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Use of Ground-based Radar for Climate-Scale Studies of Weather and Rainfall

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Abstract

Reflectivity data from weather radar provide information on the location and quantity of water and ice in the atmosphere at high spatial and temporal resolutions. Although the analysis of radar data facilitates spatially accurate climatologies of weather events and rainfall, relatively few studies have utilized data from the US Next Generation Radar (NEXRAD) network for climate-scale research. Towards the goal of increasing the use of these data by geographers, this article details the collection of radar data, their limitations, and conversion into rainfall rates. Examples of climate-scale research incorporating NEXRAD data are also presented. Although its capabilities to analyze temporal data are limited, the use of Geographical Information Systems (GIS) by non-geographers is growing. This suggests that the collaboration of geographers specializing in geospatial techniques with those pursuing research in climatology could develop new GIS-based methods for the spatial analysis of radar data that facilitate climate-scale research of weather patterns.

Introduction

Hazardous weather causes fatalities and billions of dollars in damage each year (Pielke et al. 2008). The ability to detect the quantity and location of water and ice in the atmosphere has important benefits to society such as the prediction of the depth and location of lake-effect snowfall (Laird et al. 2009b; Steenburgh et al. 2000), determining which rainfall events will lead to flash flooding (Carpenter et al. 1999; Fang et al. 2008), and to quantify the degree to which urbanization contributes to precipitation (Mote et al. 2007). Scanning the atmosphere with ground-based weather radar provides data of the high spatial and temporal resolution needed to analyze atmospheric conditions for short-term forecasting (e.g. Donavon and Jungbluth 2007) and longer-term climatological studies of rainfall (e.g. Overeem et al. 2009) and hazardous weather (e.g. Hocker and Basara 2008).

The majority of studies that utilize ground-based radar to analyze hazardous weather in the US are case studies or compare relatively few events. It is less common for radar reflectivity data to be utilized over a large temporal scale or for the analysis of multiple occurrences of a type of weather event, such as landfalling tropical cyclones. However, the high spatial and temporal resolutions of radar data render them appropriate for climatological-scale examinations of hazardous weather. A geospatial analysis of radar data can quantify characteristics such as areal coverage and spatial patterns of weather events (e.g. Basara et al. 2007; Billet et al. 1997; Matyas 2009). As geographers specialize in the analysis of spatial data, it would seem that geographer-climatologists might largely contribute to climate-scale weather analysis using radar data. Yet, after a presentation given during the 2003 Climate Specialty Group Student Paper Competition (Matyas 2003), an audience member posed the question, 'Should climatologists be using radar data in their research?'

Interestingly, four meeting abstracts published in the *Annals of the Association of American Geographers* during the 1960s suggest that geographers were involved in radar analysis that time (Prentice 1967; Rhodes and Schwarz 1967; Simpson 1965, 1966). However, an exploration of abstracts in *The Professional Geographer* and the *Annals of the Association of American Geographers*, yield only two recent studies that employ reflectivity data from ground-based weather radars (Legates 2000; Matyas 2007). Quiring (2007) demonstrated that many geographer-climatologists publish their work in non-geography journals. An examination of abstracts in the top ten journals for publication of research by geographer-climatologists listed by Quiring (2007) reveals that relatively few studies utilize ground-based radar data on a climatological scale (Table 1). Additionally, only four of the author addresses for these papers list a Geography or Geosciences Department. A search of journals that publish Geographical Information System (GIS)-related research (Table 2) yields similar results. Climate-scale research utilizing weather radar data has been published in journals other than those listed in Tables 1 and 2 as is indicated by examining the reference list for this manuscript; however, most of these authors are from atmospheric science or engineering departments. The large volumes of data required for analysis, difficulties in

Table 1. List of journals in which most geographer-climatologists publish (Quiring 2007) and articles containing key words NEXRAD and WSR-88D that feature climate-scale spatial analysis of NEXRAD reflectivity data.

Journal	NEXRAD	WSR-88D
Journal of Climate	Carleton et al. (2008) (viewed images only; spatial analysis is performed by Matyas and Carleton (2010))	X
Physical Geography	Dyer (2009)	X
Climate Research	X	X
International Journal of Climatology	X	Ashley and Ashley (2008), Croft and Shulman (1989), DeGaetano and Wilks (2009) and Hocket and Basara (2008)
Journal of Geophysical Research – Atmospheres	Cosgrove et al. (2003), Nelson et al. (2003a), Villarini et al. (2009) and Young et al. (1999)	Smith et al. (1999) and Wiens et al. (2008)
Geophysical Research Letters	Gauthier et al. (2006), Kongoli et al. (2003) and Moore and Rojstaczer (2002)	Kelley et al. (2005), Melnikov et al. (2008), Mote et al. (2007) and Nelson et al. (2005)
Bulletin of the American Meteorological Society	Ryzhkov et al. (2005b)	Hoium et al. (1997), Parker and Knievel (2005), MacGorman et al. (2008), Ortega et al. (2009), Rasmussen et al. (1994) and Westrick et al. (1999)
Professional Geographer	X	Legates (2000) and Matyas (2007b)
Annals of the Association of American Geographers	X	X
International Journal of Remote Sensing	Brunsell and Young (2008) and Cao et al. (2009)	Nirala and Cracknell (2002)
Remote Sensing of the Environment	X	X

Table 2. List of journals that publish GIS-related research and articles whose abstracts and/or key words contain 'NEXRAD' or 'WSR-88D'.

