INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **28**: 493–503 (2008)
Published online 18 July 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1554

The storm morphology of deadly flooding events in the United States

Sharon T. Ashley* and Walker S. Ashley
Meteorology Program, Department of Geography, Northern Illinois University, DeKalb, Illinois

ABSTRACT: This study investigates the synoptic and mesoscale environments associated with deadly flooding events in the United States from 1996 to 2005. A manual environment classification scheme, which includes analyses of surface charts, 500 hPa maps, and composite radar data (where available), is utilized to ascertain the primary ascent mechanisms and storm types producing these fatal flood events. Of the ten classifications in the scheme, the two most dominant ascent mechanisms associated with deadly floods include frontal boundaries (45%) and tropical systems (22%). Findings illustrate that mesoscale convective systems were responsible for 36% of the total number of flood fatalities over the period. The ten classifications are spatially and temporally analysed in order to assess region-specific risks associated with deadly flooding events. Copyright © 2007 Royal Meteorological Society

KEY WORDS flood; flash flood; United States; hazards; storm morphology

Received 29 November 2006; Revised 29 March 2007; Accepted 30 March 2007

1. Introduction

Since 1996, there have been 815 fatalities related to 502 flooding events in the United States (NOAA, 2005). Consequently, floods are one of the greatest weather hazards in the United States (French *et al*., 1983; Dittman, 1994; Wisner *et al*., 2004). Flood events are therefore of major concern to forecasters, insurers, flood control planners and engineers, as well as the public, especially since these events and their fatalities show no signs of decreasing in recent years (Ashley and Ashley, in press). The challenge in preventing these fatalities occurs because of the complexity in forecasting flood events for a specific location and time, particularly flash floods that develop within 6 h of the onset of precipitation (Moore *et al*., 2003). Additionally, a universal flood threshold value for precipitation rates and duration cannot be utilized across all river basins since a hydrological setting for an event is equally important in determining flash flood potential (Doswell, 1997). These hydrological variables include (but are not limited to) antecedent moisture conditions, permeability of the soil, and slope of the basin, which together with precipitation amounts, may create a flood event. Any underestimation of maximum point rainfall or misunderstanding of antecedent conditions will undoubtedly cause a more hazardous flood event in a populated basin because of lack of warning.

Compounding this forecast problem is the public's perception and awareness of flood hazards, i.e. the potential threat to life and property (Cutter, 2001). A 41-year study by Gamble and Meentemeyer (1997) report that some of the greatest flood magnitudes in the southeastern United States occurred during the dry season. Consequently the public is often unaware of and, therefore, unprepared for the hazard.

This perception and awareness problem is also witnessed at the local scale (Drobot *et al*., 2006). Drobot *et al*. examined people's perception of vehicle safety in flash floods, through mail-in surveys from Austin, TX and Denver, CO, which concluded that the people who are more likely to drive into flood waters include those who: (1) do not perceive flood waters to be dangerous, (2) think that they can keep themselves safe in dangerous situations, (3) have experienced fewer flash floods, and (4) are younger in age.

Comprehending the human psychology and sociology of these events is only one part of the problem in our understanding of flood hazards. In addition, a concerted effort must be made by meteorologists and climatologists to understand what the primary storm types are that are generating these fatal events. Past literature has examined the synoptic and/or mesoscale aspects of flooding in the United States (Maddox *et al*., 1979; Hirschboeck, 1987; Doswell, 1994), although many of these studies are limited to a single state or region, specific season, or flood type (Crysler *et al*., 1980, 1982; Hirschboeck, 1991; Capriola, 1992; Gamble and Meentemeyer, 1997; Konrad, 1997; Gaffin and Hotz, 2000; Kahana *et al*., 2002; Dupigny-Giroux and Loughner, 2004). Another portion of the literature examines the synoptic and/or mesoscale environments for historical flood events in the United States, e.g. the July 1997 Fort Collins flash flood, 1993 Upper Mississippi River basin flood (Kunkel *et al*.,

* Correspondence to: Sharon T. Ashley, Department of Geography, Davis Hall #118, Northern Illinois University, DeKalb, IL 60115. E-mail: sashley@niu.edu

1994; Changnon and Kunkel, 1999; Peterson *et al*., 1999; Smith *et al*., 2000).

Therefore, in order to reduce the number of flood fatalities that occur in the United States a twofold approach is required, which includes: (1) a need to improve our understanding of the spatial and temporal patterns of the various storm types responsible for deadly flooding events and (2) the comprehension of the human psychology and sociology of these hazardous events so we can further educate the public on flood safety. The focus of this study is to determine the spatial and temporal patterns of deadly flooding events in the United States by examining the primary genitor of deadly flooding events in the contiguous United States from 1996 to 2005. Understanding these types of killer storms and where they predominantly occur is fundamental in assisting forecasters, emergency managers, and flood control planners in reducing the number of fatalities associated with these events.

2. Data and methodology

This investigation includes flood events in the United States from 1996 to 2005 that have resulted in at least one fatality. The fatality reports as well as information on location, county, state, and type of flood events are based on daily report entries from the National Climatic Data Center's *Storm Data* publication. Although not a flawless database, the publication has been a primary source of severe weather event data utilized by the atmospheric and hazard communities. As noted by Changnon (1999); Curran *et al*. (2000); Ashley and Mote (2005), and Ashley and Ashley (in press), the underreporting of both casualties and damage estimates is an inherent problem with *Storm Data*. However, because there is more media attention surrounding fatal storm events and since fatalities are more likely to be reported than injuries or damage estimates, the authors are more confident in the stability of the fatality data utilized in this investigation.

Over the 10-year period, there were 815 deaths from approximately 502 *Storm Data* report entries. Each *Storm Data* flood entry included a flood type: flash flood, river flood, or tropical system. On the basis of the description of the hazard event that often accompanied the flood report entry, the authors added several other flood types including: floods from snowmelt, flash floods from levee breaks, and landslides. Additionally, the authors separated those entries labeled tropical systems into four separate categories, including: landfalling hurricanes/tropical storms, tropical storms (downgraded), tropical depressions (downgraded), and remnants of a tropical system.

Although there are data available to subjectively determine the synoptic-scale environment for all deadly flooding events found in the *Storm Data* publication (1959–2005), the more detailed analysis of the mesoscale environment by the use of radar data is unfeasible because digital radar data archives are missing or incomplete prior to 1996. Due to these data limitations, we restricted analyses to the 10-year period, 1996–2005.

Initial environmental analysis procedures included a classification of the 12 Universal Time Coordinated (UTC) synoptic-scale surface features and 500 hPa height contour pattern from NOAA's *Daily Weather Map Series* (http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html). These analyses were a manual environment-to-circulation classification scheme similar to that utilized by Maddox *et al*. (1979); Gamble and Meentemeyer (1997); Gaffin and Hotz (2000); and/or Kiem *et al*. (2005). Each fatal event was analysed and classified using six synoptic-scale charts (i.e. a surface and 500 hPa chart on the day of the death, as well as one day pre and postfatality). The placement and movement of frontal boundaries, mid-latitude cyclones, and tropical systems are determined from the surface charts, whereas the mid-level flow and location of troughs and ridges are evaluated from the 500 hPa charts. Thereafter, secondary analyses included a classification of the mesoscale environment and event types based on radar data, including mesoscale convective systems (MCSs), orographic stationary thunderstorms, or monsoon thunderstorms.

