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Analyses of the temporal and spatial structures of heavy rainfall from a catalog of high-resolution radar rainfall fields

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ABSTRACT

In this paper, we develop a storm catalog of heavy rainfall events for a region centered on the Milwaukee, Wisconsin WSR-88D (Weather Surveillance Radar — 1988 Doppler) radar. The study region includes portions of southern Wisconsin, northern Illinois and Lake Michigan. The long-term objective of this study is to develop rainfall frequency analysis methods based on a storm catalog of major rain events. The specific objectives of this study are to develop a long-term catalog of high-resolution radar rainfall fields and characterize key features of the space–time variability of rainfall. The research questions that underlie these objectives are: 1) What are the spatial heterogeneities of rainfall over the study region for major flood-producing storm systems? 2) What are the key elements of storm evolution that control the scale-dependent properties of extreme rainfall? The storm catalog contains a record of the 50 "largest" storm days during the 1996–2011 observation period. We show that mean rainfall for the 50 largest storm days exhibits pronounced spatial heterogeneity with a broad maximum in western Wisconsin and a minimum in the eastern portion of the study region over Lake Michigan. We also show that there is a narrow line of maximum mean rainfall extending from west to east along the Wisconsin–Illinois border. This feature is tied to a maximum in the probability of daily rainfall exceeding 100 mm. There are characteristic elements to the storm life cycle of heavy rainfall days that relate to size, structure and evolution of heavy rainfall. Extreme rainfall is also linked with severe weather (tornados, large hail and damaging wind). The diurnal cycle of rainfall for heavy rain days is characterized by an early peak in the largest rainfall rates, an afternoon–evening peak in rain area exceeding 25 mm h^{-1} and development of a large stratiform rain area during the night and early morning.

1. Introduction

In this paper, we develop a storm catalog of heavy rainfall events for a region centered on the Milwaukee, Wisconsin WSR-88D (Weather Surveillance Radar — 1988 Doppler) radar. The catalog covers the period from 1996 to 2011. The study region includes portions of southern Wisconsin, northern Illinois and Lake Michigan. The region has experienced a series of major flood events during the past several decades (e.g. Zhang and Smith, 2003; Changnon, 2011; Budikova et al., 2010; Strope and Budikova, 2011; Villarini et al., 2011, 2013). Some of the major flood episodes from the period include the historic 4–12 June 2008 floods in Iowa, Minnesota, and Wisconsin, the 21–25 May 2004 storms in Northeast Iowa and Southwest Wisconsin, the 18–20 August 2007 flood of the upper Mississippi river, the 17–18 June 1996 flood of Southern Wisconsin, and the 21–25 July 2010 storms producing floods in Iowa, northern Illinois, southern Wisconsin, and southern Minnesota. These floods caused by multiple heavy rainfall events all have caused extensive property damage, soil erosion, damaged and closed roads, and crop damages. In this study we omit the hydrology issues related to the floods and concentrate

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our work on analyzing the hydrometeorological properties of these flood-producing storms.

Long series (+10–15 years) of radar rainfall makes it possible to study long-term and high-resolution spatio-temporal structures of rainfall fields which have not been possible earlier with sparse rain gage observations. This creates a unique platform to better understand the spatio-temporal structure of heavy rainfall and to advance techniques that can be used to assess the frequency of occurrence of extreme flood-producing rainfall.

The long-term objective of this study is to develop rainfall frequency analysis methods based on a storm catalog of major rain events (see, for example, Alexander, 1963; Fontaine and Potter, 1989; Foufoula-Georgiou, 1989; Foufoula-Georgiou and Wilson, 1990; Wilson and Foufoula-Georgiou, 1990; Javier et al., 2007). The specific objectives of this study are to develop a long-term catalog of high-resolution radar rainfall fields and characterize key features of the space–time variation of rainfall rate. The research questions that underlie these objectives are: 1) What are the spatial heterogeneities of rainfall over the study region for major flood-producing storm systems? 2) What are the key elements of storm evolution that control the scale-dependent properties of extreme rainfall? The storm catalog contains a record of the 50 "largest" storms during the 1996–2011 observation period. We limit our study to the top 50 days (see Section 2 for definitions and details) to focus only on the events with a potential to cause significant flooding.

