Characterizing Subdiurnal Extreme Precipitation in the Midwestern United States

NATHAN M. HITCHENS, ROBERT J. TRAPP, MICHAEL E. BALDWIN, AND ALEXANDER GLUHOVSKY

Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana

(Manuscript received 19 November 2008, in final form 30 July 2009)

ABSTRACT

This research establishes a methodology to quantify the characteristics of convective cloud systems that produce subdiurnal extreme precipitation. Subdiurnal extreme precipitation events are identified by examining hourly precipitation data from 48 rain gauges in the midwestern United States during the period 1956–2005. Time series of precipitation accumulations for 6-h periods are fitted to the generalized Pareto distribution to determine the 10-yr return levels for the stations. An extreme precipitation event is one in which precipitation exceeds the 10-yr return level over a 6-h period. Return levels in the Midwest vary between 54 and 93 mm for 6-h events. Most of the precipitation contributing to these events falls within 1–2 h. Characteristics of the precipitating systems responsible for the extremes are derived from the National Centers for Environmental Prediction stage II and stage IV multisensor precipitation data. The precipitating systems are treated as objects that are identified using an automated procedure. Characteristics considered include object size and the precipitation mean, variance, and maximum within each object. For example, object sizes vary between 96 and 34 480 km², suggesting that a wide variety of convective precipitating systems can produce subdiurnal extreme precipitation.

1. Introduction

As with other convective weather hazards, inland flash flooding poses a significant forecasting and warning challenge that is made worse by its severe consequences on life, property, and agriculture. Reduction of this impact has come from advances in the understanding of the precipitation extremes that contribute to such flooding. Extreme rainfall is most often identified and studied in terms of 24-h rainfall accumulations (Bradley and Smith 1994; Konrad 2001; Schumacher and Johnson 2005, 2006; Silva and Berbery 2006; Smith et al. 1994), owing in part to a broader availability of data, especially from cooperative rain gauge networks (Hammer and Steurer 2003). For instance, Bradley and Smith (1994) used daily accumulation data from gauges to define extreme events and then further classified the events according to the strength of the larger-scale dynamical forcing.

Further advances have been made from studies relating extreme precipitation events to the type of precipitating weather systems responsible for the event. Recently, Schumacher and Johnson (2005) linked me-

so-scale convective systems (MCSs) and mesoscale convective complexes (MCCs) to daily extremes in the United States. Using hourly gauge data to examine the events more closely, and radar data for classification purposes, they found that about 65% of all the events were the result of MCSs, whereas 25% were driven by synoptic-scale processes. Other modes of cumulus convection—namely, supercell thunderstorms—have also been shown to generate extreme amounts of rainfall (Bauer-Messmer et al. 1997; Smith et al. 2001). Bauer-Messmer et al. (1997) concluded that rainfall at time scales <1 h are critical to flash-flood response.

Beyond operational forecasting and warning issues is the potential impact of anthropogenic global warming on precipitation extremes. Trends in observational data as well as climate model simulations have been used to project future increases in both the frequency and intensity of daily extremes (e.g., Chen et al. 2005; Emori and Brown 2005; Groisman et al. 2005; Hennessy et al. 1997; Karl and Knight 1998; Wilby and Wigley 2002). Whether or not these projections also apply to extremes at shorter time scales is an open question and, indeed, Trenberth (1998, 1999) and Trenberth et al. (2003) have recommended a closer examination of extreme precipitation at an hourly temporal scale in both observations and climate models. We follow this recommendation

Corresponding author address: Nathan M. Hitchens, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907-2051.
E-mail: nhitchen@purdue.edu

herein with our focus on subdiurnal extreme precipitation, as guided by the following, overarching questions: Do the convective cloud systems that produce extreme subdiurnal precipitation have unique characteristics, and are these events predictable?

