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Evaluation of a near-real time NEXRAD DSP product in evolution of heavy rain events on the Upper Guadalupe River Basin, Texas

Xianwei Wang, Hongjie Xie, Newfel Mazari, Jon Zeitler, Hatim Sharif and Weldon Hammond

ABSTRACT

This study evaluates the Next Generation Weather Radar (NEXRAD) Digital Storm-Total Precipitation product (DSP) by analyzing 30 rain events on the Upper Guadalupe River Basin, Texas, from September 2006 to May 2007. The DSP product provides relatively accurate information on the evolution of rain events at high spatial and temporal resolutions in near-real time. This is particularly important for rainfall estimation of heavy rain events and flash flood forecasting. The DSP's accuracy is comparable to the other NEXRAD product MPE (multisensor precipitation estimator, at hourly resolution and 4 km grid spacing) at both hourly and event total scales for some heavy rain events, although the DSP is inferior to the MPE product for total rainfall of all 30 rain events analyzed, especially for light rain events. The DSP product shows the best agreement with gauges at ranges of 50–150 km from the radar (with mean absolute estimation bias (MAEB) of +15–22% for total rainfall of 30 rain events), while underestimating precipitation at both close ranges (<30 km) and far ranges (>180 km). The DSP product also tends to underestimate (overestimate) precipitation during event growth (dissipation). However, the total rainfall estimate for all rain events over a long period from DSP shows range dependence and is not recommended for calculation of water resource budget.

Key words | DSP, evaluation, MPE, NEXRAD, rain

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INTRODUCTION

Flash flooding represents a significant hazard to life and property, especially in urban areas with high population density and mitigation costs associated with floods (Shepherd *et al.* 2010). Reliable flash flood simulation and forecasting require high-resolution (temporal and spatial) precipitation estimates and distributed hydrologic modeling (Sharif *et al.* 2006). Automated rain gauge networks can provide measurements in near-real time, but the density of gauge networks is typically too coarse for accurate flash flood forecasting. In addition, automated rain gauges suffer from degraded accuracy with increasing precipitation intensities (Bedient *et al.* 2003). Satellite precipitation is less useful in flash flood forecasting primarily because of large gaps in observations (e.g., 15-minute intervals for GOES-IR

outside of Rapid Scan Operations) and processing and transmission latency (roughly 30 minutes after observation time). Real-time stream gauge data are the most straightforward and accurate information for flash flood simulation and forecasting. However, deploying and maintaining a stream gauge network is expensive and only available along major river basins and in highly urbanized areas. Moreover, stream gauge data offer extremely limited lead time for flash flood forecasting. The best practically mixed input to a hydrologic model for flash flood forecasting is a combination of radar for maximum areal coverage, and rain gauges for ground truth and calibration of the radar data. The Weather Surveillance Radar-1988 Doppler (WSR-88D) Digital Storm-Total Precipitation (DSP) product

offers high temporal and spatial resolutions, with the possibility for direct input into hydrologic models to produce flash flooding predictions in near-real time for taking action to save life and property.

The WSR-88D Next Generation Weather Radar (NEXRAD) network in the United States has brought unprecedented advances in estimating real-time rainfall data over large areas for meteorological and hydrological applications (Fulton *et al.* 1998; Krajewski & Smith 2002). Such gridded radar data have been employed in several nowcast systems to provide quantitative precipitation forecasts, and can potentially result in great benefits to flash flood warning and short-term forecasting (Boldi *et al.* 2002; Mueller *et al.* 2003; Sharif *et al.* 2006).

Mitigating range effects is a significant challenge for radar precipitation estimation. The range-related effects can be generally classified into three categories. The first is beam-broadening. For example, the grid size of NEXRAD reflectivity is 2 km in range by 1.0° in azimuth on a polar stereographic projection. Thus, at farther ranges, the radar beam has wider sampling space compared with closer ranges. Second, at farther ranges the beam height is higher above ground level, increasing the difference between radar-estimated and ground-measured precipitation. An extreme example is the total evaporation of precipitation before it reaches the ground (a below-beam effect). Another range and beam effect is bright-banding. Precipitation generally has a non-uniform reflectivity profile in the vertical since ice/snow returns less reflectivity than liquid water (OFCM 2006). Most surface rainfall originally forms as snow above the freezing level, where radar detects dry snowflakes (and less reflectivity) at longer ranges, where the beam is entirely above the freezing level. Therefore, the radar-estimated precipitation is significantly less than that observed at the surface or at lower elevation angles, where liquid water is present. There is also enhanced reflectivity due to melting, water-coated snowflakes in the layers below the freezing level, where the beam intersects the melting layer and has higher reflectivity than higher beams, thus overestimating the near-surface precipitation in a narrow ring around the radar location. The bright-band effect can be mitigated by using the vertical gradient of the reflectivity profiles (Rico-Ramirez & Cluckie 2007).

Hydrological processes and models for runoff and flood forecasting are sensitive to the accumulated storm-total rainfall amount. Radar precipitation estimates, after bias adjustment using storm-total gauge accumulations, can provide good results in hydrological modeling (Smith *et al.* 1996; Landel *et al.* 1999; Ogden *et al.* 2000; Rogalus III & Ogden 2007; Weissling & Xie 2008, 2009; Weissling *et al.* 2009). Moreover, most studies validating radar precipitation products used scatter plotting and arbitrary time (hourly, daily) intervals (Jayakrishnan *et al.* 2004; Xie *et al.* 2005, 2006; Wang *et al.* 2008), and ignored the difference resulting from event evolution (e.g., changes in rain rate during the initiation, growth, and dissipation stages). This study uses 30 rain events, with special focus on four heavy rain events and on the integrated range effects on the uncalibrated radar DSP product over three sub-areas on the Upper Guadalupe River Basin from September 2006 to May 2007 (Figure 1). It is the first assessment on the performance of the radar DSP product during the evolution (e.g., initiation, growth, and dissipation) of these heavy rain events, and on the potential benefits of DSP estimates for flash flood forecasting.

STUDY AREA AND DATA SOURCES

The selected study area lies in the Hill Country of Central Texas (Figure 1), over the Upper Guadalupe River Basin, and under the umbrella of two radars: KDFX (29°21'N, 100°47'W) near Brackettville, Texas, and KEWX (29°42'N, 98°01'W) near New Braunfels, Texas. Two NEXRAD precipitation products are analyzed in this study: (1) the WSR-88D radar DSP product on polar grids of each volume scan, and (2) the Multisensor Precipitation Estimator (MPE) product – hourly accumulation on a 4 km × 4 km hydrologic rainfall analysis project (HRAP) grid produced at National Weather Service (NWS) River Forecast Centers (RFCs). The DSP products (KEWX and KDFX) are assessed by rain gauge measurements in the study period from September 2006 to May 2007. This study period is constrained by the availability of the archived radar DSP product and rain gauge data. Meanwhile, the MPE product is used as a reference since MPE represents

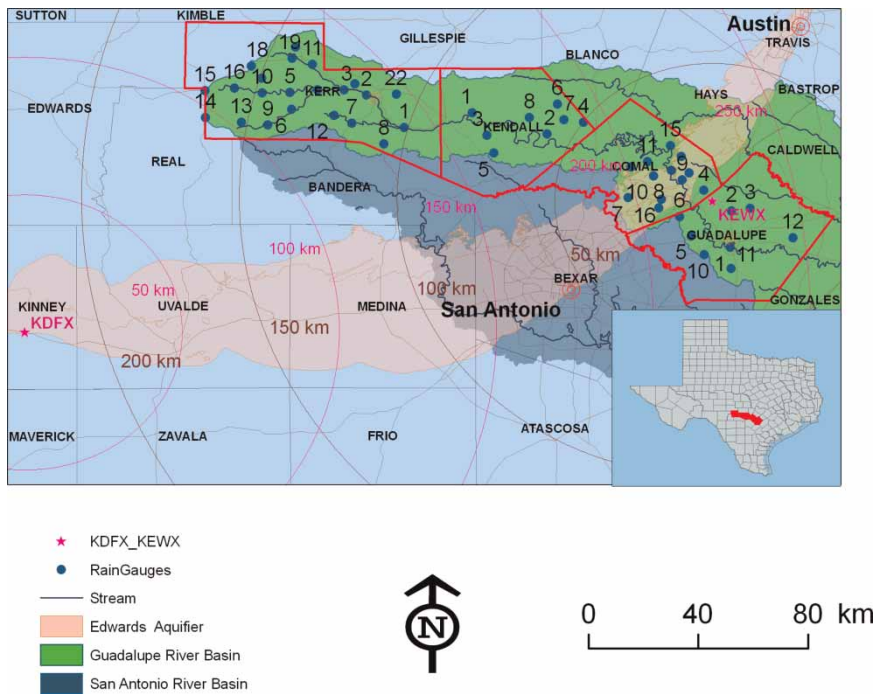


Figure 1 | Fifty rain gauge network (blue dots and numbers) on the Upper Guadalupe River Basin and Radar KEWX and its range circles (50, 100, 150, 200, and 250 km in purple) and KDFX and its range circles (50, 100, 150, 200, and 250 km in fuchsia). Rain gauges' locations from west to east are in the Kerr, Kendall, Comal, and Guadalupe Counties. For the KEWX radar, the rain gauges in Kerr County are in the range of 100–165 km range, gauges in Kendall County are in 50–100 km, gauges in Comal and Guadalupe Counties are in less than 30 km. For the KDFX radar, the rain gauges in Kerr County are in the range of 100–150 km, gauges in Kendall County are in 150–200 km, gauges in Comal and Guadalupe Counties are in 200–250 km. Radar's effective range is 230 km. The base map of this figure is also used in Wang *et al.* (2008). Please refer to the online version of this paper to see this figure in colour: <http://www.iwaponline.com/jh/toc.htm>.

the most advanced product of hourly NEXRAD precipitation (Wang *et al.* 2008; Habib *et al.* 2009).

MPE is a gauge-calibrated NEXRAD rainfall product. The gauge-based adjustments of mean field bias play a critical role in reducing the MPE estimate error. The MPE product adopts a 'mosaic-and-adjust' strategy, i.e., overlapping radars' maximum radar reflectivity is mosaicked, then a mean field bias adjustment is applied, and finally, a local bias correction (Seo & Breidenbach 2002). The mean field biases are carried out based on the gauge-only and radar-gauge analysis by the krigging- and cokriging-like algorithms of Seo & Breidenbach (2002), and are dependent on the available valid hourly gauge data. MPE shows robust performance compared with the Stage III product at the NWS West Gulf River Forecast Center (WGRFC) (Wang *et al.* 2008) and at the NWS Lower Mississippi River Forecast Center (Habib *et al.* 2009). However, the processing time required for MPE (and other hourly products) and its delayed availability is a disadvantage for application to flash flood forecasting.

The DSP product is generated from radar reflectivity using the $Z-R$ (reflectivity-rainfall) relationship $Z = 300R^{1.4}$ in nearly all cases, with the exception being $Z = 250R^{1.2}$ for precipitation in a moist tropical environment. In this study period, the first general $Z-R$ relationship was used to generate the DSP product (Mazari *et al.* 2012). The DSP product is a running accumulation, from which rainfall accumulations at shorter time intervals can be obtained through differencing. The DSP product has a polar spatial resolution of 2 km in range by 1° in azimuth at 4–7 minute intervals for each radar umbrella, out to an effective beam range of 230 km (NOAA 2005). The DSP grid sizes range from 2 km by ~ 4 km at the farthest effective beam range (230 km), to 2 km by ~ 2 km at mid ranges (115 km), and to 2 km by ~ 0.5 km at close beam ranges (30 km). The DSP product was not publicly accessible during the data collection period for this study, but is now available at: <ftp://tgftp.nws.noaa.gov/SL.us008001/DF.of/DC.radar/DS.80stp/SI.kewx/>. The DSP data for this research were archived only for days when total

daily rainfall (from one or more gauge observations) was equal to or greater than 6.4 mm (0.25 in).