The study builds on prior research concerning the development of long-term, high-resolution radar rainfall fields. We use the Hydro-NEXRAD system (described in detail in Seo et al., 2011; Krajewski et al., 2011 and applied in Yeung et al., 2011; Smith et al., 2012; Wright et al., 2012, 2013) to construct rainfall fields from volume scan radar reflectivity observations. We also build on prior research examining the hydrometeorology of heavy rainfall in the region (McAnelly and Cotton, 1989; Tuttle and Davis, 2006; Schumacher and Johnson, 2008; Smith et al., 2014).

Contents of the sections are as follows. We introduce the study region, data and storm catalog in Section 2. In Section 3 we present detailed analyses of the June 2008 storms which produced one of the largest floods observed in the study region. For this specific storm, we present storm motion analyses, analysis of storm coverage and analysis of daily rainfall totals. At the same time we use Section 3 to present methods that we apply for the composite rainfall analyses based on the 50-event storm catalog in Section 4. Furthermore, Section 4 presents probability analyses, analysis of diurnal variability, and spatio-temporal correlation analysis of the 50 storms. In Section 5 we summarize and present major conclusions of the study.

2. Data, study region and methods

The study region (Fig. 1) covers an area of 73,500 km^2 in southern Wisconsin, northern Illinois and over Lake Michigan.

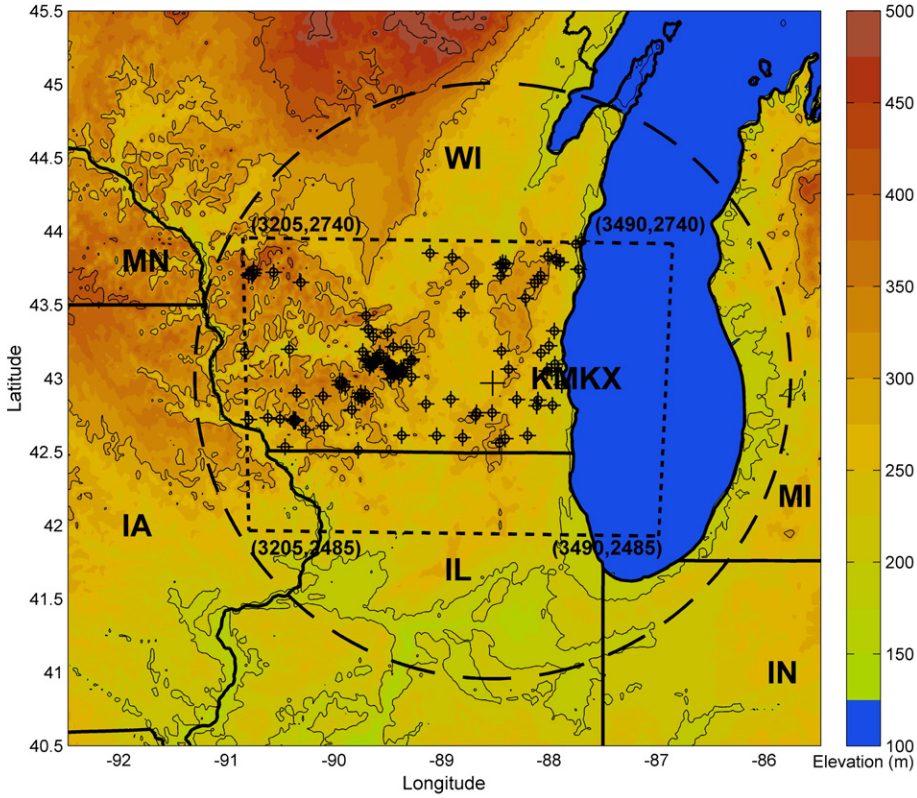

Fig. 1. Study domain (dashed rectangle, area 73,500 km^2) with surface elevation covering southern Wisconsin, Northern Illinois and part of Lake Michigan. Contour lines are 100 m in between; the dashed black circle is the 230 km range of the KMKX radar and location of the radar is marked by the black cross; crossed black circles are rain gages in the study domain. We denote the coordinate of each corner of the study domain.