Our motivation stems from the limited research to date on short time-scale rainfall extremes. Important contributions have been made by Winkler et al. (1988), who considered hourly rainfall in the conterminous United States by using the National Climatic Data Center's (NCDC) hourly precipitation dataset (HPD), gridded into cells with a horizontal dimension of $75 \text{ km} \times 75 \text{ km}$. Hourly precipitation was binned into four categories, the largest of which was for rainfall of $\geq 1.00 \text{ in. h}^{-1}$ (25.4 mm h^{-1}). Although regional variation existed, extreme hourly precipitation was found to occur later in the day, with this being more pronounced in the summer season. Similarly, Brooks and Stensrud (2000) examined the frequency of heavy rainfall using the HPD. They found a peak during June–August in hourly precipitation $\geq 1.00 \text{ in.}$ for much of the United States.

A concern expressed by Brooks and Stensrud (2000) is that the HPD is not adequate to resolve the spatial distribution of subdiurnal extreme precipitation events due to the coarse distribution of the gauge network (e.g., Bauer-Messmer et al. 1997; Smith et al. 1994). On the other hand, the national network of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars provides derived rainfall products for a nearly continuous spatial domain, although these products are not without their own biases, for example (Fulton et al. 1998). A synthesis of these two precipitation datasets is available in a product produced by the National Centers for Environmental Prediction (NCEP) known as stage II and stage IV rainfall analysis (Fulton et al. 1998). These data are available hourly as a mosaic covering the conterminous United States in a $4 \text{ km} \times 4 \text{ km}$ grid. The present study makes use of the HPD as well as the stage II/IV data to identify and characterize precipitating systems that produce subdiurnal extreme precipitation.

This research is the first component of the multi-stage project mentioned earlier, with the ultimate goal of assessing the predictability of subdiurnal extreme-precipitation-producing systems. To meet this goal, a methodology to quantify the characteristics of these systems needs to be established. Accordingly, a sample set of subdiurnal extreme precipitation events are identified using the HPD and subsequently characterized from stage II or stage IV precipitation data.

A description of HPD analysis procedures, including our definition of an extreme, is presented in section 2. In section 3, we couple the results of the HPD analysis

FIG. 1. Locations of the 48 rain gauges used to identify events.

to an analysis of stage II/IV data and characterize the precipitating systems associated with subdiurnal precipitation extremes. Two case studies are presented in section 4 to further illustrate such characteristics, and concluding remarks and future work are given in the last section.

2. Rain gauge analysis

Rain gauge stations that were continuously operating during the period 1956–2005 are considered for this study. We focus on the midwestern region of the United States, and 48 gauges are chosen to sample a broad area across this region (Fig. 1). The reason for the focus on the midwestern region is because of the lack of significant terrain in the area and the lack of tropical influences on the precipitation regime. This area is also well sampled by the stage II/IV precipitation product, and the region contains many agricultural areas that are affected by extreme precipitation events. These data required some initial preprocessing. First, data values are rounded to the nearest tenth of an inch, in response to an instrumentation change in most gauges in the 1960s that resulted in a subsequent decrease in recording precision from hundredths to tenths of inches. Second, erroneously large data values ($>4 \text{ in.}$) with no data in the hour preceding or following the large value are removed (see Brooks and Stensrud 2000).

Each 50-yr time series is fit to the generalized Pareto distribution (GPD), and exceedances over a high threshold are chosen by standard threshold selection techniques (e.g., Coles 2001). The GPD is used in favor of the generalized extreme value (GEV) distributions because

TABLE 1. Locations and 10-yr return levels (mm) for 1-, 3-, 6-, and 12-h periods at the 48 midwestern rain gauges.