A network of tipping-bucket rain gauges has been operated by the Guadalupe-Blanco River Authority (GBRA) since 2000. These rain gauges span four counties: Kerr, Kendall, Comal, and Guadalupe (Figure 1). These gauge measurements are not used to calibrate the radar DSP product since KEWX/KDFX DSP products are strictly the radar conversion of reflectivity and quality control of the precipitation processing system. Meanwhile, 17 of the GBRA gauges have been likely used as part of the MPE process, which also includes radar rainfall estimates from KEWX/KDFX, other non-GBRA gauges in the basin, and satellite data. All 17 gauges are located in Kendall and Comal Counties (Figure 1). The gauge and MPE comparison in these areas would work as a control area against Kerr and Guadalupe Counties, where no gauge data have been used in the MPE process.

All GBRA gauges are classified into three sub-areas according to their ranges from the two radar locations. This first area is in Kerr County, which contains 22 gauges

with a range to both KEWX and KDFX radars of 100–150 km. The second is Kendall County, which contains eight gauges at ranges of 50–100 km to the KEWX radar and 150–200 km to the KDFX radar. Third is Comal and Guadalupe Counties (CG), which contain 20 gauges at ranges of 3–30 km to KEWX and 200–230 km to KDFX, with two gauges beyond the effective KDFX radar range (230 km). Rain gauge data contain 6-minute, 3-hour, 6-hour, and 24-hour accumulations. The 6-minute data are used to generate storm-total accumulations to compare with the corresponding radar estimates. The local time of rain gauge data is converted to the Coordinated Universal Time (UTC) to coincide with the radar data record time. All times referred to in this study are in UTC.

METHODS

Considering potential applications of DSP in flash flood forecasting, this study emphasizes heavy rain events that may cause flooding. Four heavy rain events (Tables 1–4)

Table 1 | Mean event total precipitation estimates from gauges, KEWX DSP, KDFX DSP, MPE and estimate bias (EB) of KEWX, KDFX, and MPE for rainfall on September 17–18, 2006 (Event one)

	Gauge	KEWX	KDFX	MPE	KEWX_EB	KDFX_EB	MPE_EB
Kerr County	27.6	29.1	17.8	31.1	5%	–36%	13%
Kendall	10.4	4.4	28.1	9.8	–58%	170%	–6%
Comal and Guadalupe	17.4	9.6	25.6	15.5	–45%	47%	–11%

Table 2 | Mean event total precipitation estimates from gauges, KEWX DSP, KDFX DSP, MPE and estimate bias (EB) of KEWX, KDFX, and MPE for rainfall on January 3–4, 2007 (Event two)

	Gauge	KEWX	KDFX	MPE	KEWX_EB	KDFX_EB	MPE_EB
Kerr County	24.5	20.9	19.2	27.1	–15%	–22%	11%
Kendall	30.3	23.4	20.7	34.1	–23%	–32%	13%
Comal and Guadalupe	25.8	15.6	2.5	24.8	–40%	–90%	–4%

Table 3 | Mean event total precipitation estimates from gauges, KEWX DSP, KDFX DSP, MPE and estimate bias (EB) of KEWX, KDFX, and MPE for rainfall on March 11–12, 2007 (Event three)

	Gauge	KEWX	KDFX	MPE	KEWX_EB	KDFX_EB	MPE_EB
Kerr County	16.9	18.2	25.0	25.4	8%	48%	50%
Kendall	80.5	86.2	50.2	99.9	7%	–38%	24%
Comal and Guadalupe	47.1	45.9	11.7	67.7	–3%	–75%	44%

Table 4 | Mean event total precipitation estimates from gauges, KEWX DSP, KDFX DSP, MPE and estimate bias (EB) of KEWX, KDFX, and MPE for rainfall on April 30, 2007 (Event four)

	Gauge	KEWX	KDFX	MPE	KEWX_EB	KDFX_EB	MPE_EB
Kerr County	23.0	30.4	13.7	27.7	32%	-40%	20%
Kendall	13.8	19.2	12.0	23.7	39%	-13%	72%
Comal and Guadalupe	18.7	25.4	24.9	27.8	36%	33%	49%

are chosen for detailed analysis after analyzing all 30 rain events in the study period from September 2006 to May 2007. These four rain events occurred over all the three sub-areas, and the event total precipitation varied from 10 to 80 mm (Tables 1–4). The three sub-areas represent different ranges from gauges to the two radars, and thus can be used to examine the integrated range effects of the DSP product. In order to mitigate the spatial representative error of gauge rainfall, comparisons for the four heavy rainfall events are carried out within each sub-area, while the comparisons of the total rainfall for all 30 rain events are performed for individual gauges.

We extract only one radar grid (2 km × 1° for DSP, 4 km × 4 km for MPE) collocated with each rain gauge for comparison. The comparison focuses on the evolution of storms for short temporal intervals and storm-total accumulation. The WSR-88D is operated via volume coverage patterns (VCPs) varying from 4.5 to 10 minutes in length (OFCM 2011). The determination of which VCP to use for a particular storm event is determined by the local NWS office based on operational experience and the potential for severe weather. In fact, the VCPs used can be changed during the course of an event (e.g., a change in threat from tornadoes, large hail, and damaging winds to flash flooding). Additional time may be added to each volume product due to rounding to the nearest minute, or potentially when changing from one VCP to another. Hence, in this study, the KEWX DSP product has 4–7 minute intervals (referred to as 6-minute intervals hereafter), and KDFX DSP product has 5–12 minute intervals (referred to as 10-minute intervals hereafter). Gauge measurements have a 6-minute interval. Therefore, in order to evaluate the radar DSP product at short temporal intervals, a 3-minute buffer time is applied when matching radar DSP time to the gauges' time interval. The temporal sampling difference between radar and rain gauges causes additional uncertainty for the 6- and 10-minute

comparisons. However, the temporal sampling difference is negligible for storm total comparisons.

Estimation bias (EB) is the normalized difference of total rainfall amount between radar estimations and gauge measurements (Jayakrishnan *et al.* 2004; Wang *et al.* 2008). It is defined in Equation (1) and is used to compare the event total precipitation difference between the gauges, DSP, and MPE in the study period, with an assumption that the gauge rainfall is the true value:

$$EB = \frac{TP_r - TP_g}{TP_g} \times 100\% \quad (1)$$

where TP_r and TP_g are the total precipitation detected by radar and gauges, respectively.

RESULTS

Event one

This event began on September 17, 2006, in Kerr County, and moved eastward through Kendall County, then through Comal and Guadalupe Counties, before ending on September 18. The major rainfall occurred in different periods over the three study sub-areas. In Kerr County, the rainfall was concentrated from 5:55 to 11:50 on September 17 and had average precipitation of 27.6 mm (Table 1, Figure 2(a)). The KEWX DSP was in good agreement with gauge measurements in both timing and quantity. The KDFX DSP estimated lower precipitation than the gauges (Figure 3(a)). The KDFX DSP also had lower event total value than the KEWX DSP although both had similar ranges to the gauges (Table 1). MPE values for hourly intervals were similar to the rain gauges and had 13% higher event total value than the gauges, and slightly higher than the KEWX DSP (Table 1, Figure 4(a)).

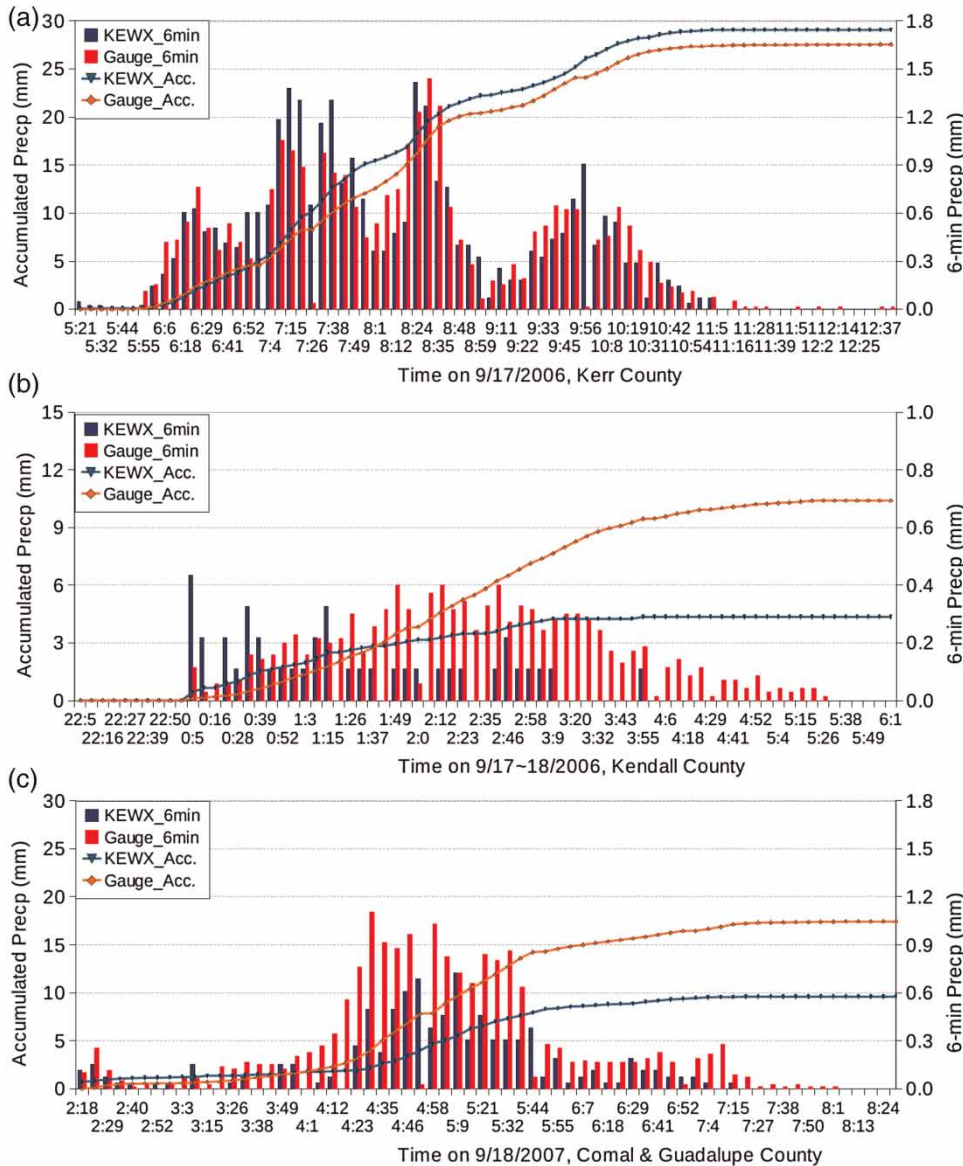


Figure 2 | Accumulated (left-hand vertical axis) and 6-minute precipitation (right-hand vertical axis) detected at three areas by gauges (red) and KEWX DSP (black) for event one on September 17–18, 2006. The ranges from gauges to the KEWX radar are 3–30 km (a), 50–75 km (b), 100–170 km (a).

Kendall County had much less precipitation than the other two sub-areas. The rainfall occurred from 00:00 to 5:00 on September 18, and the mean event total precipitation was 10.4 mm. The KEWX DSP was 4.4 mm (Table 1). In contrast, the KDFX DSP was much higher than the gauges and KEWX, with an event total of 28.1 mm (Table 1). MPE had similar event total precipitation with the gauges, but the phase of hourly peak rainfall amount was 1 hour later than the gauges (Figure 4(b)).