Some floods are aided by antecedent moisture conditions; however, this analysis does not aim to classify the environmental conditions for the days or weeks leading up to a flood death, but rather the synoptic and/or mesoscale environment on the day of the fatality and/or directly prior to the death. Any fatality in the database where the exact date of death is unknown was excluded from the analysis since more than one storm system may have contributed to the fatality. If the date of death was known but occurred during a large-scale flood event (>2 days), the report was included and the *most recent* storm system relative to the fatality date was classified as the genitor. Many of the fatalities (88%) in the 10-year database were due to flash floods or tropical system floods and, therefore, the exact storm system that caused the deadly flooding event is clearly identifiable.

A more detailed analysis of the mesoscale environment associated with each deadly flooding event was also undertaken by evaluating composited national archived radar imagery. From 1996–1997, archived national radar data was available for only one hour each day during the winter and spring months. Consequently, flood deaths occurring from November to April of these 2 years were unable to be classified by their mesoscale environment. Mesoscale storm types such as MCSs, monsoon thunderstorms, and orographic-induced stationary thunderstorms were determined subjectively from these radar archives. National radar summaries were used because of their adequate temporal/spatial resolution and depiction of the mesoscale organisation and evolution of large, persistent convective systems (Parker and Johnson, 2000). For the purposes of this study, an MCS was defined similar to the methods described by Parker and Johnson (2000) – i.e. an MCS is a convective phenomenon with a life timescale of at least 3 h and a minimum spatial scale in one dimension of 100 km. The classification of a flooding event as an MCS is therefore due solely to the analysis of

DOI: 10.1002/joc

national radar composites and their corresponding radar morphology.

Classifying each deadly flooding event is a subjective analysis procedure. A decision tree was created (after Gamble and Meentemeyer, 1997) so that evaluation process was objective as possible (Figure 1). These classifications are very similar to Gamble and Meentemeyer (1997) classification scheme of ascent mechanisms. Since their study was restricted to the southeastern United States, their classifications have been expanded for this investigation to include all storm system types that may occur across the contiguous United States. Ultimately, this analysis will be useful in determining the primary (and secondary) atmospheric factors responsible for creating deadly flooding events in the United States.

3. Results

From 1996 to 2005, there were an average of 82 flood fatalities per year with considerably fewer deaths per annum occurring in the latter period of record (Figure 2). This dataset does not include Louisiana deaths from Katrina because of the uncertainty surrounding the actual number of deaths due to flooding (Knabb *et al.*, 2005; Ashley and Ashley, 2006). The average number of deaths per year is slightly higher than the National

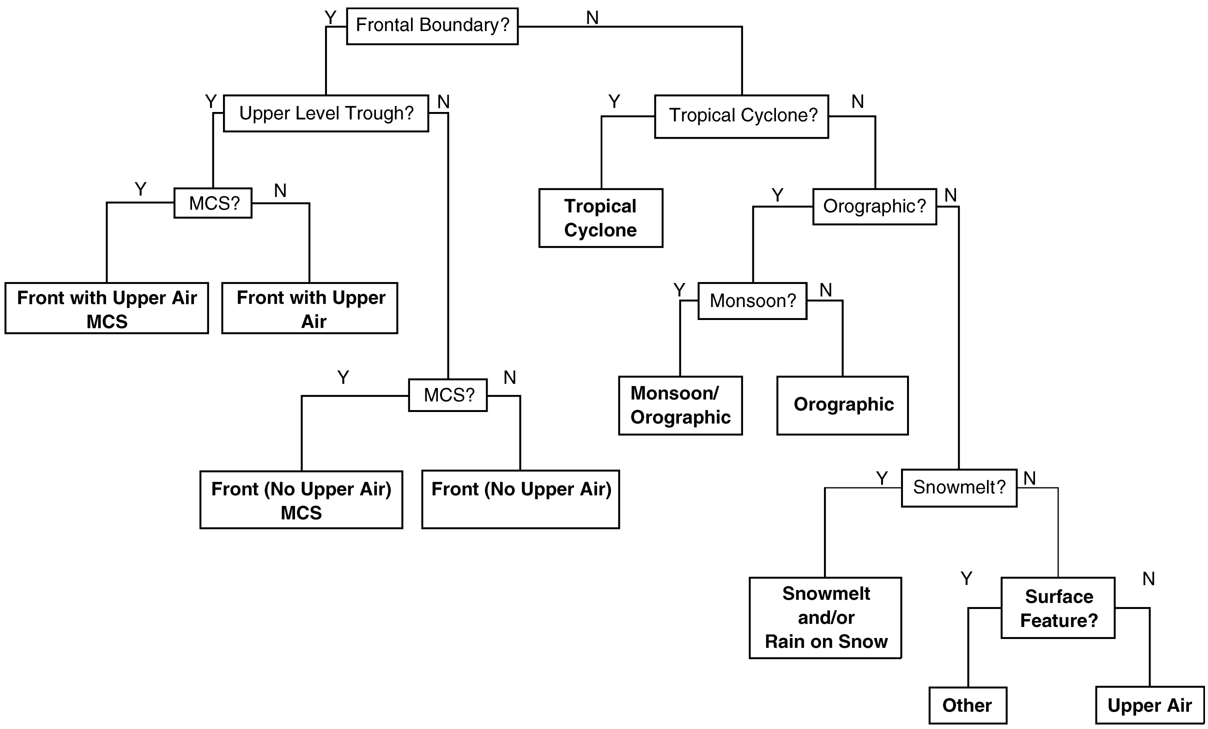

Figure 1. Flow chart for determining synoptic and mesoscale environments.

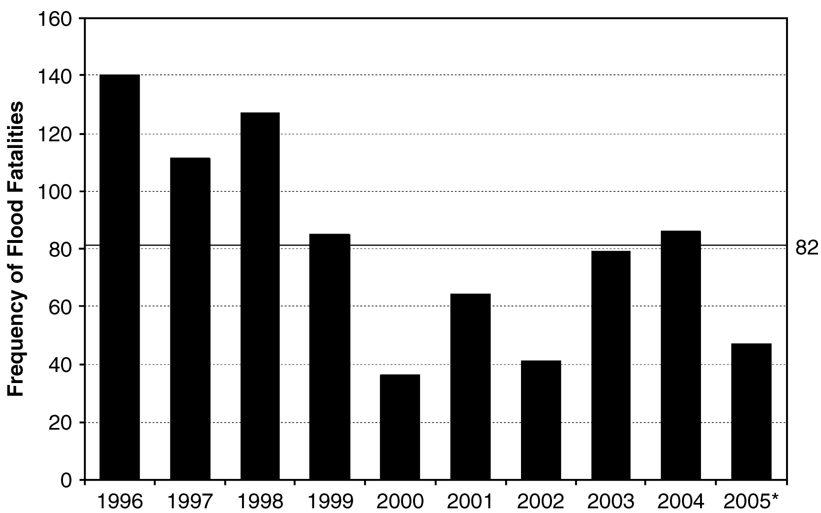

Figure 2. Flood fatalities per year for the 10-year study period. Horizontal line represents the 10-year average. ∗ indicates that 2005 data is preliminary and does not include Hurricane Katrina fatalities.