Gauge location	1 h	3 h	6 h	12 h
ILLINOIS				
Alexis	48	62	72	84
Belleville	57	72	83	95
Belvidere	45	62	74	93
Cairo	48	69	84	102
Chicago	54	71	86	98
Springfield	45	65	79	90
INDIANA				
Brazil	53	70	80	94
Columbia City	41	56	65	71
Columbus	46	58	71	81
Evansville	44	62	72	83
Fort Wayne	43	51	63	69
West Lafayette	50	63	73	84
IOWA				
Centerville	53	68	78	86
Remsen	48	64	75	82
Strawberry Point	53	67	72	82
Wallin	52	76	93	100
Washington	48	60	68	75
Webster City	52	65	74	84
MICHIGAN				
Ann Arbor	42	52	54	61
Muskegon	34	46	56	67
Owosso	42	50	56	64
Trout Lake	48	53	59	69
Vanderbilt	34	44	54	62
Wakefield	46	54	64	76
MINNESOTA				
Gulf Lake	50	64	68	75
Le Sueur	50	64	73	80
Luverne	50	57	64	72
Rushford	55	69	74	80
Thief Lake	41	53	61	72
Wales	36	46	61	62
MISSOURI				
Clearwater	50	62	75	90
Downing	50	58	71	81
Jefferson City	46	57	61	72
Miller	55	70	84	103
Steffenville	46	60	71	83
Warrensburg	54	75	94	109
OHIO				
Cambridge	51	55	61	70
Germantown	47	55	61	73
Mansfield	41	53	61	71
Portsmouth	46	57	67	74
Toledo	39	51	61	69
Youngstown	39	53	60	71

TABLE 1. (Continued)

Gauge location	1 h	3 h	6 h	12 h
WISCONSIN				
Babcock	44	61	68	78
Blanchardville	51	67	72	80
Green Bay	39	48	55	63
Hartford	49	59	65	75
New Richmond	47	58	70	75
Park Falls	50	57	60	68

the GEV uses a block maxima approach to fit the observations instead of the peak-over-threshold approach used by the GPD. The block maxima approach limits the number of observations used, whereas the peak-over-threshold approach is preferred in this study because it uses any observation that exceeds the threshold. To investigate precipitation at other subdiurnal time frames, the observations in an HPD time series are grouped into consecutive 3-h periods [0000–0300 local standard time (LST), 0400–0600 LST, and so on], 6-h periods (0000–0600 LST, 0700–1200 LST, and so on), and 12-h periods (0000–1200 LST, and so on), and 10-yr return levels are calculated for each of these groupings of observations (Table 1). A moving-window approach was considered to construct the observation periods but was dismissed. However, the issue of underestimation based on window selection as well as other aspects of defining extreme events from the HPD will be more carefully explored in future work, based on reliable estimates of the tail index (e.g., Qi 2008), a key parameter in predicting extreme events. Using these return levels, an extreme precipitation event is defined as a 6-h period that surpasses the respective 10-yr return level at a gauge. The choice of a 6-h period follows the upper-temporal boundary for events that commonly produce flash flooding (NOAA 2006).

Over the 48 gauges, the return levels for 6-h events range from 54 to 94 mm. In general, the return levels are lower in the states that are farther north (Michigan, Minnesota, Wisconsin) as well as in Ohio, which is the easternmost state. During the 50-yr period of study, there are a total of 336 events that surpass the return level for 6-h events. Furthermore, 78% of the 6-h extreme events contain a period that also qualifies as a 3-h event, and 71.8% of the events that meet the criteria for both 3- and 6-h events are part of a 12-h event.

If each 6-h extreme event is analyzed by hour (the highest one hour of precipitation, the highest two consecutive hours of precipitation, and so on), as in Fig. 2, it is seen that on average the hour with the highest precipitation accounts for nearly half of the total rainfall. Likewise, the 2-h period of highest precipitation accounts for 71% of the total accumulated rainfall during the 6-h event.

FIG. 2. Contribution to the 6-h total by largest precipitation accumulation over consecutive hours as a mean of all 36 events.

3. Stage II/IV precipitation analysis

In this section, we consider only those extreme precipitation events that additionally have corresponding stage II/IV precipitation data, which are available beginning May 1996 (January 2002 for stage IV). Of the 336 total gauge events, 36 meet this additional criterion. As indicated in Table 2, each event occurs on a different date, hence they are treated here as independent samples.