This event affected Comal and Guadalupe Counties from 2:00 to 8:00 (Figure 2(c)). The mean event total gauge rainfall was 17.4 mm, 9.6 mm for the KEWX DSP, 25.6 mm for the KDFX DSP, and 15.5 mm for MPE (Table 1). KEWX had less precipitation than gauges for the entire event in this sub-area (Figure 2(c)), while KDFX was in good agreement with the gauge before 6:00, but had much higher values than gauges in the last 2 hours of event dissipation (Figure 3(c)). MPE was in good agreement

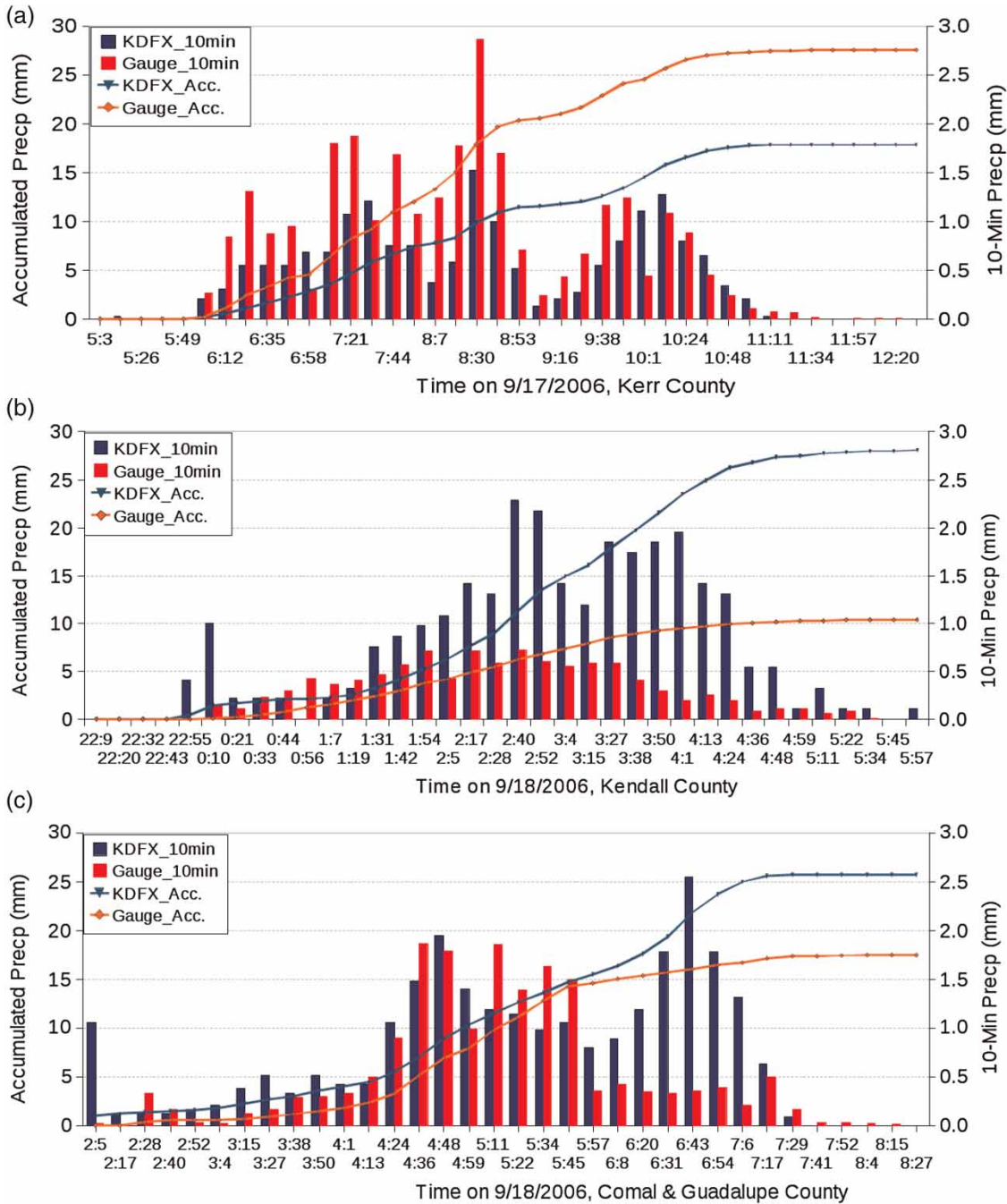


Figure 3 | Accumulated (left-hand vertical axis) and 10-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KDFX DSP for event one on September 17–18, 2006. The ranges from gauges to the KDFX radar are 100–150 km (a), 160–200 km (b), 200–230 km (c).

with gauges except for a lower estimate in the fourth hour (Figure 4(c)).

In summary, both radars and gauges adequately captured the event evolution. The KEWX DSP was in good agreement with gauges in Kerr County, but much poorer

agreement over Kendall, Comal, and Guadalupe Counties, with general underestimation of the event total precipitation. The KDFX DSP had good phase agreement with, but lower precipitation amounts than, gauges in Kerr County, and had larger precipitation amounts (up to

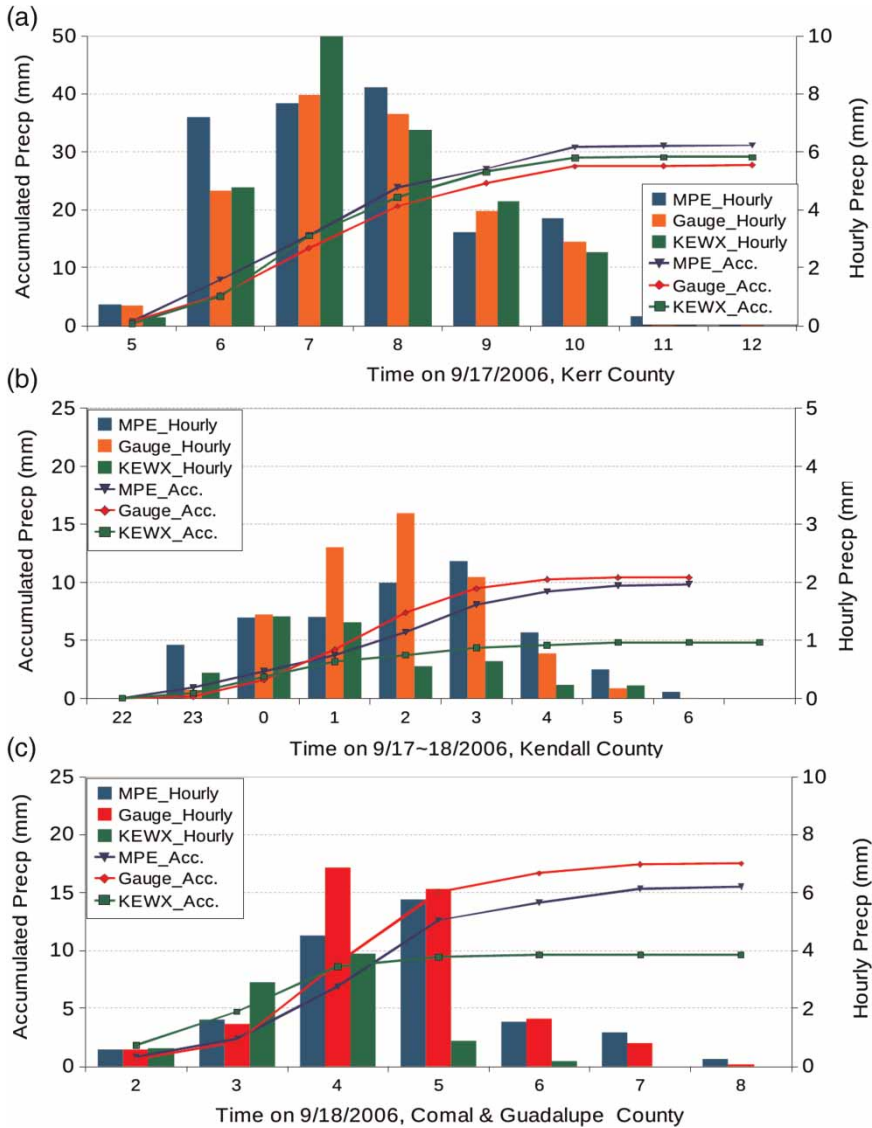


Figure 4 | Accumulated (left-hand vertical axis) and hourly (right-hand vertical axis) precipitation detected at three areas by gauges, MPE and KEWX DSP for event one on September 17–18, 2006.

170%) than gauges for the other two sub-areas, especially during event dissipation. In the event evolution, MPE had large differences with gauge-only values at the hourly scale, but had overall good agreement with gauges' event total precipitation and better agreement with gauges than KEWX and KDFX DSP in all three sub-areas.

Event two

This event also started from the west in Kerr County at 17:00 on January 3, 2007, moved eastward to Guadalupe

County, ending around 10:00 on January 4, 2007. In Kerr County, the event ended by 7:00 on January 4 with total precipitation of 24.5 mm (Table 2). The KEWX and KDFX radars, and rain gauges, captured four peaks of rainfall, but the radars underestimated or did not detect rainfall from 18:00 to 00:30, yet overestimated the peak rainfall, especially from 5:30 to 6:09 on January 4. Overall, the radars underestimated the event total accumulation (Figures 5(a) and 6(a)). MPE had good agreement with the gauges' event accumulation, in spite of individual hour differences (Figure 7(a)). MPE caught the rainfall

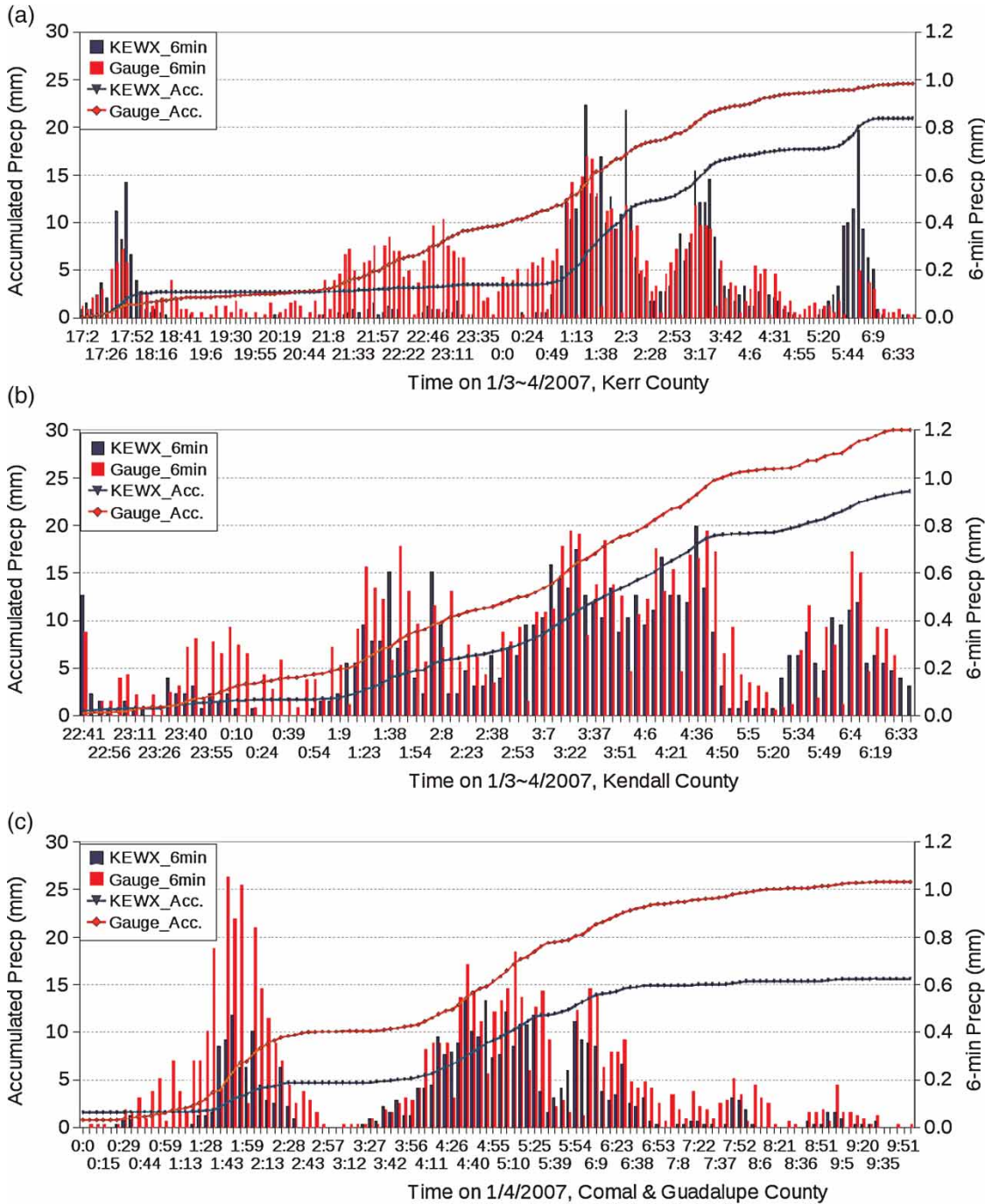


Figure 5 | Accumulated (left-hand vertical axis) and 6-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KEWX DSP for event two on January 3–4, 2007.

peak 21:00 to 00:00, when both KEWX and KDFX DSPs had near zero values.