DOI: 10.1002/joc

Weather Service (NWS) summary of national hazard statistics (http://www.weather.gov/os/hazstats.shtml) for the United States for flood fatalities. The NWS average is 75.6 deaths per year based on records from *Storm Data* from 1996 to 2005. Since both estimates are based on *Storm Data*, the apparent difference between the average value found here and that of the NWS occurs due to the inclusion of flood deaths from tropical systems in this study; whereas, the NWS classifies fatalities from flood events associated with tropical systems as 'tropical cyclone' hazards and not 'flood' hazards. From 1996 to 2005, the NWS reports an average of 22.5 deaths from hurricanes, but this includes all deaths and not exclusively flooding deaths. Therefore, combining these values and removing deaths not due to flooding, the two averages are similar.

Over the 10 years of the study, there were 815 fatalities attributable to flooding in the United States from 302 storm systems. Ten classifications of deadly flooding storm systems in the United States are identified (Table I). The monthly distribution of all fatalities shows a peak in September that represents the influence of tropical systems in the United States (Figure 3). Additionally, the months of June–August have elevated frequencies of fatalities from floods. High frequencies during the summer months are explained by deaths from monsoon thunderstorms in the Southwest, tropical systems in the Southeast and Eastern Seaboard, and frontal storms between the Rockies and Appalachian Mountains. Furthermore, the secondary maximum in January occurs due to frontal systems in the west and rain-on-snow events across the northern-tier of the United States. Over the 10 years of the study there were 7 storm system events that caused greater than 20 deaths throughout their lifespan over the United States (Table II). These events were restricted to tropical cyclones and synoptic-scale mid-latitude cyclones, perhaps because of the large spatial area encompassed as they tracked across the country.

Of the 815 deaths in the database, the majority were due to flash flood events (60%), while 12.1% were due to floods, and 6.9% were due to snowmelt flooding events (Figure 4). The three deadliest storm types during the 10 years (Figure 5) include; frontal systems with upper-air enhancement (24.4%), tropical systems (22.1%; including hurricanes through remnants), and frontal systems with upper-air enhancement and a radar-defined MCS (20.4%). Interestingly, 51.3% of all tropical system deaths (11.2% of all deaths in the 10-year dataset) occurred after the initial landfall of the storm and, consequently, after the storm had been downgraded or merged with a frontal boundary and become extratropical. In a study on the loss of life from tropical cyclones from 1970 to 1999, Rappaport (2000) found that over half of the tropical cyclone-related flood deaths were due to freshwater flooding from intense rainfall. He speculates that the reduction in media attention as the storm moves inland may factor into the many deaths that occur during this time period.

Another deadly storm type includes thunderstorms during the Southwest's monsoon season, which contribute to

Table I. Classification and description of deadly storm system types found in United States.

	Name of Storm System	Description
1	Frontal boundary with upper-level enhancement associated with an MCS	Typically, these were propagating cold and warm fronts associated with a mid-latitude cyclone and found downstream of an upper-level trough. Radar-detected MCS.
2	Frontal boundary with upper-level enhancement	Same as (1), except with *no* radar-detected MCS.
3	Frontal boundary with *no* upper-level enhancement associated with an MCS	Typically, these were quasi-stationary frontal boundaries associated with either zonal upper-level flow or weak upper-level troughs. Radar-detected MCS.
4	Frontal boundary with *no* upper-level enhancement	Same as (3), except with *no* radar-detected MCS. Convection along frontal boundary was not found to be organized.
5	Tropical cyclone	Includes hurricanes, tropical storms, tropical depressions, and remnants from the tropical cyclone that becomes extratropical.
6	Orographic-induced thunderstorm	Includes thunderstorms that occur in an environment with no predominant surface feature (e.g. frontal boundary) or upper-level forcing (e.g. trough). Typically, the thunderstorm is stationary or training occurs.
7	Monsoon/Orographic thunderstorm	Thunderstorm that develops during the monsoon season (July–September) in the Southwest. May be aided by the topography of the region.
8	Snowmelt/Rain-on-snow	Typically occurs under an upper-level ridge in the late winter/spring months, while rain-on-snow events are associated with a frontal boundary.
9	Upper air	No surface feature is located in vicinity of event, although a notable upper-level trough or closed low exists. This type classification may be associated with an MCS.
10	Other/Unidentifiable	'Other' includes any surface feature or upper-level pattern that does not fit into one of the nine categories, whereas, 'unidentifiable' includes fatal events where the surface and/or upper-air maps were unavailable.

DOI: 10.1002/joc

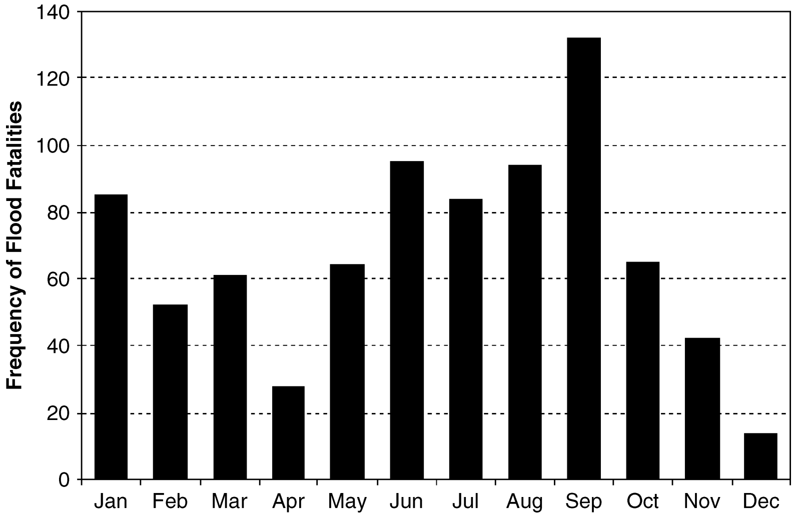

Figure 3. Flood fatalities per month for the 10-year study period. Excludes fatalities from Hurricane Katrina.

Table II. Top seven leading storm system killers in the United States from 1999 to 2005 (does not include Katrina).

Rank	Year	States Impacted	Type of Storm System/Event	Deaths
1	1999	CT, DE, NC, NJ, NY, VA	Tropical Cyclone Floyd (55-hurricane, 2-remnants)	57
2	1997	IN, KY, MO, OH, TN, WV	Mid-latitude Cyclone	31
3	2005	FL, GA, KY, NC, OH, PA, WV	Tropical Cyclone Ivan (13-hurricane, 3 tropical depression, 11 remnants)	27
4	1998	TX	Quasi-stationary Cold Front associated with Mid-latitude Cyclone	25
5	2001	FL, PA, TX	Tropical Storm Allison (22-tropical depression, 2-remnants)	24
6	1996	PA, VA, VT, WV	Rain on Snow (Mid-latitude Cyclone)	22
7	1996	NC, PA, SC, VA, WV	Tropical Cyclone Fran (11-hurricane, 7 tropical storm, 2 remnants)	20

almost 7% of all deaths. The rapid onset of these flash floods, in part, explains this relatively large percentage in this dry region of the United States. Another important contributor to flood fatalities occurs from snowmelt due to high temperatures. These events occurred typically under a persistent 500 hPa ridge or were due to a rain-on-snow storms associated with a frontal system. Together these flood types produced about 6.5% of all flood fatalities in the United States during the period of record.