The stage II/IV data are analyzed at the hour of peak precipitation at the gauge, as well as for several hours preceding and following the peak hour, using the Baldwin object identification algorithm (BOIA; Baldwin et al. 2005). This algorithm forms precipitation “objects” from pixels with values over a user-defined threshold (Figs. 3a,b). For the purpose of this study, the threshold is 6 mm hr^{-1} , which is considered the lower bounds for convective rainfall (Johnson and Hamilton 1988). Objects are constrained by a user-defined search radius, defined here as one pixel, which has physical dimensions of $4 \text{ km} \times 4 \text{ km}$. Hence, areas of pixels with no more than a single-pixel gap are grouped into objects (Figs. 3b,c). A 1-pixel search radius is used with the BOIA to identify objects to study only the area of intense rainfall that was directly affecting the gauge. A larger search radius may include areas of precipitation in the object that are being influenced by different processes. The BOIA then diagnoses attributes of these objects, such as size (area); precipitation mean, maximum, and variance; and centroid location.

The characteristics of precipitating systems associated with the gauge extremes are revealed by the attributes of the objects affecting the gauge location at the time of peak event precipitation (Table 2). For example, the size of these objects varies between $34\,480$ and $96\,000 \text{ km}^2$, with a mean of 8054 km^2 . As a point of reference, an MCC has an interior cloud shield (satellite IR brightness temperature $\leq -52^\circ\text{C}$) with an area $\geq 50\,000 \text{ km}^2$, which corresponds to its convective region (Maddox 1980). Hence, morphologically, the associated precipitating sys-

tems range from MCCs and large MCSs to much smaller, relatively isolated, and slow-moving convective storms (see section 4). These smaller systems, and thus smaller objects, may pose challenges for predictability, whereas larger systems present a potential for more widespread flooding.

The size of the object and hence precipitating system would appear to relate to the object’s precipitation characteristics. In comparing the size of an object at the time of peak precipitation at the gauge to the maximum object precipitation (Fig. 4), there is a moderately positive trend in the data (R^2 value of 0.3), suggesting that larger objects have a higher amount of maximum precipitation. Object size also correlates positively to precipitation variance, because maximum precipitation relates nearly linearly to variance (Table 2). It should be noted that discrepancies between the gauge maximum precipitation and the corresponding object’s maximum precipitation value are partly because of spatial offsets between the gauge location and the location of the object maximum and also because of quality control procedures performed during the processing of stage II and stage IV data, effectively dampening these object maxima.

4. Case studies

In this section, we highlight two of the events in our database that illustrate the range of association between a gauge extreme and its corresponding precipitation object.

a. Wallin, Iowa: 7 August 1999

On 7 August 1999 and beginning at 0500 UTC, 157 mm of rain were recorded over six hours at the gauge located in Wallin, Iowa. This total surpassed the return level for 6-h events (93 mm), and the maximum 3-h accumulation of 119 mm also exceeded the 3-h event return level of 76 mm for this location. The hour ending 0800 UTC was the hour of peak precipitation, with 46 mm of rainfall. This hour accounted for 29% of the 6-h event total, and with the addition of the precipitation from the next consecutive hour, 38 mm, these two hours make up more than 52% of the total.

The stage II data for the peak hour of precipitation are shown in Fig. 5a, the radar reflectivity factor at 0700 UTC from the Des Moines, Iowa, WSR-88D (DMX) is shown in Fig. 5b, and the results of the BOIA applied to the stage II data are given in Fig. 5c. There are two precipitation maxima in Iowa during this hour, with the greater of the two near Wallin. The object affecting the gauge location, object number 48, has a size of 7616 km^2 , a mean precipitation of 14 mm, and a maximum precipitation of 58 mm.

TABLE 2. Attributes of precipitation objects associated with extreme precipitation.

