPH hourly rainfall exhibits a near-linear relationship comparing to WRF data (Figure 16a). However, the adjusted CMORPH accumulated rainfall (Figure 15c) still shows much lower magnitude than WRF simulated rainfall (Figure 15a). This inconsistency between the Q-Q plots and accumulated rainfall fields is due to that the CMORPH low rain rates
(less than 0.1 mm/h) that are not accounted in the Q-Q bias adjustment. In Gard2007 case, 81% of the original CMORPH rain rates over fitting domain are less than 0.1 mm/h. Therefore, the adjusted CMORPH data can only apply on the 19% of the CMORPH estimates, which did not allow significant improvement on the accumulated rainfall map. Figure 16b substantiates the claim because adjusted CMORPH rain rates still have large bias comparing to WRF. These bias ratios are much higher than the Fella and Sesia cases.

The rainfall fields over the radar domain are shown in Figure 17. The rainfall structure of adjusted CMORPH data is very similar to radar rainfall distribution but with lower rainfall magnitudes and a misplacement to the east. Figure 18a shows good result for the comparison between adjusted CMORPH and radar data. However, since this Q-Q plot is also based on filtered rain rates, it does not guarantee good results for the overall adjusted CMORPH rain rates. Hence, it is understandable that the adjusted CMORPH data only have slight improvement in BS plot (Figure 18b) while WRF data perform best. To the contrary, HSS plot (Figure 18c) shows that WRF data have lowest scores and that the adjusted CMORPH data provide the highest scores. This can be explained by the time series plot (Figure 18d). Although WRF has similar amount of accumulated rainfall as the radar data, these values come at different peak times, which causes the low HSS values. On the other hand, the adjusted CMORPH data detected the major rainfall peaks correctly.
5.5 Gard2008 case

Gard2008 case was a two-day rainfall event with consistently increasing rain rates that ended after the maximum rainfall peak time. Figure 19 shows the accumulated rainfall fields of WRF and CMORPH data. WRF simulations developed considerable precipitation over Gard area while CMORPH estimates only exhibited moderate precipitation. Moreover, the location of CMORPH precipitation shifted a bit to the west comparing to WRF rainfall distributions.

The fitting domain was extended to contain the rainfall areas of both WRF and CMORPH. Parameters a=1.38 and b=1.13 were determined for the power-law function based on the fitting domain. The adjustment provides CMORPH a visible improvement (Figure 19c), but the accumulated rainfall of the adjusted CMORPH is still lower than WRF. However, the Q-Q plot (Figure 20a) indicates a near-linear relationship between WRF and adjusted CMORPH data, which is contrasted to the adjusted CMORPH rainfall map. This inconsistency was also happened in the Gard2007 case and is explained by the high coverage of very low rainfall rates where the adjustment is not effective.

The bias ratios (Figure 20b) of WRF against adjusted CMORPH data are consistently around two at all rain rates thresholds, while the original CMORPH data is significantly less than WRF at the higher rain rates thresholds. This plot illustrates that the adjustment procedure enhanced the accuracy of CMORPH estimation by removing its rain rates magnitude dependence.

The Q-Q plot over the radar domain (Figure 22a) shows significant improvement of the adjusted CMORPH data relative to the original CMORPH
estimates. However, underestimation of the adjusted CMORPH data remains at reference hourly rain rates below 6 mm/h. Again this is due to the fact that there are nearly 70% of CMORPH hourly rain rates over radar domain with values less than 0.1 mm/h. CMORPH adjustment is not effective in those low rainfall rates. Therefore, the increase in the adjusted CMROPH accumulated rainfall (Figure 21d) is not enough to reach the radar level (Figure 21a). Meanwhile, WRF provides more accurate accumulated rainfall estimates (Figure 21b) than the adjusted CMORPH. The hourly rainfall time series (Figure 22d) also indicates that the missed detection of CMORPH rain rates cannot be meliorated by the adjustment procedure. The bias score plot (Figure 22b) also illustrates that the improvement of adjusted CMORPH data is insufficient, while WRF provides better estimation at all rain rate thresholds. However, it is important to note that bias score only shows the ratio of occurrences number between CMORPH and WRF rain rates. HSS plot (Figure 22c) gives more information such as the probability of detection and occurrences by chance. The CMORPH adjustment provides significant improvement in terms of HSS especially for large rain rate thresholds. The adjusted CMORPH data outperformed the other two estimators in HSS plot.

6 Conclusions

This study investigated the use of Weather Research and Forecasting (WRF) model analysis in satellite rainfall estimation (CMORPH) over complex terrain areas based on five extreme storm cases that occurred in southern Europe. Radar
derived precipitation was considered as reference rainfall to evaluate the possible improvements of the WRF-based adjusted CMORPH estimates.