Journal	NEXRAD	WSR-88D
International Journal of Geographical Information Science	X	X
Journal of Geographical Systems	X	X
Transactions in GIS	X	Basara et al. (1997)
GeoInformatica	X	X
Geographical Analysis	X	X
Cartography and Geographic Information Science	X	X
Geographical and Environmental Modeling	X	X
Computers and Geosciences	Krajewski et al. (2006), Kruger et al. (2006) and Xie et al. (2005)	Nelson et al. (2003b)

the analysis of temporal data within GIS, and, until recently, the lack of tools to incorporate radar data into a GIS (Ansari and Del Greco 2005; Shipley 2005), may explain why few geographers currently analyze these data.

The goals of this article are to provide basic information about the format and limitations of radar reflectivity data, and to demonstrate how geographers might utilize radar reflectivity or rainfall estimate data in their research and develop new methods of spatial analysis with these data. As many geographers may be unfamiliar with these data, section two of this article briefly discusses the development of the USA weather radar network and the spatial and temporal components of radar data. The third section details important limitations and causes of erroneous data of which users should be aware. The issues that must be considered before creating a mosaic of data from adjoining radar sites are explained next, including data interpolation, as geographers have special expertise in spatial analysis that could lead to new interpolation techniques. Next, the conversion of radar reflectivity values into rainfall rates is described, which is a key step in increasing the accuracy of rainfall climatologies and hydrologic models. Then, a brief overview of several climatological-scale studies that have employed data from US weather radar is accompanied by suggested research directions that could be taken by geographers, Finally, the last section discusses the use of GIS to analyze radar data and suggests that the spatial analytic skills of geographers could lead to new radar geovisualization and analysis techniques. Data from radars are also analyzed for weather research in other countries, in mobile radars such as the Doppler on Wheels, and aboard aircraft and spacecraft. As these radars utilize different wavelengths from those employed by the US National Weather Service and their data may not be widely available for research use, they are not discussed in this paper.

Radar Operations

Radar, or radio detecting and ranging, was developed prior to World War II to monitor aircraft positions (Atlas 1990; Doviak and Zrnic 1993; Skinner et al. 2009; Whiton et al. 1998). Users discovered that the pulses of microwave energy emitted by the radar could be employed to detect phenomenon such as birds or water droplets in addition to aircraft

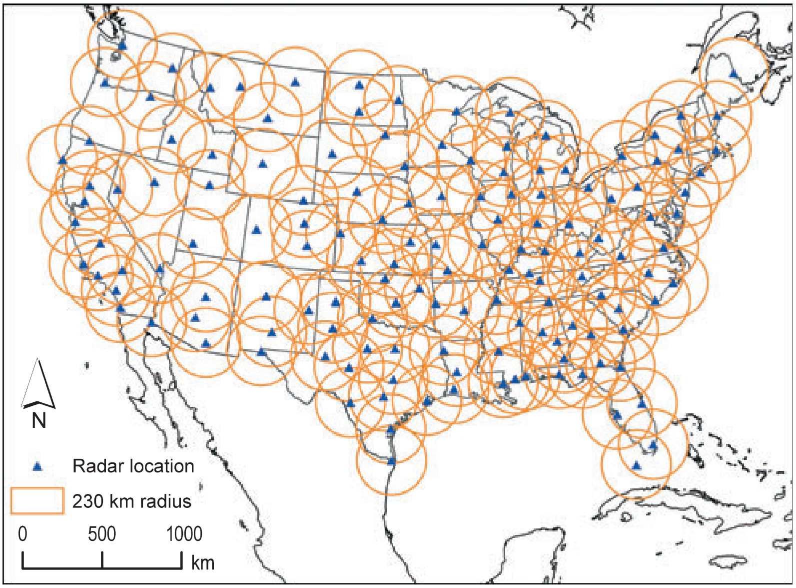

Fig. 1. Location of WSR-88D sites in the lower 48 states and the 230 km radius over which the atmosphere is sensed by each radar. Beam blockage by mountains prevents continuous spatial sampling of the atmosphere in the western USA.

(Maynard 1945). Thus, modifications were made to increase the ability of radar to detect weather systems for short range weather forecasting and rainfall prediction (Marshall et al. 1947; Maynard 1945; Wexler 1948). Damage caused by tornadoes and landfalling hurricanes prompted the US Weather Bureau to develop a network of ground-based radars, the Weather Surveillance Radar – 1957 (WSR-57) (Whiton et al. 1998).