3.1. Overview of storm systems

As previously mentioned, this study utilizes an environment-to-circulation classification scheme to determine primary storm types associated with fatal flood events in the United States (refer to Table I). The first and second classification types are storm systems that form along frontal boundaries associated with a migratory extratropical mid-latitude cyclone. These events are coupled with a 500 hPa trough (or closed low centers) and may be linked with flooding events across several states. This deadly storm type may be associated with a propagating MCS (Type 1; Moore *et al.*, 2003), which may take on a squall line structure related to uplift along a linear, synoptic-scale boundary (Doswell *et al.*, 1996). Those storms not associated with a propagating MCS (Type 2) were related typically with frontal convection (Randerson, 1976). The third and fourth types are also associated with frontal boundaries, although no upper-air enhancement is detectable on the 500 hPa map. Occasionally, these frontal boundaries may be coupled with a weak upper-level trough; consequently, these boundaries are typically quasi-stationary or slow-moving and can be associated with regenerative MCSs (Type 3; Pontrelli *et al.*, 1999). The Type 4 storm classification is similar to Type 3, although no organized convection (i.e. MCS) could be determined from radar images for the fourth storm type.

One of the more well known types of storm systems that cause widespread flood-related fatalities in the United States are tropical cyclones (Type 5). Over the 10 years of this study, all deaths within the 'tropical cyclone' classification occurred with landfalling Atlantic tropical cyclones along the Gulf Coast or Eastern Seaboard. Since 1996, one of the deadliest tropical systems (excluding Hurricane Katrina) was Hurricane Floyd. Floyd's tremendous flooding killed 57 people from North Carolina to New York between the time it made landfall and until it became extratropical (Attalah and Bosart, 2003).

DOI: 10.1002/joc

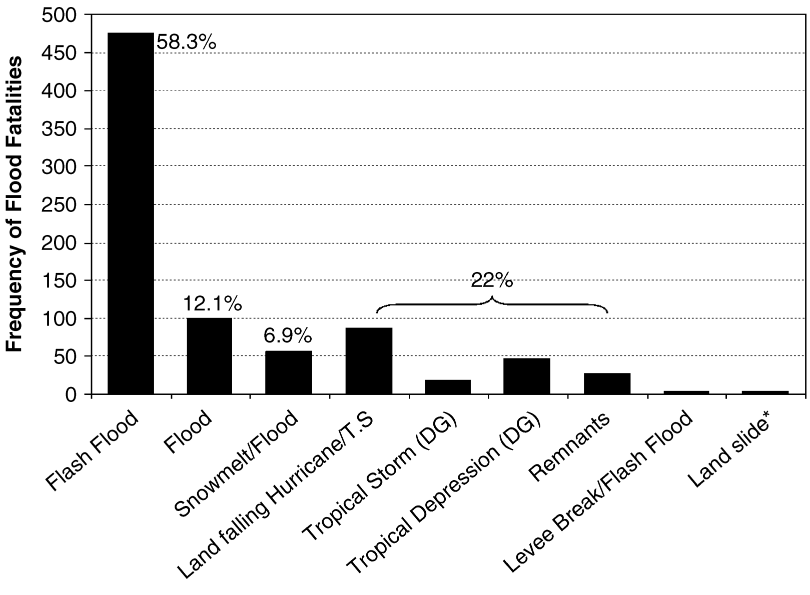

Figure 4. Flood fatalities from 1996 to 2005 separated by flood type. Percentages are given to indicate percent each category contributes to all flood fatalities. DG represents tropical systems downgraded from stronger classification. * Represents high-precipitation events. Excludes fatalities from Hurricane Katrina.

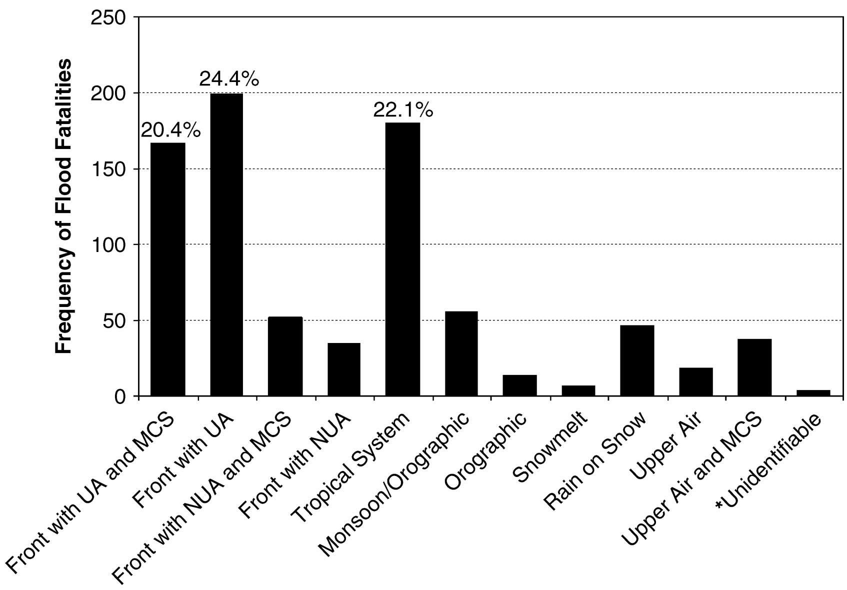

Figure 5. Flood fatalities from 1996 to 2005 separated by the synoptic and mesoscale environments. * Includes the category 'other'. Excludes fatalities from Hurricane Katrina.

The next two storm event types include those floods that are generated due to the orography of the landscape in the absence of any synoptic-scale boundary. These include both upslope precipitation (Type 6) and monsoonal thunderstorms (Type 7). The dominant surface wind direction becomes important in determining these types of flood events. In these cases, the precipitation is generated when warm, moist air is forced to rise through contact with the topographic barrier (e.g. see Maddox *et al.*, 1978; Caracena *et al.*, 1979; Farfán and Zehnder, 1994; Doswell *et al.*, 1996; Dupigny-Giroux *et al.*, 2006).

Floods that are generated through rain-on-snow events or simply snowmelt alone are found in the northern-tier of the United States (Type 8; Kattelmann, 1996; Leathers *et al.*, 1998; Graybeal and Leathers, 2006). Rain-on-snow events are associated with a frontal boundary (mostly with a propagating mid-latitude cyclone and 500 hPa level trough), while rapid snowmelt events take place with no surface features and occur typically beneath a 500 hPa ridge. Unlike rain-on-snow events, floods that form from snowmelt alone generally require anomalously high temperatures to rapidly melt the snow. This type of deadly event occurs characteristically when

DOI: 10.1002/joc

the state/region is dominated by surface high pressure for several days.

The penultimate storm type in the classification scheme occurs with no prominent feature at the surface but can be associated with either a weak 500 hPa trough or closed low (Type 9; e.g. see Maddox and Grice, 1986). Thunderstorms that develop under these conditions are common in Texas and are coupled with onshore flow from a surface high-pressure system centered over the easternUnited States. This pattern may persist for several days. Similar to this storm classification is a subtype that includes floods that are generated in the absence of both mid-level and surface forcing. These 'airmass' convective thunderstorms, which typify the Southeast United States (Geerts, 1998), are generated due to strong daytime surface heating in a warm, unstable airmass. The last classification (Type 10) includes those events that do not fit into one of the nine categories, or includes fatal events where the surface and/or upper-air maps were unavailable.