The event in Kendall County began at 22:00 on January 3 and ended at 07:00 on January 4 with total

precipitation of 30.3 mm (Table 2). The KEWX DSP captured four peaks of rainfall, but with lower estimates as the event proceeded, resulting in an overall lower event total precipitation (Table 2, Figure 5(b)). The KDFX

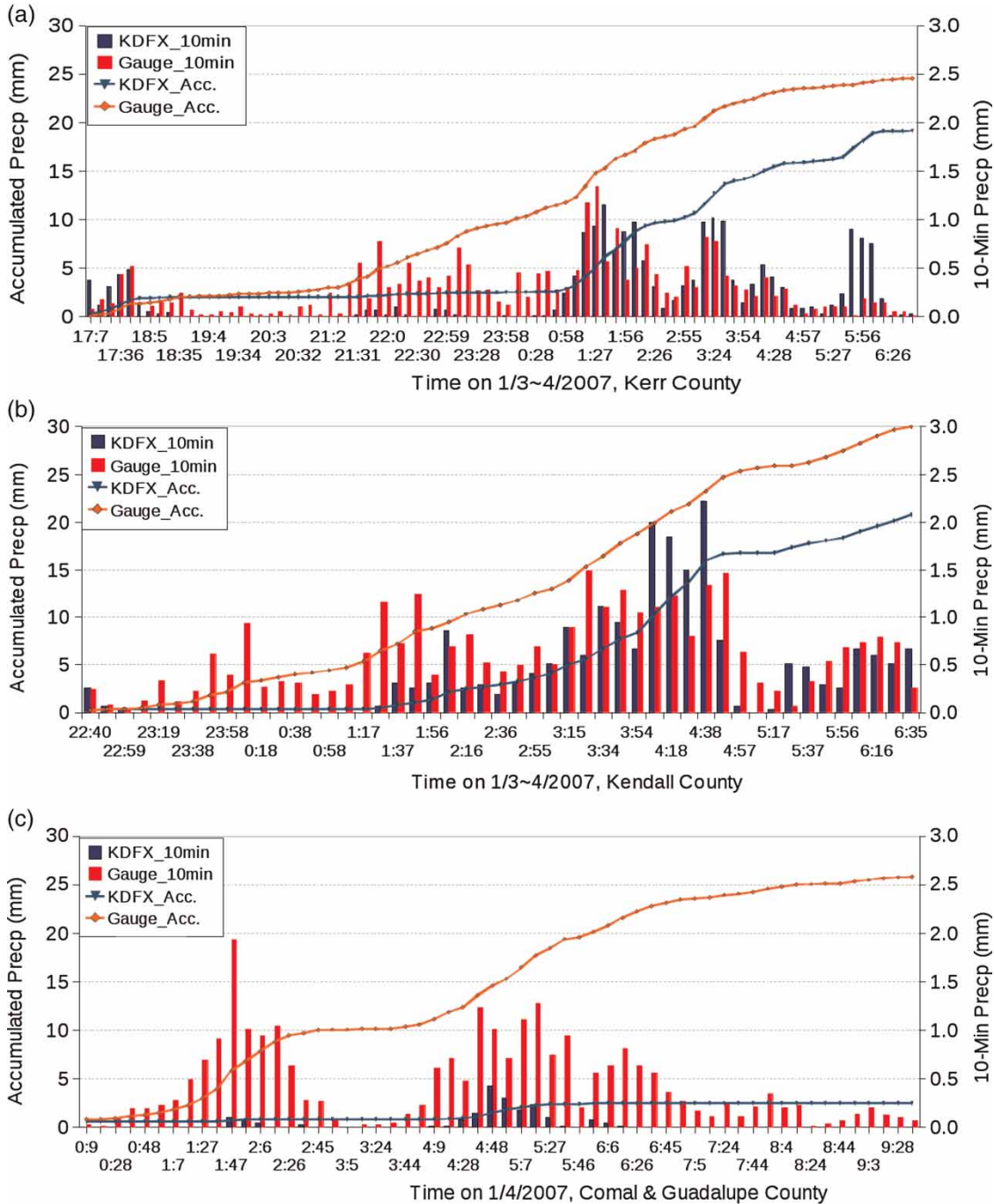


Figure 6 | Accumulated (left-hand vertical axis) and 10-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KDFX DSP for event two on January 3-4, 2007.

DSP had lower estimates than gauges except the 04:00 hour, leading to lower event total precipitation than the gauges (Table 2, Figure 6(b)). In contrast, MPE was in good agreement with gauge accumulation during the

event evolution and with the event total precipitation (Table 2, Figure 7(b)).

The event for Comal and Guadalupe Counties started at 00:00 and ended at 10:00 on January 4 with total

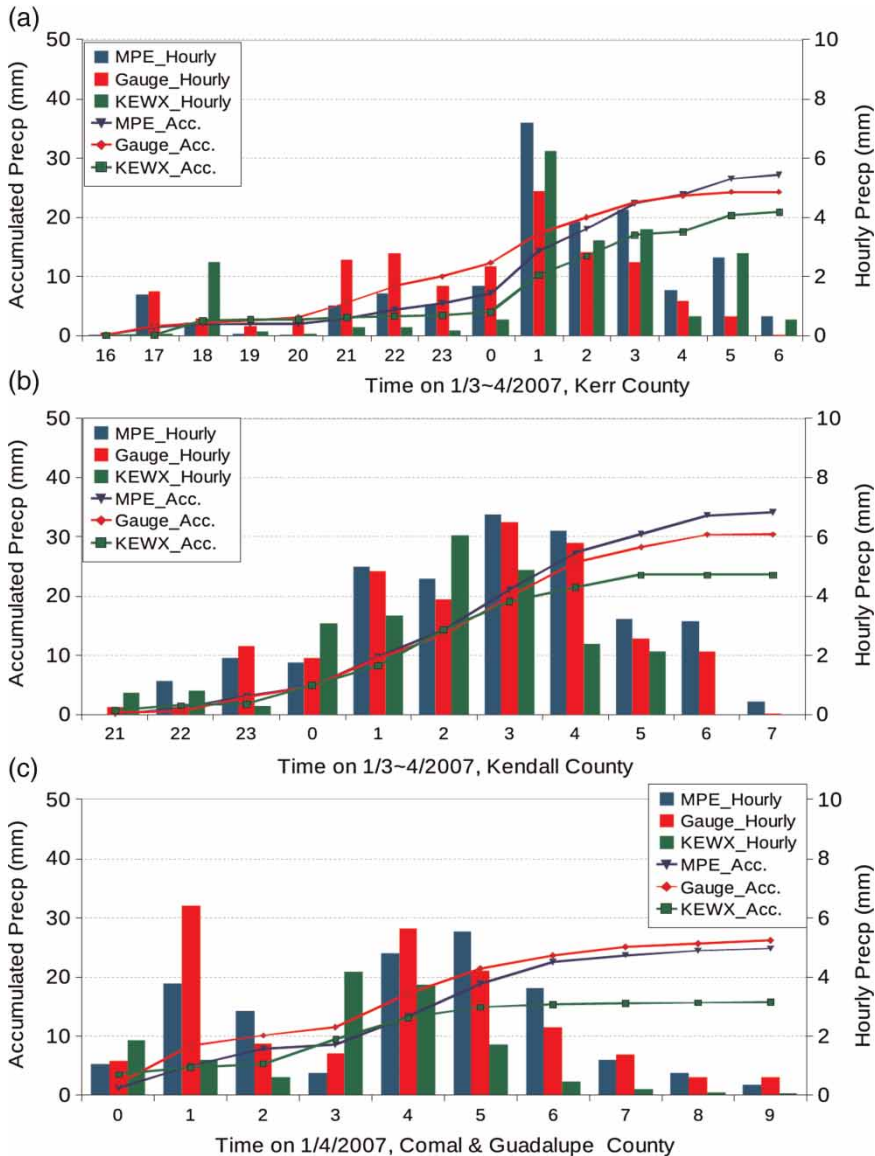


Figure 7 | Accumulated (left-hand vertical axis) and hourly (right-hand vertical axis) precipitation detected at three areas by gauges, MPE and KEWX DSP for event two on January 3-4, 2007.

precipitation of 25.8 mm. The KEWX DSP captured the event evolution, but had lower values than gauges in the hours 00:00-3:00 (Table 2, Figure 5(c)). The KDFX DSP almost missed this event entirely, and only received 10% of the total precipitation (Table 2, Figure 6(c)). MPE was in good agreement with gauges except for its lower value for hours 01:00, 03:00, and 04:00, and higher values at hours 02:00, 05:00, and 06:00 (Table 2, Figure 7).

The KEWX DSP accurately captured the event evolution for all three areas, but with lower values or zero at

times during the event, resulting in lower event total precipitation. The magnitude of underestimation around the radar (range <30 km) in Comal and Guadalupe Counties was larger than for Kendall County (range 50-75 km) and Kerr County (range 100-170 km). The KDFX DSP also had lower event total precipitation than the gauges in all three sub-areas. The magnitude of the difference increased with range, particularly for Comal and Guadalupe Counties at ranges >180 km. After mosaicking all available radar and being calibrated with gauge measurements,