On one hand, CMORPH has a tendency to substantially underestimate rainfall magnitude. In some cases, low rain rates are not even detected by CMORPH. Meanwhile, CMORPH performs well in capturing the major rainfall peaks according to radar hourly rainfall time series. On the other hand, WRF high-resolution analysis tends to provide relatively accurate estimation in terms of overall rain rates intensity. However, a time difference always exists between WRF and radar rainfall peaks. WRF also missed rainfall peaks in some storm events. Overall, we noted improvements by using WRF-adjusted CMORPH estimates relative to the original CMORPH and WRF analysis data. Adjustments were applied using a power-law function with parameters determined on a storm-to-storm basis. The main findings from the analysis of the five storm cases are summarized as follows:

The adjusted CMORPH hourly rain rates exhibit improvements as long as the original CMORH observation has detected the rainfall. The missed detections of original CMORPH estimates have major limitation in the application of the proposed technique. From the five storm events examined herein, the CMORPH estimates of Fella2003 and Sesia2006 cases had the least missed detections than the other three cases. These cases exhibited the most significant improvements from the WRF-based adjustment.

In most cases, the intense rain bands estimated from CMORPH data were slightly misplaced relative to the radar rainfall. This misplacement cannot be
corrected by the adjustment procedure and was mainly due to snow contamination effects on the microwave retrievals.

The adjustment was shown to provide significant improvement for the high rain rates, which sometimes caused the adjusted CMORPH rain rates exceeding the radar rainfall rates. Meanwhile, there was only slight improvement for the relatively low rain rates, which was not enough to reach the radar rainfall values.

In all storm cases, the bias scores of the original CMORPH versus radar exhibited strong rain rate magnitude dependence. After CMORPH adjustment, this magnitude dependence has been moderated.

The storms occurring in same area tend to have similar CMORPH performance on rainfall estimation. For example, both Sesia2005 and Sesia2006 CMORPH accumulated rainfall fields show a slight misplacement of intense rain band to the eastern direction comparing to radar rainfall fields. This misplacement is attributed to the high elevation mountainous area located at the west part of Sesia domain. Moreover, relative to HSS, the BS is more sensitive to the CMORPH adjustment of Sesia cases. In the contrary, HSS is more sensitive to the CMORPH adjustment for the Gard cases than BS.

Overall, the adjusted CMORPH rainfall performed consistently better than the original CMORPH data. Furthermore, in most of the cases, the adjusted CMORPH rainfall provided better estimation than the WRF analysis in terms of specific skill scores.
7 References


Table 1. Storm events information.

<table>
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<tbody>
<tr>
<td>Location</td>
<td>Fella</td>
<td>Sesia</td>
<td>Sesia</td>
<td>Gard</td>
<td>Gard</td>
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<td>2006-09-14 00:00</td>
<td>2007-11-19 06:00</td>
<td>2008-10-31 06:00</td>
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<tr>
<td>Duration</td>
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<td>47 hrs</td>
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<td>253 mm</td>
<td>353 mm</td>
<td>294 mm</td>
<td>409 mm</td>
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<td>Radar mean hourly precipitation</td>
<td>8.8 mm</td>
<td>2.6 mm</td>
<td>4.1 mm</td>
<td>2.1 mm</td>
<td>3.7 mm</td>
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<tr>
<td>Percentage of grids having heavy precipitation (≥10 mm/h)</td>
<td>20.1%</td>
<td>2.8%</td>
<td>4.3%</td>
<td>0.9%</td>
<td>5.3%</td>
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<td>Percentage of grids having effective precipitation (≥0.1 mm/h)</td>
<td>65%</td>
<td>50%</td>
<td>70%</td>
<td>51%</td>
<td>81%</td>
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Table 2. Data resolutions.

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<td>CMORPH</td>
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<tr>
<td>Radar</td>
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<td>WRF</td>
<td>2 km</td>
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Table 3. WRF simulation domain size for each storm case.

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<th>Domain</th>
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<tr>
<td>Resolution</td>
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<table>
<thead>
<tr>
<th>Storm events</th>
<th>Domain size</th>
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<tr>
<td>Fella2003</td>
<td>156x120</td>
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<tr>
<td>Sesia2005</td>
<td>156x120</td>
</tr>
<tr>
<td>Sesia2006</td>
<td>156x120</td>
</tr>
<tr>
<td>Gard2007</td>
<td>156x120</td>
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<tr>
<td>Gard2008</td>
<td>156x120</td>
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Table 4. WRF physical parameterizations.