Location	Date	Gauge precipitation (mm)	Size (km ²)	Mean (mm)	Variance	Max (mm)
Alexis	4 Aug 1998 2000	51	1840	9	5.53	16
Cairo	26 Jul 2001 1400	46	5856	11	20.14	25
Chicago	17 Jul 1996 2000	36	5472	11	14.42	23
Chicago	8 Aug 2001 1400	38	3888	14	46.13	30
Brazil	8 Sep 1997 0000	76	768	11	18.03	26
Columbia City	28 June 2005 1000	36	288	14	48.00	30
Columbus	16 Apr 1998 0200	38	13 248	10	15.44	26
Columbus	10 Jul 2003 0400	25	14 144	17	100.31	63
Evansville	9 Jul 2001 0900	23	4584	10	11.56	22
Fort Wayne	7 Jul 2003 0300	46	10 496	13	31.41	34
West Lafayette	12 Jun 2004 1000	48	17 952	14	61.37	60
Centerville	30 May 2004 0800	46	5488	12	28.01	31
Remsen	5 Aug 2002 0600	41	6704	14	37.76	46
Remsen	15 Sep 2004 0400	46	16 016	16	72.10	50
Remsen	25 Jun 2005 1300	41	2096	12	12.63	22
Strawberry Point	18 Aug 2005 1300	28	10 416	14	54.84	47
Wallin	7 Aug 1999 0800	46	7616	14	100.73	58
Ann Arbor	16 Jul 2005 1400	56	96	18	48.07	31
Owosso	22 Sep 2005 2100	38	4512	11	12.79	22
Wakefield	25 Aug 2004 2300	48	1120	14	20.94	22
Gull Lake	8 Jul 2002 0500	41	12 432	14	57.87	55
Thief Lake	31 Jul 2001 2300	20	10 768	14	21.78	27
Wales	5 Jul 1999 0700	23	13 424	12	26.44	33
Downing	2 Aug 2004 1400	33	8624	12	27.55	32
Miller	26 Sep 1996 0800	53	17 504	12	26.58	33
Miller	5 Oct 1998 0800	38	4496	9	4.72	15
Cambridge	12 Aug 2001 1500	61	2176	14	25.63	30
Germantown	27 Jul 2002 1200	48	7360	17	76.99	41
Portsmouth	24 Aug 1999 1800	36	416	9	4.76	14
Toledo	20 Sep 1997 0400	46	6016	15	42.59	30
Youngstown	22 Jul 2003 0100	36	7552	18	92.16	51
Babcock	25 Jun 1998 0500	36	6000	11	13.17	26
Babcock	19 Jul 1999 0600	38	416	7	0.58	9
New Richmond	19 Jun 2002 1200	41	4720	10	15.75	31
New Richmond	5 Oct 2005 0400	41	34 480	10	14.34	40
Park Falls	8 Jul 2002 1100	28	20 976	11	32.09	42
Mean		40.78	8054	12.68	34.53	33.09
Standard dev		11.11	7156	2.68	27.19	13.44
Minimum		20.32	96	6.78	0.58	9.19
Maximum		76.20	34 480	18.00	100.73	62.75

The Wallin, Iowa, object is chosen as an example of an average-sized object, with its mean size closest to the mean size of all 36 events (8054 km²). However, the mean and maximum precipitation in this object is greater than the averages of all events. In terms of a representative radar reflectivity presentation (Fig. 5b), this precipitating system most closely matches the “training line/adjoining stratiform” classification employed by Schumacher and Johnson (2005).

b. Columbia City, Indiana: 28 June 2005

On 28 June 2005, a total of 81 mm of rain was measured at the gauge located in Columbia City, Indiana, over a 6-h period beginning with the hour ending at 0900 UTC. This surpassed the 10-yr return level of 65 mm. A 3-h accu-

mulation of 76 mm also exceeded the 10-yr return level of 56 mm. The 36 mm of rain that fell during the hour of peak precipitation (hour ending at 1000 UTC) accounted for 44% of the 6-h accumulation. An additional 28 mm was recorded the next hour, with the 2-h precipitation making up 78% of the total.

A plot of the stage IV data for the hour of peak precipitation is provided in Fig. 6a, the radar reflectivity factor at 0902 UTC from the northern Indiana WSR-88D (IWX) is shown in Fig. 6b, and the associated objects identified by the BOIA is presented in Fig. 6c. It is seen that the area of precipitation affecting the gauge at Columbia City is relatively small, but a concentrated area of heavier precipitation can be observed. The object (#207) can be characterized as having a size of

FIG. 3. Illustration of the BOIA. (a) An idealization of stage II/IV precipitation is shown. (b) The objects are identified after the 6 mm threshold is applied to (a). Objects 1 and 2 are separated by 1 pixel and are individually labeled at this point in the algorithm. (c) The last object labels are established after applying the “search radius” of 1 pixel.