3.2. Spatial and temporal analysis of deadly storm systems by region

Each of the five top ascent mechanisms or storm system types has a distinct peak season (Table III). Included in the table are the four abovementioned storm types as well as frontal systems with no upper-air enhancement. Additionally, frontal systems with upper-air enhancement with and without radar-defined MCSs are combined into one category. Synoptic-scale frontal systems with upper-air enhancement, which typically include a mid-latitude cyclone and an associated upstream upper-level trough, produced the most fatalities during winter to early spring (January–March). This maximum in deaths is similar to the spring peak (March–May) for flood events generated from migratory extratropical cyclones found by Capriola (1992). During the late spring to early summer, synoptic-scale frontal systems with no upper-air enhancement become more important in creating flood fatalities. This peak time period also coincides with Capriola (1992) highest frequency of flood events from quasi-stationary fronts.

As expected, both tropical systems and monsoonal thunderstorm flood fatalities peak during each storm system's respective seasonal climatological maximum – i.e. summer to early fall (Neumann *et al*., 1993; Higgins *et al*., 1997). The deaths from rain-on-snow events peak in the winter through early spring coincides with the dominant months for mid-latitude cyclone activity; whereas,

Table III. Temporal distribution of flood fatalities by the top five ascent mechanisms. Excludes fatalities from Hurricane Katrina.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Front with upper air	**85**	**44**	**54**	28	39	37	20	11	13	20	29	12
Front with no upper air	10	7	3	2	**14**	**16**	**25**	10	0	1	1	1
All tropical systems	0	0	0	0	0	**24**	**6**	**25**	**115**	10	0	0
Monsoon	0	0	0	0	1	0	**13**	**37**	**4**	0	0	0
Rain on Snow/*Snowmelt*	**37**	**7**	**4**	0	***1***	***3***	0	0	0	0	0	0

*Bolded values indicate peak season/months.

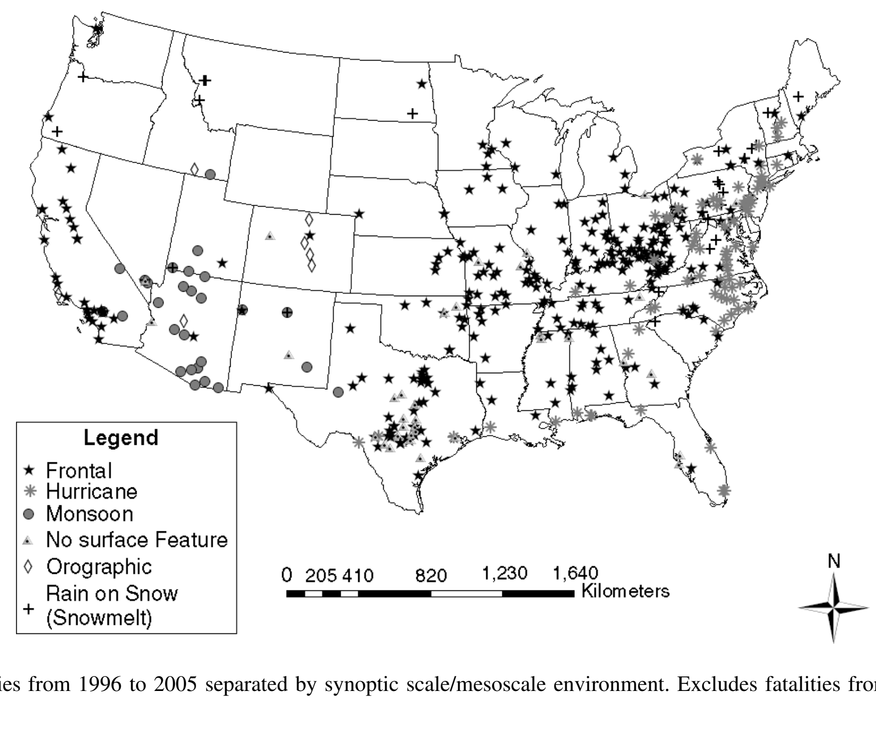

Figure 6. All fatalities from 1996 to 2005 separated by synoptic scale/mesoscale environment. Excludes fatalities from Hurricane Katrina.

snowmelt events tend to occur in the late spring or early summer when temperatures may be abnormally high when snow is still on the ground in higher latitudes and/or elevations. In rain-on-snow events, the amount of run-off from the snowpack is maximized and added to the precipitation-induced run-off, such that excess run-off is generated quickly and extreme flooding can occur (Singh *et al*., 1997; Leathers *et al*., 1998).

A spatial examination of all storm system types responsible for flood fatalities illustrates regional patterns across

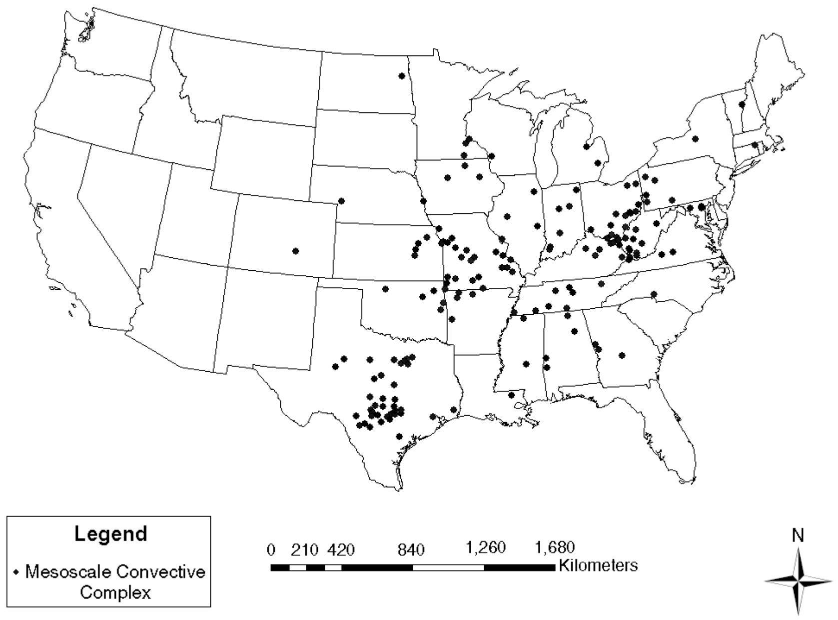

Figure 7. All fatalities from 1996 to 2005 from radar-identified MCSs. Excludes fatalities from Hurricane Katrina.