<table>
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<tr>
<th>WRF simulation parameters</th>
<th>Values</th>
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<tr>
<td>Microphysics Scheme</td>
<td>Eta microphysics</td>
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<tr>
<td>Longwave Radiation</td>
<td>Rapid Radiative Transfer Model</td>
</tr>
<tr>
<td>Shortwave Radiation</td>
<td>Dudhia scheme</td>
</tr>
<tr>
<td>Cumulus Parameterization</td>
<td>Kain-Fritsch scheme for the parent domain; No cumulus for the nest domains</td>
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<tr>
<td>Land-surface Scheme</td>
<td>Unified Noah land-surface model</td>
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<td>Number of soil layers in land surface model</td>
<td>4</td>
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Table 5. Time periods of WRF simulations

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<td>Starting time</td>
<td>2003-08-29-00:00</td>
<td>8/1/2005 12:00</td>
<td>9/13/2006 18:00</td>
<td>2007-11-19-00:00</td>
<td>2008-10-31-00:00</td>
</tr>
<tr>
<td>Ending time</td>
<td>2003-08-30-12:00</td>
<td>8/3/2005 00:00</td>
<td>9/16/2006 06:00</td>
<td>2007-11-23-12:00</td>
<td>2008-11-02-12:00</td>
</tr>
<tr>
<td>Duration</td>
<td>36 hrs</td>
<td>36 hrs</td>
<td>60 hrs</td>
<td>108 hrs</td>
<td>60 hrs</td>
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Figure 1. Study areas. Left: Gard radar domains for Gard2007 and Gard2008 cases. Middle: Sesia radar domain for Sesia2005 and Sesia 2006 cases. Right: Fella radar domain for Fella2003 case.
Figure 2. Flow chart of data processing and error analyses
Figure 3. Fella2003 case: accumulated rainfall distribution (a) WRF; (b) CMORPH; (c) adjusted CMORPH. The area encompassed by the black rectangle box is the fitting domain; the area encompassed by the gray inner rectangle box is the radar domain.
Figure 4. Fella2003 case: plots over fitting domain. (a) Q-Q plot; (b) Bias ratio.
Figure 5. Fella2003 case: accumulated rainfall distribution over radar domain. (a) radar; (b) WRF; (c) CMORPH; (d) adjusted CMORPH
Figure 6. Fella 2003 case: plots over radar domain. (a) Q-Q plot; (b) Bias scores; (c) Heidke skill scores; (d) Hourly rainfall time series.
Figure 7. Sesia2005 case: accumulated rainfall distribution (a) WRF; (b) CMOPRH; (c) adjusted CMORPH. The area encompassed by the black rectangle box is the fitting domain; the area encompassed by the gray inner rectangle box is the radar domain.
Figure 8. Sesia2005 case: plots over fitting domain. (a) Q-Q plot; (b) Bias ratio.
Figure 9. Sesia2005 case: accumulated rainfall distribution over radar domain. (a) radar; (b) WRF; (c) CMORPH; (d) adjusted CMORPH.
Figure 10. Sesia2005 case: plots over radar domain. (a) Q-Q plot; (b) Bias scores; (c) Heidke skill scores; (d) Hourly rainfall time series.
Figure 11. Sesia2006 case: accumulated rainfall distribution (a) WRF; (b) CMORPH; (c) adjusted CMORPH. The area encompassed by the black rectangle box is the fitting domain; the area encompassed by the gray inner rectangle box is the radar domain.
Figure 12. Sesia2006 case: plots over fitting domain. (a) Q-Q plot; (b) Bias ratio.
Figure 13. Sesia2006 case: accumulated rainfall distribution over radar domain. (a) radar; (b) WRF; (c) CMORPH; (d) adjusted CMORPH.
Figure 14. Sesia2006 case: plots over radar domain. (a) Q-Q plot; (b) Bias scores; (c) Heidke skill scores; (d) Hourly rainfall time series.
Figure 15. Gard2007 case: accumulated rainfall distribution (a) WRF; (b) CMORPH; (c) adjusted CMORPH. The area encompassed by the black rectangle box is the fitting domain; the area encompassed by the gray inner rectangle box is the radar domain.
Figure 16. Gard2007 case: plots over fitting domain. (a) Q-Q plot; (b) Bias ratio.
Figure 17. Gard2007 case: accumulated rainfall distribution over radar domain. (a) radar; (b) WRF; (c) CMORPH; (d) adjusted CMORPH.
Figure 18. Gard2007 case: plots over radar domain. (a) Q-Q plot; (b) Bias scores; (c) Heidke skill scores; (d) Hourly rainfall time series.
Figure 19. Gard2008 case: accumulated rainfall distribution (a) WRF; (b) CMORPH; (c) adjusted CMORPH. The area encompassed by the black rectangle box is the fitting domain; the area encompassed by the gray inner rectangle box is the radar domain.
Figure 20. Gard2008 case: plots over fitting domain. (a) Q-Q plot; (b) Bias ratio.
Figure 21. Gard2008 case: accumulated rainfall distribution over radar domain. (a) radar; (b) WRF; (c) CMORPH; (d) adjusted CMORPH.
Figure 22. Gard2008 case: plots over radar domain. (a) Q-Q plot; (b) Bias scores; (c) Heidke skill scores; (d) Hourly rainfall time series.