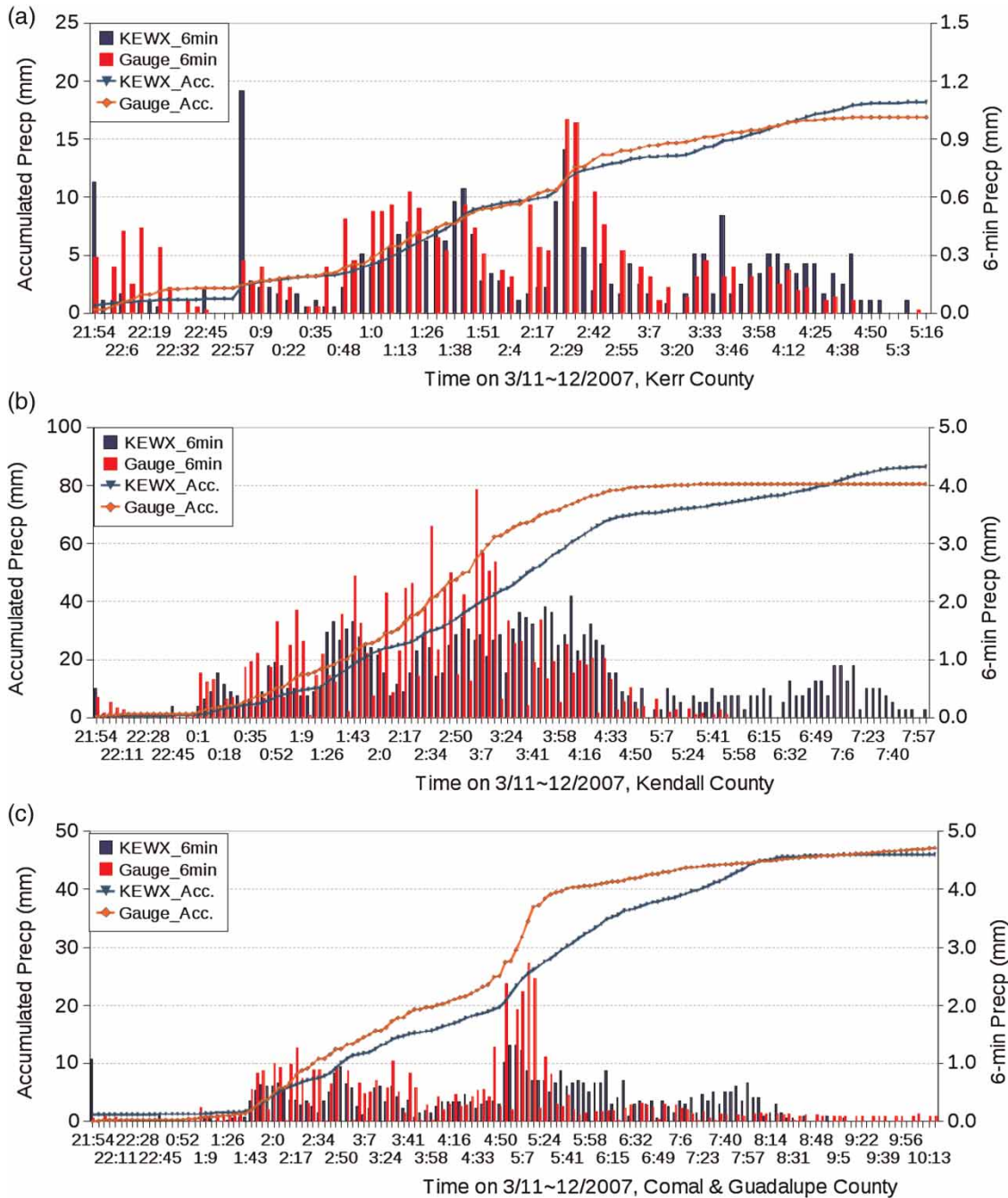


Figure 8 | Accumulated (left-hand vertical axis) and 6-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KEWX DSP for event three on March 11–12, 2007.

MPE was in good agreement with gauges and better agreement with gauges during the event evolution and for the event total precipitation, but varied in over- or underestimation at times.

Event three

This was the heaviest event and began in Kerr County at 21:54 on March 11, 2007 and ended in Comal and

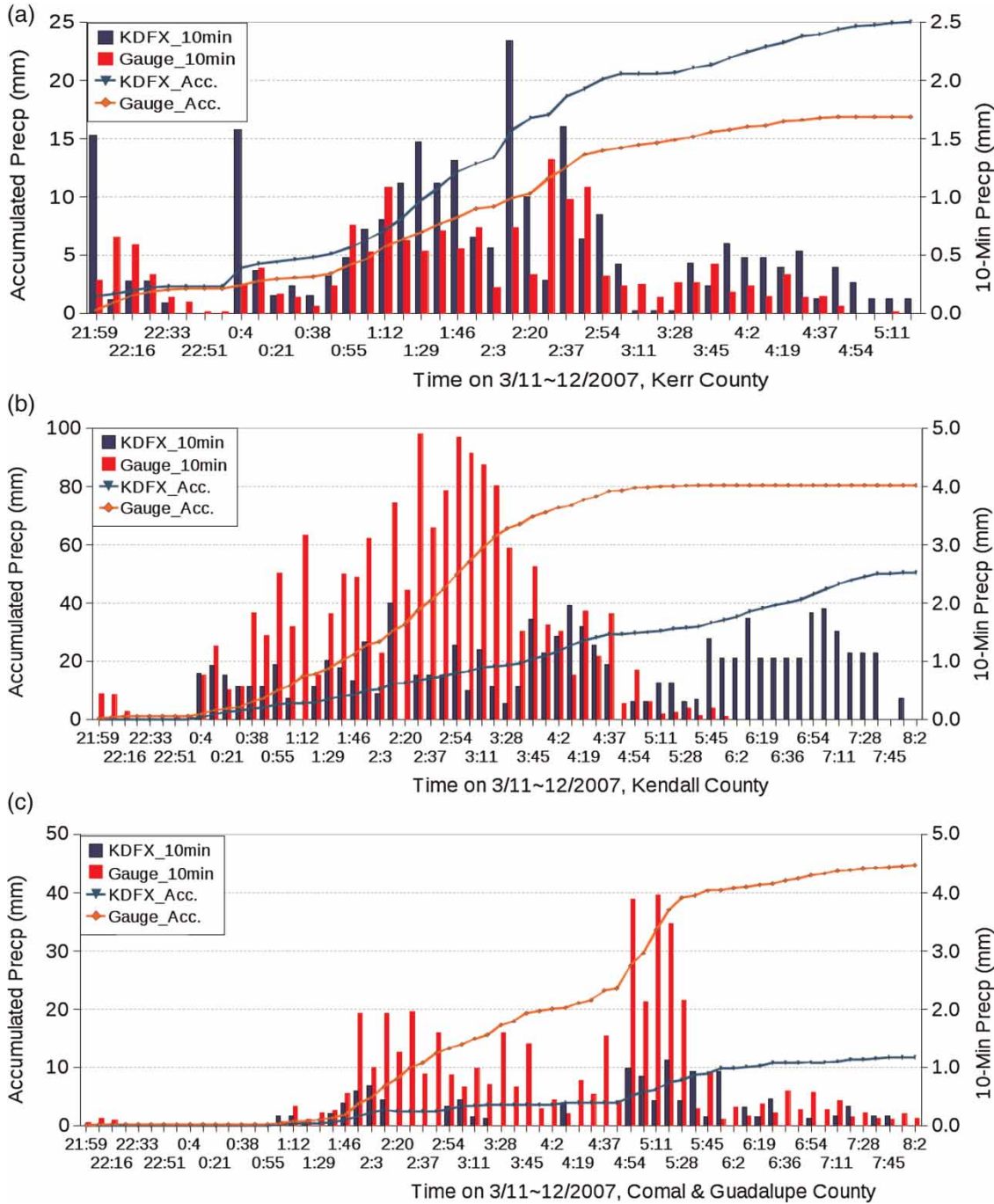


Figure 9 | Accumulated (left-hand vertical axis) and 10-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KDFX DSP for event three on March 11–12, 2007.

Guadalupe Counties at 10:00 on March 12. The centroid of the event was in Kendall County with an event total precipitation of 80.5 mm in 4 hours (Table 3).

In Kerr County, the event total precipitation was 16.9 mm. The KEWX DSP was in good agreement with gauges for the event evolution and event total precipitation, except for some spikes of higher rainfall at the 6-minute

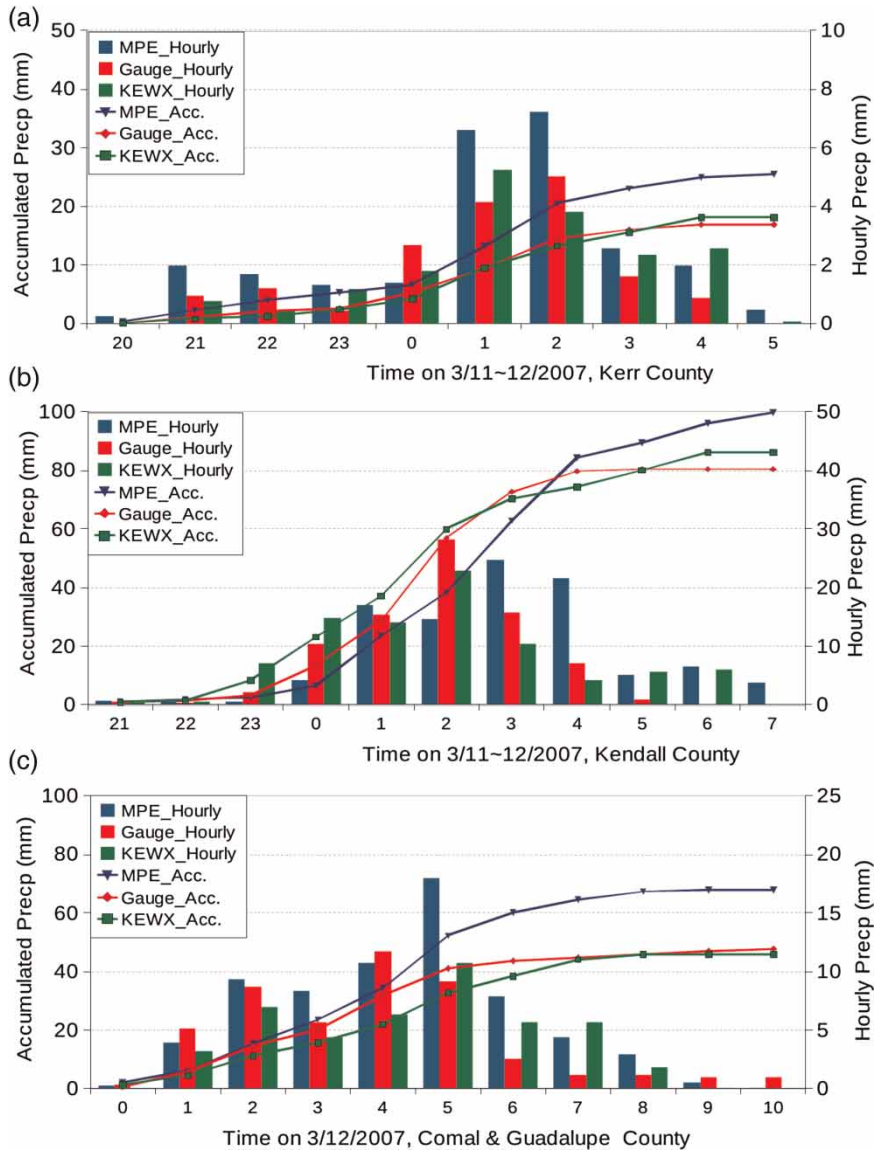


Figure 10 | Accumulated (left-hand vertical axis) and hourly (right-hand vertical axis) precipitation detected at three areas by gauges, MPE and KEWX DSP for event three on March 11–12, 2007.

scale (Figure 8(a)). The KDFX DSP had larger values than gauges for most of the event, leading to larger event total precipitation than the gauges (Figure 9(a)). MPE behaved similarly to the KDFX DSP (Figure 10(a)).

In Kendall County, the KEWX DSP had lower values than the gauges during the event growth, but larger values around the event dissipation, with similar event total precipitation (Table 3, Figure 8(b)). Some larger estimates within the 3 hours from 5:00 to 7:00 were caused by the radar estimate in Comal and Guadalupe Counties that was

not detected by gauges in Kendall County. The KDFX DSP had much lower values than gauges before the event peak time and had much larger values during the event dissipation, when gauges did not detect any rainfall (Figure 9(b)). MPE behaved similarly with the KEWX DSP (Figure 10(b)).