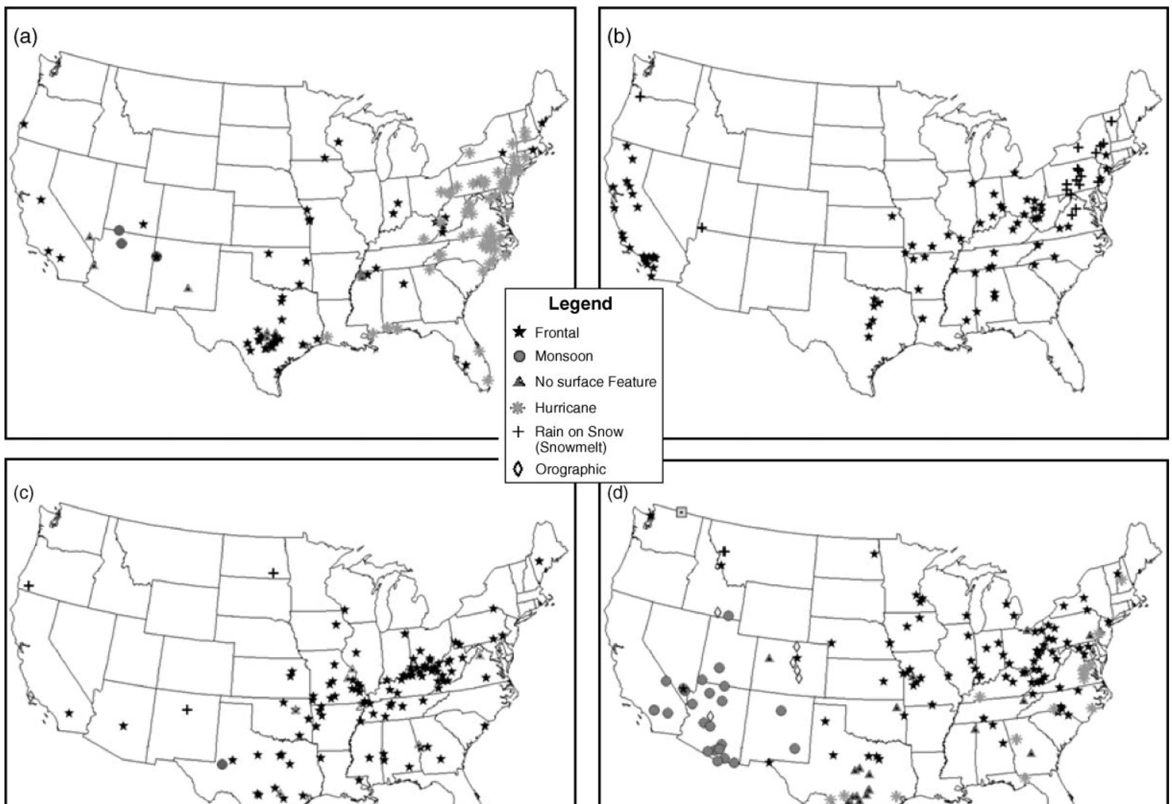

Figure 8. Spatial distribution of deadly storm types (a) fall (Sept–Nov), (b) winter (Dec–Feb), (c) spring (Mar–May), and (d) summer (Jun–Aug).

DOI: 10.1002/joc

the United States (Figure 6). As expected, monsoonal thunderstorm fatalities cluster in the Southwest, while orographically-induced flash floods are found along the Front Range of the Rockies and snowmelt or rain-on-snow events are evident at high elevation locations. Frontal storm deaths dominate the West Coast and throughout the eastern United States, while deadly 'air-mass' convective thunderstorms or thunderstorms generated from the onshore flow of warm, moist air occur throughout the United States with a notable cluster in Texas. Lastly, tropical system deaths are found predominantly from the New England states through the southern and Gulf Coast states with the most noticeable cluster of tropical storm deaths situated from extreme southern New York to North Carolina. Many of these deaths occur inland, away from the immediate coast.

As mentioned previously, out of 179 deaths from tropical systems, 92 of them occurred after the storm had made landfall and been downgraded. Out of the 92 deaths, 47 (52%) of the deaths from tropical systems were due to tropical depression (downgraded from hurricane/tropical storm). This begs the question, is there a perception in the public's mind that once a storm has been downgraded, the hazards associated with the storm are downgraded as well?

Fatalities from snowmelt-related flooding are distributed across the northern states with many of the deaths occurring along the Appalachian Mountains in the eastern United States. Frontal systems have two general clusters across the United States; the West Coast and from the southern Great Plains states north through the central Mississippi Valley and eastwards through the Ohio River Valley.

The spatial distribution of deaths due to MCSs falls primarily east of the Rockies and west of the Appalachians with clusters in central Texas, the central Mississippi Valley, and the Ohio River Valley (Figure 7). Out of the 502 *Storm Data* entries, 182 event entries (36%) were due to MCS flooding. As previously mentioned, MCSs have been linked to high-precipitation amounts and flash flooding in the literature (Doswell, 1994; Moore *et al*., 2003). MCSs typically cause a brief period of very heavy rainfall followed by a longer period of moderate rainfall, subsequently causing significant rainfall tallies and possible flooding (Doswell, 1994). The distribution of MCS flood fatalities coincides with the spatial distribution of fatalities from frontal boundaries most likely because synoptic-scale processes support the training of MCSs over one location. Additionally, the clustering of MCSs fatalities from central Texas through the Mississippi Valley coincides with the area of high mesoscale convective complex (MCC) rainfall contributions to annual totals found in Ashley *et al*. (2003). Although this study focuses on the largest of the MCSs (i.e. MCCs), their spatial distribution of MCC rainfall could be inferred to be similar to the total due to all MCSs.

As suggested previously, many of these fatal storm systems have a preferred seasonal distribution (Figure 8).

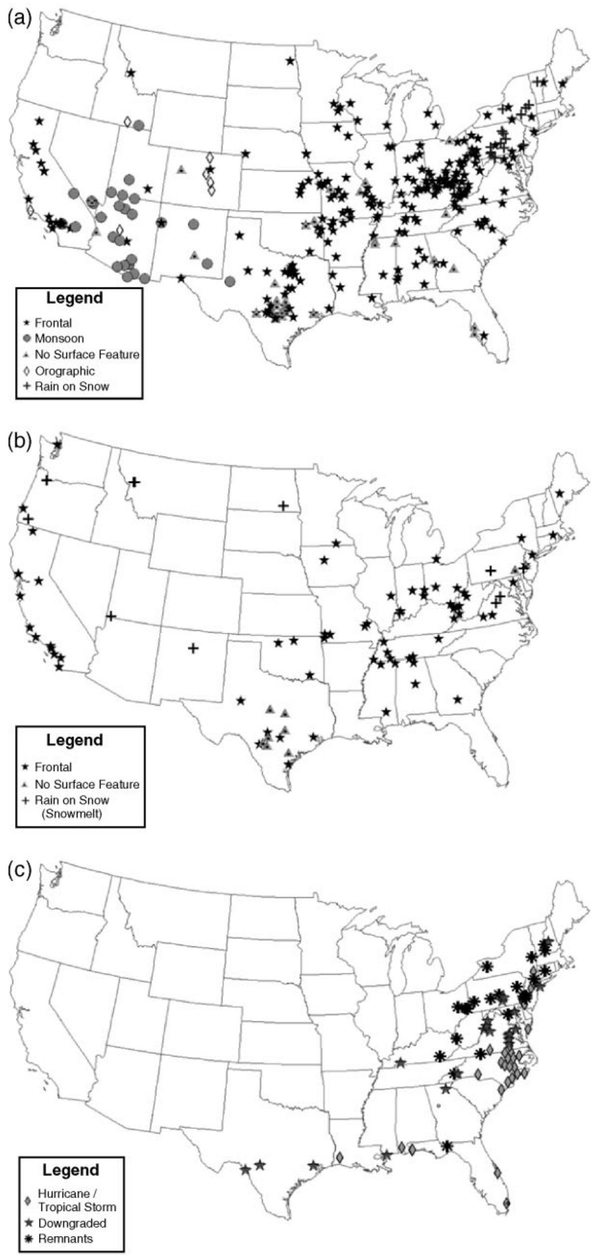

Figure 9. Spatial distribution of deadly storm types by the three dominant flood types, including (a) flash flood, (b) river flood, and (c) tropical system flood. Excludes fatalities from Hurricane Katrina.