FIG. 4. Scatterplot comparing object size to maximum precipitation for the 36 events.

288 km², a mean precipitation of 14 mm, and a precipitation maximum within the object of 30 mm.

The Columbia City, Indiana, event is chosen as an example of an extreme-precipitation-producing system that is much smaller in size than most other events. The mean precipitation, however, is above average over all events. The maximum precipitation in this case compares well to the accumulation recorded by the gauge, suggesting a fortuitous track of the precipitation core over the rain gauge station. We would classify this precipitating system as a relatively isolated convective storm and also relatively slow moving, because the average propagation speed of the object is 3.61 m s⁻¹. In comparison, the object of interest in section 4b had an average propagation speed of 7.50 m s⁻¹.

5. Conclusions

The goal of this work was to establish a methodology to identify and characterize extreme subdiurnal precipitation events, which ultimately will be used toward the assessment of the predictability of subdiurnal extreme-precipitation-producing systems. Such systems are capable of generating inland flash floods, which pose a significant hazard to life, property, and agriculture. HPD data were examined to define thresholds for extreme events at selected locations. An extreme precipitation event is one in which precipitation exceeded the 10-yr return level over a 6-h period. Our analysis revealed that the majority of precipitation in these subdiurnal extremes fell over one or two hours. We suggest here the possibility that many of the extreme events defined by daily accumulations are also influenced heavily by precipitation over a few hours.

Those events that had corresponding stage II/IV data were examined further using the BOIA, with object attributes compiled at the hour of peak gauge precipitation. The use of the BOIA is a unique approach for the quantitative and objective characterization of precipitating systems, and it showed that the size (area) and maximum precipitation of the systems varied strongly across the

FIG. 5. Plots of the (a) stage II precipitation, (b) radar reflectivity, and (c) the objects identified by the BOIA for the event at Wallin, Iowa, on 7 Aug 1999 for the hour ending at 0800 UTC. The gauge location is identified in (a).

events. In particular, some events featured relatively small, isolated, convective storms that likely would not have been considered in other classification schemes. The analyses of the sample events for which stage II/IV precipitation data are available provide basic character-

FIG. 6. Same as Fig. 5 but for Columbia City, Indiana, on 28 Jun 2005 for the hour ending at 1000 UTC.

istics for these events—information which is currently unknown.

This study has built on the work of Brooks and Stensrud (2000), Schumacher and Johnson (2006), Smith et al. (2001), Winkler et al. (1988), and others, and serves as an important next step in characterizing subdiurnal extreme precipitation events. It is important to emphasize

that the current study did not attempt to identify extreme precipitating systems per se but rather sought to characterize those systems that produced extreme precipitation at specific point locations. Hence, one branch of our future research will be devoted to the identification of extreme systems, through the use of the BOIA. We will also attempt to relate these events to the larger-scale forcing, and to explore their predictability, by way of high-resolution model simulations.

Acknowledgments. Analysis of the HPD time series was enabled by the Extremes Toolkit (extRemes), developed by the University Corporation for Atmospheric Research and the R Project for Statistical Computing. The constructive comments and suggestions made by the anonymous reviewers helped improve the manuscript. The National Science Foundation is acknowledged for its support of this research through Grants ATM-0541491 and ATM-0756624.