In Comal and Guadalupe Counties, the event total precipitation was 47.1 mm (Table 3). KEWX DSP had lower values than gauges during the event, particularly near peak time, but had larger values during the event dissipation,

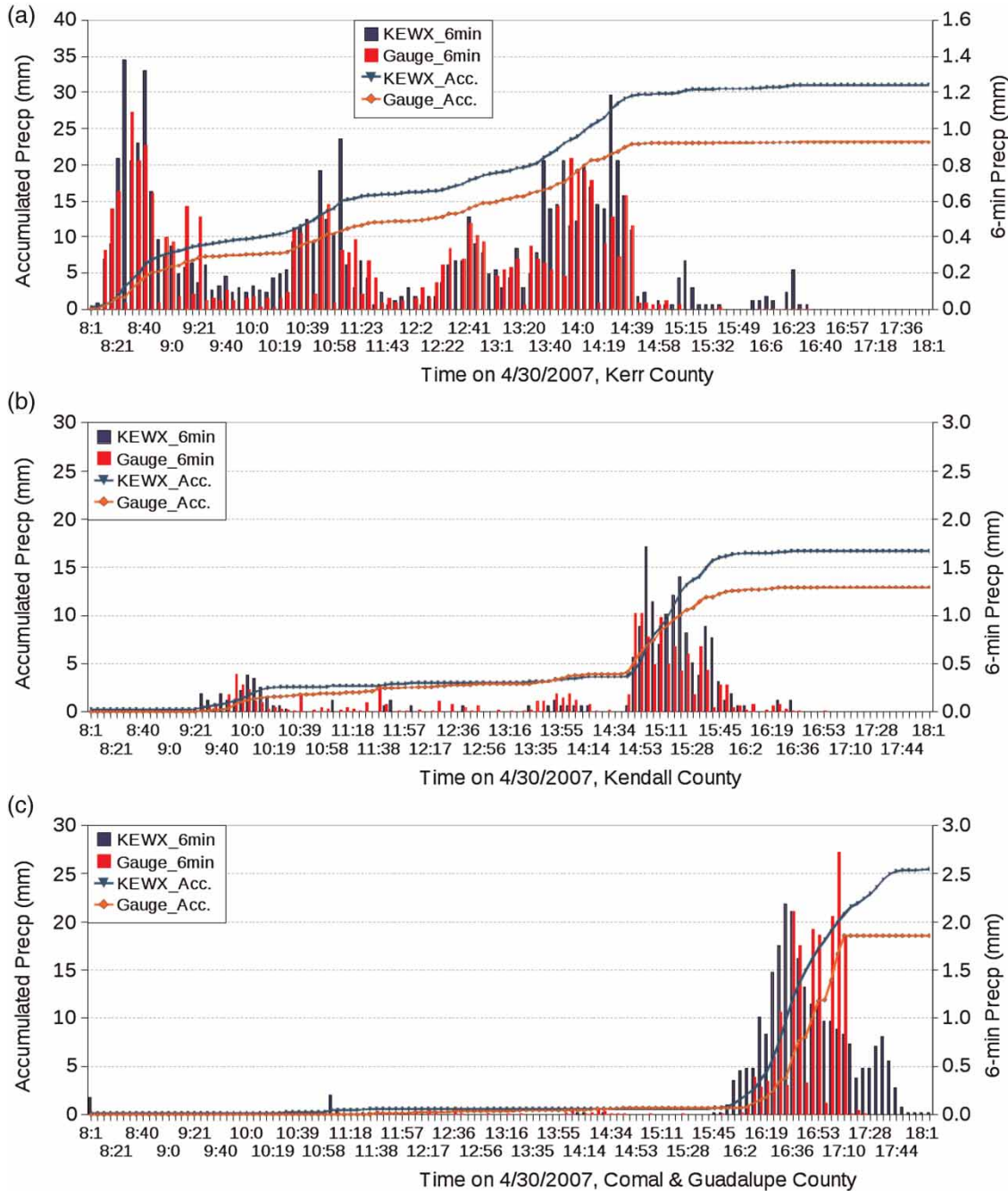


Figure 11 | Accumulated (left-hand vertical axis) and 6-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KEWX DSP for event four on April 30, 2007.

resulting in a similar event-total precipitation as gauges (Figure 8(c)). Similar to the January 4 event (Figure 6(c)), the KDFX DSP had dramatically lower values (only 11.7 mm) than gauges (47.1 mm) for ranges >180 km (Figure 9(c)). MPE had larger values than gauges, especially near the event peak and dissipation times (Figure 10(c)).

Overall, this event was the most intense one among the four events studied. The KEWX DSP had the best agreement with gauges for the three areas for event total precipitation. This indicates a potential benefit of DSP for flash flood forecasting, although more studies are needed for different rainfall events, in different environments, and for different

radars. The KDFX DSP had worse performance than the KEWX DSP, and it worsened at far ranges over Comal and Guadalupe Counties. MPE tended to have larger event total precipitation than gauges and KEWX DSP for all three sub-areas, but had a lower sub-hourly peak value near the storm center in Kendall County, and larger event peak values for the other two sub-areas.

Event four

This event also moved eastward from Kerr County to Guadalupe County. The storm center was in Kerr County with three peaks and total precipitation of 23.0 mm (Table 4). The event actually lasted around 1 hour in Kendall, Comal and Guadalupe Counties with total precipitation of 13.8 and 18.7 mm, respectively (Table 4, Figures 11 and 12). The KEWX DSP accurately captured the event evolution, but had higher storm accumulations and storm total values than gauges for all three sub-areas. Higher estimates occurred during the storm peak time in Kerr and Kendall Counties (Figures 11(a) and (b)), and in the storm growth and dissipation times in Comal and Guadalupe Counties (Figure 11(c)). The KDFX DSP performed similarly to the KEWX DSP for all three sub-areas except it had slightly lower sub-hourly accumulations and event total precipitation than gauges in Kendall County (Figure 12). MPE also behaved similarly with KEWX, but it dramatically overestimated the peak rainfall in Kendall County (Figure 13).

Total precipitation comparison

Besides the detailed analysis on the above four rain events, we also compare the total precipitation in all 30 rain events detected by individual gauges, DSP, and MPE from September 11, 2006 to May 10, 2007 (Figures 14(a) for KEWX radar and 14(b) for KDFX radar since KEWX and KDFX radars have different archive time and time intervals). KEWX radar recorded 30 events larger than 6.5 mm, for a total of 313.4 hours of rainfall and total accumulations up to 434 mm. KDFX radar also recorded 30 events larger than 6.5 mm, for a total of 234.3 hours of rainfall and total accumulations up to 408 mm.

The range from KEWX to the gauges varies from 3 to 165 km (Figures 1 and 14(a)). Over Kerr County, where the range varies from 100 to 165 km, the KEWX DSP values are higher (mean absolute EB (MAEB) = 22%) than the gauge observations except at one gauge with an EB of -42%, while MPE values are less than gauge values with an MAEB of 25%. In Kendall County, where the range between KEWX and the gauges varies from 50 to 85 km, both the KEWX DSP and MPE values are slightly higher than gauge observations with MAEBs of 15 and 12%, respectively. In Comal and Guadalupe Counties, where the KEWX to gauges range is less than 30 km, both the KEWX DSP and MPE values are lower than gauge observations with MAEBs of 28 and 17%, respectively.

Overall, the range from KDFX radar to the same rain gauges is much larger than KEWX, varying from 100 to 230 km (Figures 1 and 14(b)). However, the ranges from gauges in Kerr County to the KEWX and KDFX radars are similar (100–150 km). Like KEWX, the KDFX DSP is slightly higher than the gauge observations with an MAEB of 16%, while MPE has an MAEB of 13%. In Kendall County, where the range to KDFX varies from 160 to 190 km, the KDFX DSP is lower than the gauges with an MAEB of 28%, while MPE values are higher than the gauges with an MAEB of 11%. Over Comal and Guadalupe Counties, where the range is large (207–228 km), KDFX DSP values are much lower than the gauges with an MAEB of 58%, while MPE are close to the gauges with an MAEB of 11%.

Compared with gauge observations, the DSP values from the two radars display strong range dependence for the total precipitation within the study period. The range dependence for the uncalibrated DSP product is stronger for lighter rainfall than the four heavier storms in this study. Thus, DSP is not recommended for applications such as a total water resource budget calculation over a long period. Surrounding each radar station (range <30 km), DSP estimates less rainfall (MAEB = 28%) than gauge observations. At ranges of 50–100 km and 100–150 km, DSP has slightly higher estimates (MAEB = 15–22%) than gauges, as well as the closest agreement with rain gauge data. At farther ranges of 175–200 km, DSP estimates less rainfall (MAEB = 28%) than gauges, with a much larger deficit (MAEB = 58%) at the furthest ranges >200 km. Compared with DSP estimates for individual radars, MPE does not show any clear range dependence,

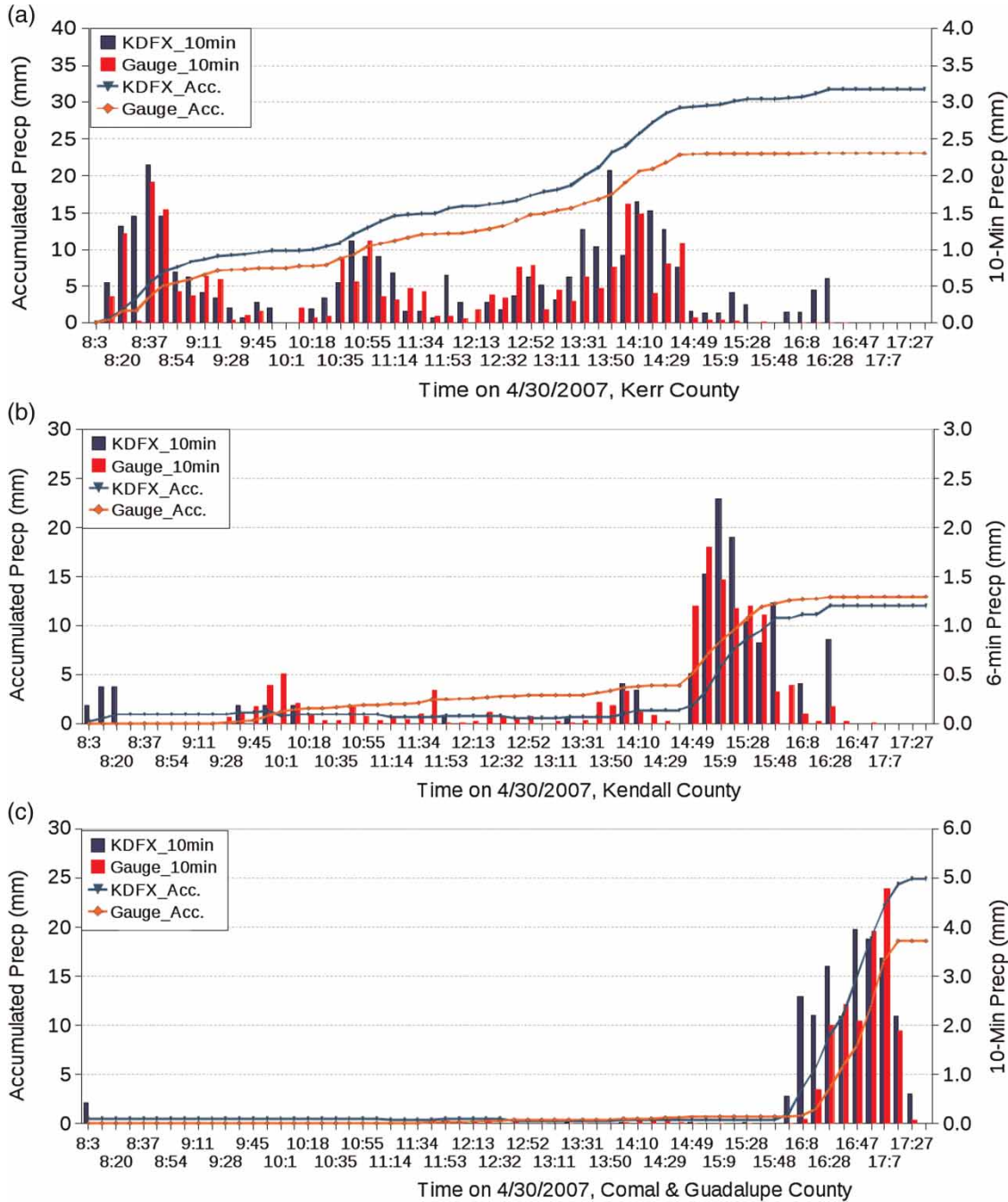


Figure 12 | Accumulated (left-hand vertical axis) and 6-minute (right-hand vertical axis) precipitation detected at three areas by gauges and KDFX DSP for event four on April 30, 2007.