During the fall months, tropical systems in the Mid-Atlantic are the dominant storm type associated with fatal flooding events in the United States. During the winter months, fatalities occur mostly from frontal storms and rain-on-snow events in mountainous terrain. Spring months are dominated by frontal system deaths, while the summer distribution of fatalities includes frontal, monsoonal thunderstorms, tropical, orographic and deaths from onshore flow or airmass convection.

Flood fatalities separated by flood type (including flash flood, river flood, and tropical system flood) and further subdivided by the synoptic scale and mesoscale environment illustrate that each type of flood is associated with specific environmental processes (Figure 9). Deadly

DOI: 10.1002/joc

flash floods are found throughout the United States and are associated with five types of dominant surface features, with those generated by frontal lifting the dominant type. Large-scale river floods fatalities are found throughout the United States, with few events through the Rocky Mountain States and the Southwest. They are generated predominantly from frontal systems and snowmelt or rain-on-snow events. In many instances, these flood events occur because of recurring storm systems and, subsequently, saturated soils. Therefore, the storm systems associated with these deaths may not have been the sole genitor of the flood but, in actuality, one of many storm systems to have contributed to the flooding event.

Tropical system floods are restricted to the eastern and southern states. Fatalities from Atlantic cyclones during this period tended to favor the Mid- Atlantic. This spatial distribution illustrates the impact that tropical cyclones can have on the people after the storms have lost intensity. This is an important implication especially for western parts of coastal states and other inlands states where people may not understand that they are at risk (or at as much risk as coastal locations) from the flood waters of tropical systems (e.g. TN, WV, OH, western PA, and western NC).

4. Summary and conclusions

Synoptic-scale and mesoscale environmental ascent mechanisms surrounding *deadly* flooding events in the United States have not been investigated previously. Existing literature has examined specific ascent mechanisms associated with flooding events, but these studies did not distinguish between deadly and non-deadly events. Moreover, these investigations are restricted by space and time or address a specific flood type, e.g. flash flood or unseasonable flood. From this study, which focuses exclusively on deadly flood event in the United States from 1996–2005, a better understanding of the type of storm systems that are linked to flood deaths for each region of the United States is understood. This knowledge may aid forecasters, insurers, hazard mitigation specialists, and flood control planners in reducing the number of unnecessary deaths that occur each year due to flooding. In addition, there is a need for further education of the public to improve their perception of floods since many are unaware or naïve of the water's potentially deadly power (Brilly and Polic, 2005; Drobot *et al*., 2006).

From 1996 to 2005, there were 815 fatalities from flood events and 302 storm systems from 502 *Storm Data* entries. The fatalities were predominantly from flash floods (58%) and floods caused by Atlantic tropical systems (22%). The results from this study illustrate that floods generated from frontal boundaries and tropical systems are the dominant causes of death from floods in the United States. Additionally radar image analysis indicates, deaths from MCSs, associated typically with synoptic-scale frontal boundaries, mid-level troughs, or closed lows, contributed to 36% of the total deaths during the period. Moreover, each storm system has a specific spatial and temporal distribution across the United States. For example, deadly floods generated from frontal boundaries associated with upper-air enhancement peak in the late winter to early fall and are concentrated along West Coast and from the southern Great Plains through the Mississippi Valley and eastward to the Ohio Valley. Deaths from flash floods generated from monsoonal thunderstorms dominate the Southwest during the summer and early fall. Interestingly, out of the 179 deaths caused by floods from tropical cyclones, 92 of them were due to either a downgraded, landfalling hurricane/tropical storm or the extratropical remnants of the tropical cyclone.

Further investigation into the synoptic and mesoscale environment surrounding these deadly events is needed over an extended period of record. The 10 years analysed here does not reveal fully the spatial and temporal distributions that a longer period of record could provide. A more extensive analysis period could verify the unique distributions of storm types associated with deadly floods found in this study. Additionally, investigations into the public perception of floods are integral in reducing the number of fatalities each year. As Drobot *et al*. (2006) illustrates in his investigation of the public's perception of vehicle safety in flash flood situations, people have the faulty understanding that they can keep themselves safe when faced with a dangerous circumstances. Moreover, people who have experienced fewer flash floods do not seem to have an appreciation for the deadly powers of the flood waters that may only reach six inches (15.2 cm) in depth. In order to reduce future United States flood fatalities, future work should try to bring together the results from larger-scale studies, such as this investigation, with smaller-scale studies examining localized flood storm types and human perception.

Acknowledgements

We appreciate the efforts of two anonymous referees who provided thoughtful and beneficial reviews.

References

Ashley WS, Mote TL. 2005. Derecho hazards in the United States. *Bulletin of the American Meteorological Society* **86**: 1577–1592.
Ashley ST, Ashley WS. 2006. Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology* (in press).
Ashley WS, Mote TL, Dixon PG, Trotter SL, Powell EJ, Durkee JD, Grundstein AJ. 2003. Distribution of mesoscale convective complex rainfall in the United States. *Monthly Weather Review* **131**: 3003–3017.
Attalah EH, Bosart LF. 2003. The extratropical transition and precipitation distribution of Hurricane Floyd. *Monthly Weather Review* **131**: 1063–1081.
Brilly M, Polic M. 2005. Public perception of flood risks, flood forecasting and mitigation. *Natural Hazards and Earth System Sciences* **5**: 345–355.
Capriola SJ. 1992. An analysis of synoptic scale flood events in the eastern United States during 1980–1989. Eastern Region Technical Attachment, No. 92-5A. National Weather Service Forecast Office: Portland, ME; 15.