REFERENCES

- Baldwin, M. E., J. S. Kain, and S. Lakshmivarahan, 2005: Development of an automated classification procedure for rainfall systems. *Mon. Wea. Rev.*, **133**, 844–862.
- Bauer-Messmer, B., J. A. Smith, M. L. Baeck, and W. J. Zhao, 1997: Heavy rainfall: Contrasting two concurrent Great Plains thunderstorms. *Wea. Forecasting*, **12**, 785–798.
- Bradley, A. A., and J. A. Smith, 1994: The hydrometeorological environment of extreme rainstorms in the southern Great Plains of the United States. *J. Appl. Meteor.*, **33**, 1418–1431.
- Brooks, H. E., and D. J. Stensrud, 2000: Climatology of heavy rain events in the United States from hourly precipitation observations. *Mon. Wea. Rev.*, **128**, 1194–1201.
- Chen, M., H. Mao, R. Talbot, and D. Pollard, 2005: Changes in precipitation characteristics over North America for doubled CO₂. *Geophys. Res. Lett.*, **32**, L19716, doi:10.1029/2005GL024535.
- Coles, S., 2001: *An Introduction to Statistical Modeling of Extreme Values*. Springer Verlag, 208 pp.
- Emori, S., and S. J. Brown, 2005: Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate. *Geophys. Res. Lett.*, **32**, L17706, doi:10.1029/2005GL023272.
- Fulton, R. A., J. P. Breidenbach, D. J. Seo, D. A. Miller, and T. O'Bannon, 1998: The WSR-88D rainfall algorithm. *Wea. Forecasting*, **13**, 377–395.
- Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V. A. N. Razuvaev, 2005: Trends in intense precipitation in the climate record. *J. Climate*, **18**, 1326–1350.
- Hammer, G., and P. Steurer, 2003: Data documentation for data set 3240 (DSI-3240) hourly precipitation data. National Climatic Data Center Rep., 10 pp.
- Hennessy, K. J., J. M. Gregory, and J. F. B. Mitchell, 1997: Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dyn.*, **13**, 667–680.
- Johnson, R. H., and P. J. Hamilton, 1988: The relationship of surface pressure features to the precipitation and air-flow structure of an intense midlatitude squall line. *Mon. Wea. Rev.*, **116**, 1444–1472.
- Karl, T. R., and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.*, **79**, 231–241.
- Konrad, C. E., 2001: The most extreme precipitation events over the eastern United States from 1950 to 1996: Considerations of scale. *J. Hydrometeorol.*, **2**, 309–325.
- Maddox, R. A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374–1387.
- NOAA, cited 2006: Definitions of flood and flash flood. [Available online at <http://www.srh.noaa.gov/mrx/hydro/flooddef.php>.]
- Qi, Y., 2008: Bootstrap and empirical likelihood methods in extremes. *Extremes*, **11**, 81–97.
- Schumacher, R. S., and R. H. Johnson, 2005: Organization and environmental properties of extreme-rain-producing mesoscale convective systems. *Mon. Wea. Rev.*, **133**, 961–976.
- , and —, 2006: Characteristics of U.S. extreme rain events during 1999–2003. *Wea. Forecasting*, **21**, 69–85.
- Silva, V. B. S., and E. H. Berbery, 2006: Intense rainfall events affecting the La Plata Basin. *J. Hydrometeorol.*, **7**, 769–787.
- Smith, J. A., A. A. Bradley, and M. L. Baeck, 1994: The space–time structure of extreme storm rainfall in the southern plains. *J. Appl. Meteor.*, **33**, 1402–1417.
- , M. L. Baeck, Y. Zhang, and C. A. Doswell, 2001: Extreme rainfall and flooding from supercell thunderstorms. *J. Hydrometeorol.*, **2**, 469–489.
- Trenberth, K. E., 1998: Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change. *Climatic Change*, **39**, 667–694.
- , 1999: Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change*, **42**, 327–339.
- , A. G. Dai, R. M. Rasmussen, and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1217.
- Wilby, R. L., and T. M. L. Wigley, 2002: Future changes in the distribution of daily precipitation totals across North America. *Geophys. Res. Lett.*, **29**, 1135, doi:10.1029/2001GL013048.
- Winkler, J. A., B. R. Skeeter, and P. D. Yamamoto, 1988: Seasonal variations in the diurnal characteristics of heavy hourly precipitation across the United States. *Mon. Wea. Rev.*, **116**, 1641–1658.