and has superior accuracy over the two DSP products. The better agreement of MPE with gauge measurements is in part due to the fact that MPE data are calibrated by the measurements from the 17 GBRA gauges and other gauges nearby. When separating the 17 gauges that are used in

the MPE generation from the other 30 gauges in the GBRA, MPE has closer agreement with the 17 gauges (MAEB = 16%) than with the other 30 gauges (MAEB = 22%). In addition, the agreement of both MPE and DSP with gauge values did not show any dependence on

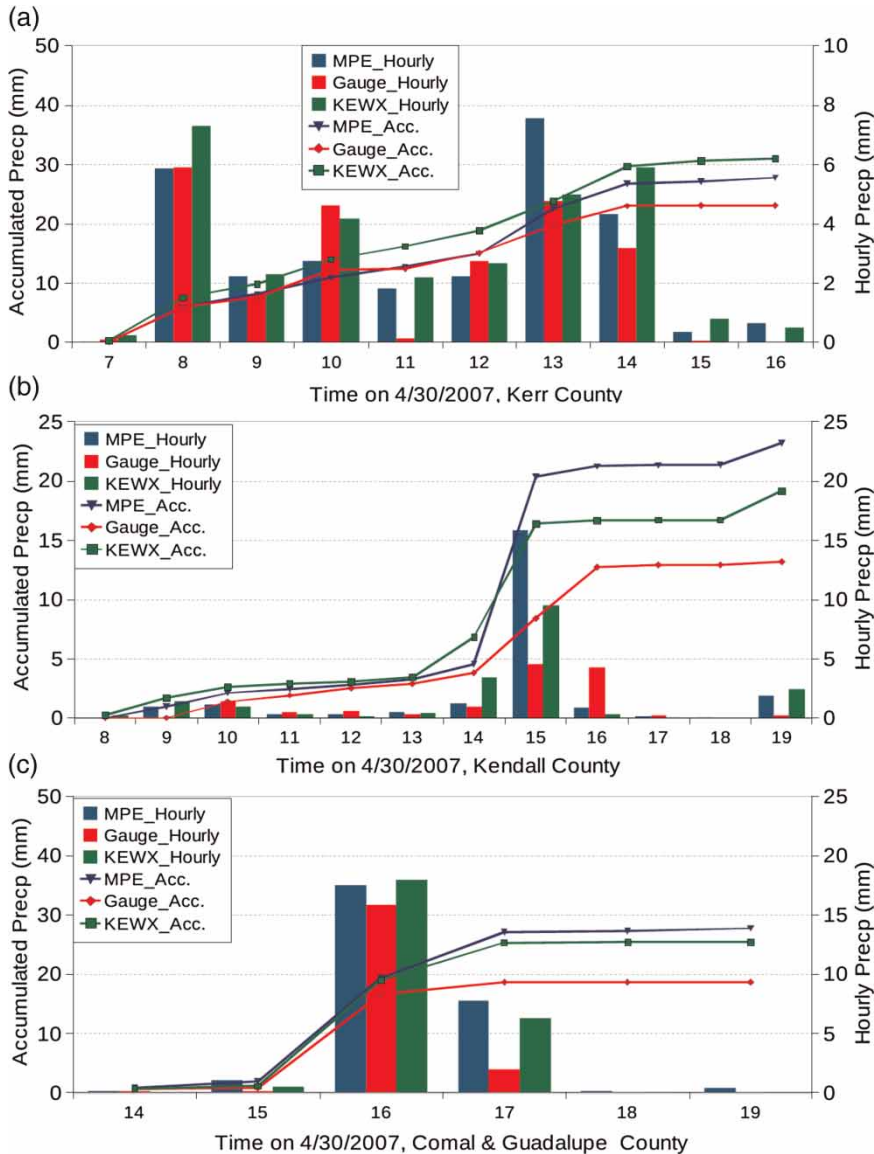


Figure 13 | Accumulated (left-hand vertical axis) and hourly (right-hand vertical axis) precipitation detected at three areas by gauges, MPE and KEWX DSP for event four on April 30, 2007.

elevation at the gauge sites, which varies from 150 to 750 m above sea level (not shown) over the study area.

DISCUSSIONS

Spatial representative errors

This study assumes that gauge measurements are ground truth for precipitation in a radar grid (i.e., $2\text{ km} \times 1^\circ$ for

DSP, $4\text{ km} \times 4\text{ km}$ for MPE). This assumption may introduce representative errors between point gauge measurements and the areal sampling of the radar beam because of the spatial heterogeneity of rainfall (Ciach & Krajewski 1999; Gage *et al.* 1999; Wang *et al.* 2008; Cole & Moore 2009; Mandapaka *et al.* 2009). In order to mitigate the spatial representative error of gauge rainfall observation, comparisons for the four heavy rainfall events are carried out for spatially averaged rainfall within each sub-area, while the comparisons of the total rainfall for all 30 rain

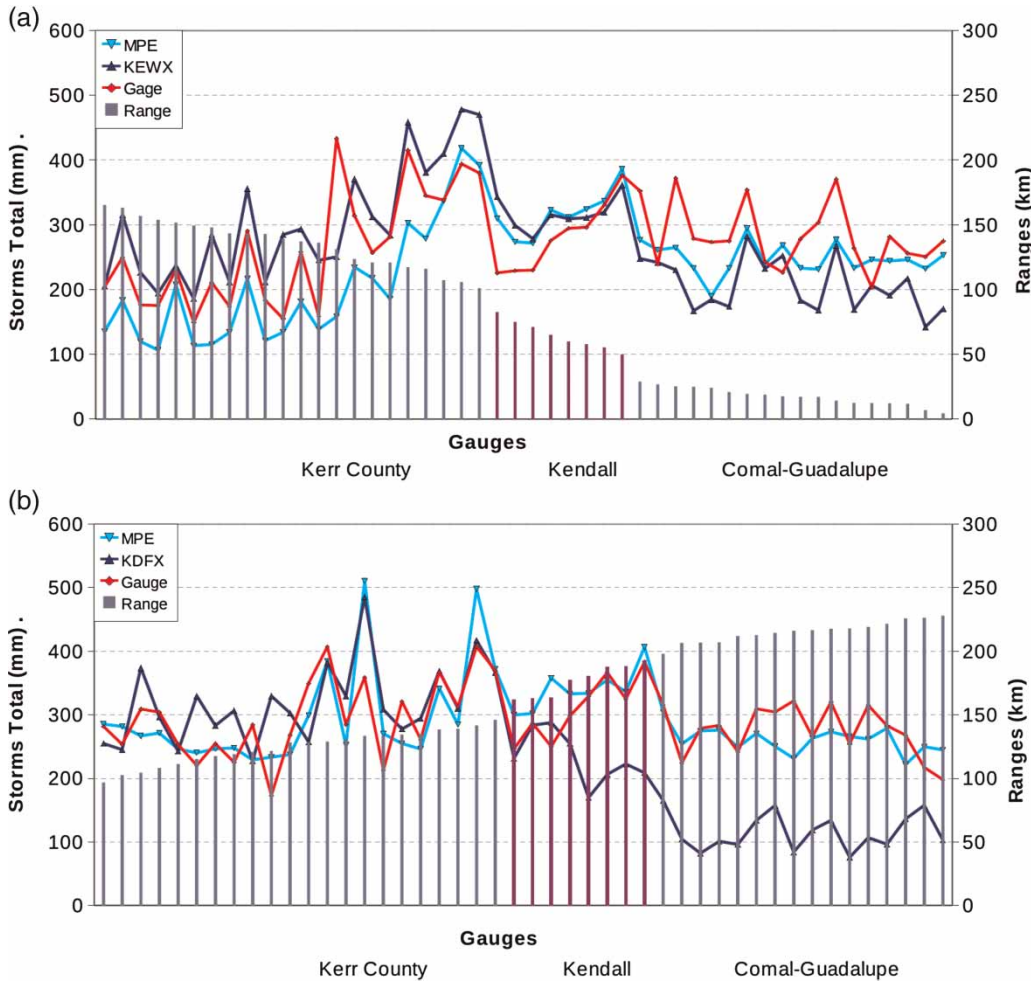


Figure 14 | Total gauge and radar MPE and DSP precipitation (left-hand vertical axis) of all events at each rain gauge from September 11, 2006 to May 10, 2007, and the range (right-hand vertical axis) from each radar to gauges. KDFX radar does not have data at two rain gauge grids, which are removed from the comparison because they are out of the effective beam range. Another two gauges are removed from the event total comparison for both KDFX and KEWX radars because of a gauge data quality problem.

events are implemented at individual pairs of gauge-radar cell. In the four events illustrated, MPE and gauge measurements show good agreement at the hourly and storm-total scales, which implies that the spatial average would mitigate the spatial representative error of gauge rainfall (Wang et al. 2008).

MPE product

Seventeen GBRA gauges located in Kendall and Comal Counties (Figure 1) were likely used as part of the MPE process although it is not clear when and how the 17 gauge data were used in the MPE process among the total 1,771 rain gauges used in the WGRFC. The MPE process is subjective

in that WGRFC forecasters examine the input data and perform quality control, and may include or exclude any source thought to improve the precipitation analysis in their judgment. In contrast, the DSP product is strictly the radar conversion of reflectivity with objective quality control of the precipitation processing system. MPE is presented as a bridge variable incorporating both radar and gauge data, but having lower spatial and temporal resolutions than the DSP product.

It is possible that incorporation of the 17 GBRA gauges and other nearby gauges into the MPE process may elevate the agreement of MPE estimate with the GBRA gauge observations on the entire Upper Guadalupe River Basin as shown in Wang et al. (2008). When separating the 17

gauges that were partly used in the MPE generation from the other 30 gauges in the GBRA, MPE indeed shows a closer agreement with the 17 gauges (MAEB = 16%) than the other 30 gauges (MAEB = 22%) for the total rainfall of 30 rain events. As for the four heavy rain events illustrated in Figures 4, 7, 10, and 13, there is no consistent discrepancy in MPE's agreement with gauges in Kerr County (where GBRA gauges are not included in the MPE process), versus Kendall County, where GBRA gauges are included in the MPE process.

DSP product

DSP often shows lower estimates during the event growth period, but higher estimates during the event dissipation period. For example, on September 18, 2006, the KDFX DSP had larger values than gauges during storm dissipation over Kendall, Comal, and Guadalupe Counties (Figures 3(b) and 3(c)). On January 3–4, 2007, both the KEWX and KDFX DSPs had lower precipitation than gauges for Kerr County from hour 19:00 to 00:00, and then had larger values within hour 05:00 the next day (Figures 5(a) and 6(a)). The amount of the lower estimate in the event growth is relatively small compared with the event total rainfall and is compensated by overestimates in the event dissipation period (KEWX DSP, Figures 8(b) and 8(c)). However, the effect of such underestimates during the event growth period is not negligible and would certainly affect the ability to forecast flash flooding.