Caracena F, Maddox RA, Hoxit LR, Chappell CF. 1979. Mesoanalysis of the Big Thompson Storm. *Monthly Weather Review* **107**: 1–17.
Changnon SA. 1999. Data and approaches for determining hail risk in the contiguous United States. *Journal of Applied Meteorology* **38**: 1730–1739.
Changnon SA, Kunkel KE. 1999. Record flood-producing rainstorm of 17–18 July in the Chicago Metropolitan area. Part 1: synoptic and mesoscale features. *Journal of Applied Meteorology* **38**: 257–265.
Crysler KA, Hoxit LR, Maddox RA. 1980. A climatology of the flash flood hazard in a four state region of Appalachia. *Preprints: Conference on Flash Floods: Hydrometeorological Aspects and Human Aspects*. American Meteorological Society: Boston, MA; 62–68.
Crysler KA, Maddox RA, Hoxit LR, Muller BM. 1982. Diurnal distribution of very heavy precipitation over the central and eastern United States. *National Weather Digest* **7**: 33–37.
Curran EB, Holle RL, Lopez RE. 2000. Lightning casualties and damages in the United States from 1959 to 1994. *Journal of Climate* **13**: 3448–3464.
Cutter SL. 2001. The changing nature of risks. In *American Hazardscapes: The Regionalization of Hazards and Disasters*, Cutter S (ed.). Joseph Henry Press: Washington, DC; 1–12.
Dittman RH. 1994. Annual flood death statistics per state per capita for the United States and Puerto Rico during the period 1959–1991. NOAA Technical Memorandum NWS SR-153. NWS Southern Region: Fort Worth, TX; 11.
Doswell CA III. 1994. Flash flood-producing convective storms: current understanding and research. In *Preprints, U.S.-Spain Workshop on Natural Hazards*, Barcelona, Spain, 8–11 June 1993; 97–107.
Doswell CA III. 1997. Flash flood forecasting – techniques and limitations. *Preprints, Jornades de Meteorologia Eduard Fontsere*. Catalan Meteorological Society: Barcelona.
Doswell CA III, Brooks HE, Maddox RA. 1996. Flash flood forecasting: an ingredients-based methodology. *Weather and Forecasting* **11**: 560–581.
Drobot S, Gruntfest E, Barnes L, Benight C, Hayden M, Schultz D. 2006. Driving under the influence of weather: perceptions of flash floods and vehicle safety. In *The 2006 Annual Meeting of the Association of American Geographers*, Chicago, IL, March 2006.
Dupigny-Giroux LL, Loughner C. 2004. A synoptic climatology of flooding in New England. *Preprints, 14th Conference on Applied Climatology*. American Meteorological Society: Seattle, WA.
Dupigny-Giroux LL, Hanning JR, Engstrom E. 2006. Orographic influence of frontally-produced flooding in northern Vermont – The July 14–15, 1997, event. *Physical Geography* **27**: 1–38.
Farfán LM, Zehnder JA. 1994. Moving and stationary mesoscale convective systems over Northwest Mexico during the Southwest Monsoon Project. *Weather and Forecasting* **9**: 630–639.
French J, Ing R, Von Allmen S, Wood R. 1983. Mortality from flash floods: a review of the National Weather Service reports, 1969–1981. *Public Health Reports* **98**: 584–588.
Gaffin DM, DG Hotz. 2000. A Precipitation and Flood Climatology with Synoptic Features of Heavy Rainfall across the Southern Appalachian Mountains. *National Weather Digest* **24**: 3–15.
Gamble DW, Meentemeyer VG. 1997. A synoptic climatology of extreme unseasonable floods in the southeastern United States, 1950–1990. *Physical Geography* **18**: 496–524.
Geerts B. 1998. Mesoscale convective systems in the Southeast United States during 1994–95: a survey. *Weather and Forecasting* **13**: 860–869.
Graybeal DY, Leathers DJ. 2006. Snowmelt-related flood risk in Appalachia: first estimates from snow climatology. *Journal of Applied Meteorology and Climatology* **45**: 178–193.
Higgins RW, Yao Y, Wang WL. 1997. Influence of the North American monsoon system on the U.S. summer precipitation regime. *Journal of Climate* **10**: 2600–2622.
Hirschboeck KK. 1987. Catastrophic flooding and atmospheric circulation anomolies. In *Catastrophic Flooding*, Mayer L, Nash D (eds). Allen and Unwin: Boston, MA.
Hirschboeck KK. 1991. The role of climate in the generation of floods. In *National Water Summary 1988–89, USGS Water-Supply Paper 2375*, Paulson RW, Chase EB, Roberts RS, Moody DW (eds). United States Geologic Survey: Denver, CO.
Kahana R, Ziv B, Enzel Y, Dayan U. 2002. Synoptic climatology of major floods in the Negev Desert, Israel. *International Journal of Climatology* **22**: 867–882.
Kattelmann R. 1997. Flooding from rain-on-snow events in the Sierra Nevada. In *Destructive Water: Water-caused Natural Disasters, their Abatement and Control*, Leavesley GH, Lins HF, Nobilis F, Parker RS, Schneider VR, Van De Ven FHM (eds). IAHS Publication 239, International Association of Hydrological Sciences: Wallingford, U.K.; 59–65.
Kiem BD, Meeker LD, Slater JF. 2005. Manual synoptic climate classification for the East Coast of New England (USA) with an application to $PM_{2.5}$ concentration. *Climate Research* **28**: 143–154.
Knabb RD, Rhome JR, Brown DP. 2005. Tropical Cyclone Report Hurricane Katrina 23–30 August 2005 National Hurricane Center, 42, [http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf.].
Konrad CE. 1997. Synoptic-scale features associated with warm season heavy rainfall over the interior Southeastern United States. *Weather and Forecasting* **12**: 557–571.
Kunkel KE, Changnon SA, Angel JR. 1994. Climatic aspects of the 1993 upper Mississippi River basin flood. *Bulletin of the American Meteorological Society* **75**: 811–822.
Leathers DJ, Kluck DR, Kroczynski S. 1998. The severe flooding event of January 1996 across North-Central Penssylvania. *Bulletin of the American Meteorological Society* **79**: 785–797.
Maddox RA, Grice GK. 1986. The Austin, Texas, flash flood: an examination from two perspectives – forecasting and research. *Weather and Forecasting* **1**: 66–76.
Maddox RA, Chappell CF, Hoxit LR. 1979. Synoptic and meso-alpha scale aspects of flash flood events. *Bulletin of the American Meteorological Society* **60**: 115–123.
Maddox RA, Hoxit LR, Chappell CF, Caracena F. 1978. Comparison of meteorological aspects of the Big Thompson and Rapid City flash floods. *Monthly Weather Review* **106**: 375–389.
Moore JT, Glass FH, Graves CE, Rochette SM, Singer MJ. 2003. The environmental of warm-season elevated thunderstorms associated with heavy rainfall over the central United States. *Weather and Forecasting* **18**: 861–878.
Neumann CJ, Jarvinen BR, McAdie CJ, Elms JD. 1993. Tropical cyclones of the North Atlantic Ocean, 1871–1992, Prepared by the National Climatic Data Center, Asheville, NC, in cooperation with the National Hurricane Center, Coral Gables, FL, 193.
NOAA. 2005. *Storm Data*. National environmental satellite, data and information service, National Climatic Data Center: Asheville, NC.
Parker MD, Johnson RH. 2000. Organizational modes of midlatitude mesoscale convective systems. *Monthly Weather Review* **128**: 3413–3436.
Peterson WA, Carey LD, Rutledge SA, Knievel JC, Doesken NJ, Johnson RH, McKee TB, Vonder Haar T, Weaver JF. 1999. Mesoscale and radar observations of the Fort Collins flash flood of 28 July 1997. *Bulletin of the American Meteorological Society* **80**: 191–216.
Pontrelli MD, Bryan G, Fritsch JM. 1999. The Madison County, Virginia, flash flood of 27 June 1995. *Weather and Forecasting* **14**: 384–404.
Randerson D. 1976. Meteorological analysis for the Las Vegas, Nevada, flood of 3 July 1975. *Monthly Weather Review* **104**: 719–727.
Rappaport EN. 2000. Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bulletin of the American Meteorological Society* **81**: 2065–2073.
Singh P, Spitzbart G, Hubl H, Weinmeister HW. 1997. Hydrological response of snowpack under rain-on-snow events: a field study. *Journal of Hydrology* **202**: 1–20.
Smith JA, Baeck ML, Morrison JE, Sturdevant-Rees P. 2000. Catastrophic rainfall and flooding in Texas. *Journal of Hydrometeorology* **1**: 5–25.
Wisner B, Blaikie P, Cannon T, Davis I. 2004. *At Risk: Natural Hazards, People's Vulnerability and Disaster*. Routledge: New York; 447.