One likely reason for overestimation of rainfall during the dissipation of a rain event is the increasing importance of below-beam effects as the rain event ends. Even though rainfall ends at the surface due to evaporation of raindrops, the intra-cloud drops detected by radar will still result in the radar rainfall processing algorithm to indicate precipitation. For instance, during 06:00–08:00 on March 12 (see Figure 8), gauges recorded light rainfall in Comal and Guadalupe Counties at close radar range but no rainfall in Kendall County at mid-radar range; in contrast, KEWX DSP showed rainfall in both ranges. In addition, the moist atmosphere after heavy rainfall may also contribute to higher reflectivity and overestimation in the event dissipation period.

Range effects can explain most of the differences between radar estimates and gauge measurements. The

integrated range effects are strong at ranges further than 180 km for the KDFX DSP in Comal and Guadalupe Counties, particularly for shallow and light rainfalls. For example, at similar ranges in Kerr County, both the KEWX and KDFX DSP had good agreement with gauge measurements ((A) in Figures 2–13). However, over the same sampling areas in Kendall, Comal, and Guadalupe Counties, the KEWX DSP at shorter ranges (<85 km) and lower beam heights (<1,200 m AGL) had much better agreement with gauges than the KDFX DSP at longer ranges (160–230 km) and higher beam heights (2,900–5,100 m AGL) ((B) and (C) in Figures 2–13). The radar beam height represents the altitude above ground for the lowest radar beam with scan elevation angle of 0.5° according to the 4/3 Earth model, which explains the integrated effect of Earth's atmosphere on electromagnetic waves traveling through atmosphere, and the beam height at each rain gauge is proportional to the radar beam range with a geometric relationship (OFCM 2005).

Besides the four heavy rain events, the range dependence of DSP is more severe for total precipitation estimation during the study period (Figures 14(a) and 14(b)), particularly in those areas where the radar range is more than 190 km and the beam height is higher than 4 km AGL. In part of Kendall County and in Comal and Guadalupe Counties, the KDFX DSP total precipitation in the study period is much lower (–58%) than the gauge measurements, and lower than the KEWX DSP which is at the close range (<30 km) for the same areas. Ranges to the KEWX radar vary from 5 to 165 km for the 50 gauge sites, and the radar beam heights above these gauge sites vary from 50 to 3,040 m AGL. Ranges to the KDFX radar vary from 97 to 228 km, and the radar beam heights vary from 1,400 to 5,120 m AGL. In addition, rainfall detected at a high altitude (e.g., over 4,000 m AGL), may move/drift as it falls to the ground, in which case a collocated rain gauge may no longer measure the same rain drops detected at that beam height. In addition, beams over 4,000 m AGL are usually above the freezing level, where the ice particles have lower radar reflectivity. Moreover, the attenuated reflectivity and larger noise ratio for longer beam ranges may also contribute to the lower radar DSP estimates. Overcoming range dependences and combining estimates at different beam heights for areas with overlapping radar coverage would

improve the DSP product, and should be a priority for further development.

SUMMARY

This study evaluates the NEXRAD DSP product with gauge measurements through analyzing 30 rain events, with detailed analysis on four heavy rain events from September 2006 to May 2007 on the Upper Guadalupe River Basin, Texas, to assess its potential application for flash flood forecasting. Overall, for short temporal intervals and in near-real time, the DSP product provides detailed and relatively accurate information on the rainfall event evolution, which suggests the potential benefits of DSP for flash flood forecasting, at least in south central Texas, USA, although more studies are needed to evaluate the DSP for different rain events, in different river basins, and for different radars. More often, the DSP product tends to have lower values or even zero values during the event initiation, but has larger estimates during event dissipation compared with rain gauge measurements.

The radar range directly affects the accuracy of the DSP product, especially for light rainfall. At the ranges of 50–150 km, DSP has the best agreement with gauges, with overestimates for some events and underestimates for others. For all events in the study period, an overall DSP overestimation (MAEB 15–22%) is found. Over the same sampling areas, different radars may have different precipitation estimates due to differences in their range to (and beam height above) the sampling areas. For example, the sub-area in the Guadalupe and Comal Counties is very close to KEWX, but at the extreme far range of KDFX. The magnitude of underestimates for locations near KEWX (<30 km) is smaller than that for KDFX at the far end of its range (>200 km).

Compared with DSP, MPE has been mosaicked with neighboring radar estimates, infused with estimates from satellite data (but not usually in the study area), and has been calibrated with rain gauge data. As expected, MPE is superior to the uncalibrated DSP product for the total rainfall of 30 rain events analyzed, but such superiority is not consistent for the four heavy rain events. MPE also shows better agreement with the 17 gauge measurements that

were used in the MPE generation than the other 30 gauge measurements that were not used. However, the processing time for MPE and its unavailability in near-real time limit its application for flash flood forecasting. Thus, further study toward reducing errors in the DSP product for all ranges from the radar site, and combining data from multiple radars for areas with overlapping coverage, may improve the DSP product and provide better rainfall estimates and product availability in near-real time.

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REFERENCES

- Bedient, P. B., Holder, A., Benavides, J. A. & Vieux, B. E. 2003 [Radar-based flood warning system applied to Tropical Storm Allison](#). *J. Hydrol. Eng.* **8**, 308–318.
- Boldi, R. A., Wolfson, M. M., Johnson Jr., R. J., Theriault, K. E., Forman, B. E. & Wilson, C. A. 2002 An automated, operational two hour convective weather forecast for the corridor integrated weather. Preprints, In: *10th Conference on Aviation, Range, and Aerospace Meteorology*, Portland, OR, American Meteorological Society, pp. 116–119.
- Ciach, G. J. & Krajewski, W. F. 1999 [Radar-rain gauge comparisons under observational uncertainties](#). *J. Appl. Meteorol.* **38**, 1519–1525.
- Cole, S. J. & Moore, R. J. 2009 [Distributed hydrological modeling using weather radar in gauged and ungauged basins](#). *Adv. Water Resour.* **32**, 1107–1120.

- Fulton, R. A., Breidenbach, J. P., Seo, D. J. & Miller, D. A. 1998 The WSR-88D rainfall algorithm. *Weather Forecast* **13**, 377–395.
- Gage, K. S., Williams, C. R., Ecklund, W. L. & Johnston, P. E. 1999 Development and application of Doppler Radar Profilers to ground validation of satellite precipitation measurements. *Adv. Space Res.* **7**, 931–934.
- Habib, E., Larson, B. F. & Grasel, J. 2009 Validation of NEXRAD multisensor precipitation estimates using an experimental dense rain gauge network in south Louisiana. *J. Hydrol.* **373**, 463–478.
- Jayakrishnan, R., Srinivasan, R. & Arnold, G. J. 2004 Comparison of rain gauge and WSR-88D Stage III precipitation data over the Texas-Gulf basin. *J. Hydrol.* **292**, 135–152.
- Krajewski, W. F. & Smith, J. A. 2002 Radar hydrology: rainfall estimation. *Adv. Water Res.* **25**, 1387–1394.
- Landel, G., Smith, J. A., Baeck, M. L., Steiner, M. & Ogden, F. L. 1999 Radar studies of heavy convective rainfall in mountainous terrain. *J. Geophys. Res.* **104** (D24), 31451–31466.
- Mandapaka, P. V., Krajewski, W. F., Ciach, G. J., Villarini, G. & Smith, J. A. 2009 Estimation of radar-rainfall error spatial correlation. *Adv. Water Resour.* **32**, 1020–1030.
- Mazari, N., Xie, H., Zeitler, J. & Sharif, H. 2012 Validation of the NEXRAD DSP product with a dense gauge network. *J. Hydrol. Eng.* doi:10.1061/(ASCE)HE.1943-5584.0000676.
- Mueller, C., Saxen, T., Roberts, R., Wilson, J., Betancourt, T., Dettling, S., Oien, N. & Yee, J. 2003 NCAR Auto-Nowcast system. *Weather Forecast.* **18**, 545–561.
- NOAA 2005 Precipitation processing system (PPS) product format description. Online article, retrieved in June, 2009. Available from: http://www.weather.gov/oh/hrl/wsr88d_prods/docs_bld08/DSP.pdf.
- OFCM 2005 Federal Meteorological Handbook No.11 Part B. Doppler radar meteorological observations: Doppler radar theory and meteorology. FCM-H11B-2005. Retrieved on January 12 2010. Available from: <http://www.ofcm.gov/fmh11/fmh11partb/2005pdf/fmh-11B-2005.pdf>
- OFCM 2006 Federal Meteorological Handbook No.11 Part C. Doppler radar meteorological observations: WSR-88D products and algorithms. FCM-H11C-2006. Retrieved on January 12 2010. Available from: <http://www.ofcm.gov/fmh11/fmh11partc/2005pdf/fmh-11C-2005.pdf>
- OFCM 2011 Federal Meteorological Handbook No.11 Part A. Doppler radar meteorological observations: System concepts, responsibilities, and procedures. FCM-H11A-2011. Retrieved on June 10, 2012. Available from: http://www.ofcm.gov/fmh11/fmh11parta/pdf/_PartA_FMH11_07-10-OFCM-Rev11.pdf.
- Ogden, F. L., Sharif, H. O., Senarath, S. U. S., Smith, J. A., Baeck, M. L. & Richardson, J. R. 2000 Hydrologic analysis of the Fort Collins, Colorado flash flood of 1997. *J. Hydrol.* **228**, 82–100.
- Rico-Ramirez, M. A. & Cluckie, I. D. 2007 Bright-band detection from radar vertical reflectivity profiles. *Int. J. Remote Sens.* **28** (18), 4013–4025.
- Rogalus III, M. J. & Ogden, F. L. 2007 Comparison of GCIP and stage III radar-rainfall estimates over the Mississippi River Basin for 1997. *J. Hydrol.* **341**, 177–185.
- Seo, D.-J. & Breidenbach, J. P. 2002 Real-time correction of spatially nonuniform bias in radar rainfall data using rain gauge measurements. *J. Hydrometeorol.* **3** (2), 92–111.
- Sharif, H. O., Yates, D., Roberts, R. & Mueller, C. 2006 The use of an automated now-casting system to forecast flash floods in an urban watershed. *J. Hydrometeorol.* **7**, 1.
- Shepherd, M., Mote, T., Dowd, J., Roden, M., Knox, P., McCutcheon, S. C. & Nelson, S. E. 2010 An overview of synoptic and mesoscale factors contributing to the disastrous Atlanta flood of 2009. *Bull. Am. Meteorol. Soc.* **92**, 861–870.
- Smith, J. A., Seo, D. J., Baeck, M. L. & Hudlow, M. D. 1996 An intercomparison study of NEXRAD precipitation estimates. *Water Resour. Res.* **32**, 2035–2045.
- Wang, X., Xie, H., Sharif, H. & Zeitler, J. 2008 Validating NEXRAD MPE and Stage III precipitation products for uniform rainfall on the Upper Guadalupe River Basin of the Texas Hill Country. *J. Hydrol.* **348**, 73–86.
- Weissling, B. & Xie, H. 2008 Proximal watershed validation of a remote sensing-based streamflow estimation model. *J. Appl. Remote Sens.* **2**, 023549.
- Weissling, B. & Xie, H. 2009 MODIS biophysical states and NEXRAD precipitation in statistical evaluation of antecedent moisture condition and streamflow. *J. Am. Water Resour. Assoc.* **45** (2), 419–433.
- Weissling, B., Xie, H. & Murray, K. 2009 Evaluation of NRCS curve number and MODIS time series proxies for antecedent moisture condition. *Civ. Eng. Environ. Syst.* **26** (1), 85–101.
- Xie, H., Zhou, X., Hendrickx, J., Vivoni, E., Guan, H., Tian, Y. & Small, E. 2006 Evaluation of NEXRAD Stage III precipitation data over semiarid region. *J. Am. Water Resour. Assoc.* **42** (1), 237–256.
- Xie, H., Zhou, X., Vivoni, E. R., Hendrickx, J. M. H. & Small, E. E. 2005 GIS based NEXRAD precipitation database: automated approaches for data processing and visualization. *Comput. Geosci.* **31**, 65–76.