The current radars in use today, the Weather Surveillance Doppler-1988 Doppler (WSR-88D), or Next Generation Radar (NEXRAD), were commissioned in the 1990s; their deployment and management is a joint effort of the Department of Commerce, the Federal Aviation Administration, and the Department of Defense (Crum et al. 1998; OFCM 2006). The enhanced power output, increased gain, and narrowed beam width of the WSR-88D units allows for a greater sensitivity and better spatial resolution of target echoes when compared to the WSR-57 units (Fulton et al. 1998). More than 150 WSR-88D radars operate within the USA (Figure 1). Current improvements to the WSR-88D units include modifications allowing radio waves emitted by the radar to have both horizontal and vertical orientations (Doviak et al. 2000; Zrnic et al. 2006). Polarimetric radar will allow for improved rain rate estimation and precipitation-type detection (Doviak et al. 2000; Ivic et al. 2009; Meischner 2004; Ryzhkov et al. 2005a,b).

The radar generates short pulses of radio waves that are concentrated into a narrow beam and transmitted across a 360° sweep of the atmosphere every 5–10 min (Burgess and Ray 1986; Crum et al. 1998; Krajewski et al. 2006; Meischner 2004; Skinner et al. 2009). A receiver detects the amount of signal that reflects off of a target back towards the radar and computers calculate the strength of the returned signal and its travel time. The amount of the total power output that is returned to the receiver is measured in dBZ, or decibels of Z where Z is the radar reflectivity factor (Meischner 2004). The amount of power that reaches the receiver depends on the size and shape of the target.

Doppler radar also detects the phase shift of the pulse of energy so that the speed and direction of a target's motion can be determined. After each sweep, the tilt of the radar is changed through a range of 0.5° to 20° from the horizon so that the atmosphere is sampled at multiple elevations to produce a volume scan. Different scan elevations and times, or volume coverage patterns (VCPs), are implemented by meteorologists at each National Weather Service (NWS) Office depending on the type of weather that is detected (Fulton et al. 1998; Kruger et al. 2006; Maddox et al. 1999; Miller et al. 1998; OFCM 2006). The data produced during each volume scan, which include reflectivity (Figure 2a,b), mean radial velocity, and spectrum width, are termed Level II data and are best-suited for most research applications (Crum et al. 1998) and rainfall estimation (Fulton et al. 1998).

Reflectivity values are produced every one kilometer outward from the radar in each 1° arc of the 360° circle with 0.5-dBZ precision (Crum et al. 1998; Fulton et al. 1998). However, the azimuthal spacing of each bin in which data are collected, as well as the beam width, increases as distance from the radar site increases (Zhang et al. 2005), leading to a decrease in spatial resolution. Also, the beam increases in altitude as it travels outbound (Figure 3). At the lowest scan elevation of 0.5°, which is known as the base scan (Figure 2a), beam height is approximately 2.5 and 5 km at distances of 150 and 230 km from the site, respectively. Given the decreasing sample resolution and the fact that the lowest layers of clouds may not be sampled at large distances away from the radar site, only data within a 230 km radius of the radar site (Figure 1) are utilized for most analyses (OFCM 2006). Several products are created from Level II data including a composite analysis where the highest reflectivity value out of all elevations is recorded for each data bin (Figure 4), and one hour precipitation totals (Figure 5). A total of 41 products created from the Level II data are available in the Level III dataset (Collier 1996; OFCM 2006). These data are available from the National Climatic Data Center (NCDC) website (NCDC 2009a), and can be ordered for most WSR-88D sites beginning in 1995, although Level II data are not available from some sites after 2001.

Conditions that Produce Erroneous Reflectivity Values

Anomalous beam curvature, ground clutter, and the presence of melting ice can cause erroneous reflectivity values or instances where reflectivity values are absent when they should be present. The amount of curvature of a radar beam (Figure 6) is affected by the rate of decrease in pressure, temperature, and humidity with height in the troposphere. Under normal atmospheric conditions, a radar beam curves slightly less than the surface of the earth, causing it to sense higher altitudes at farther distances (Burgess and Ray 1986; Rinehart 1991). False echoes in radar reflectivity data can be caused by anomalous propagation of the beam when moisture and temperature do not change with height as expected (Moszkowicz et al. 1994). Fortunately, researchers have developed and implemented automatic detection and removal algorithms for false echoes under conditions associated with abnormal refraction (Fulton et al. 1998; Moszkowicz et al. 1994; Steiner and Smith 2002).

Ground clutter produces false echoes as energy that is returned to the receiver is scattered off of objects near or on the earth's surface (Doviak and Zrnic 1993). Fixed objects such as trees, buildings, wind farms, and hills are sources of ground clutter (Chang et al. 2009). The size and intensity of the echoes produced by these objects can cause rainfall estimates to be erroneously large (Chang et al. 2009; Smith et al. 1996). Algorithms exist that successfully detect and remove ground clutter as false

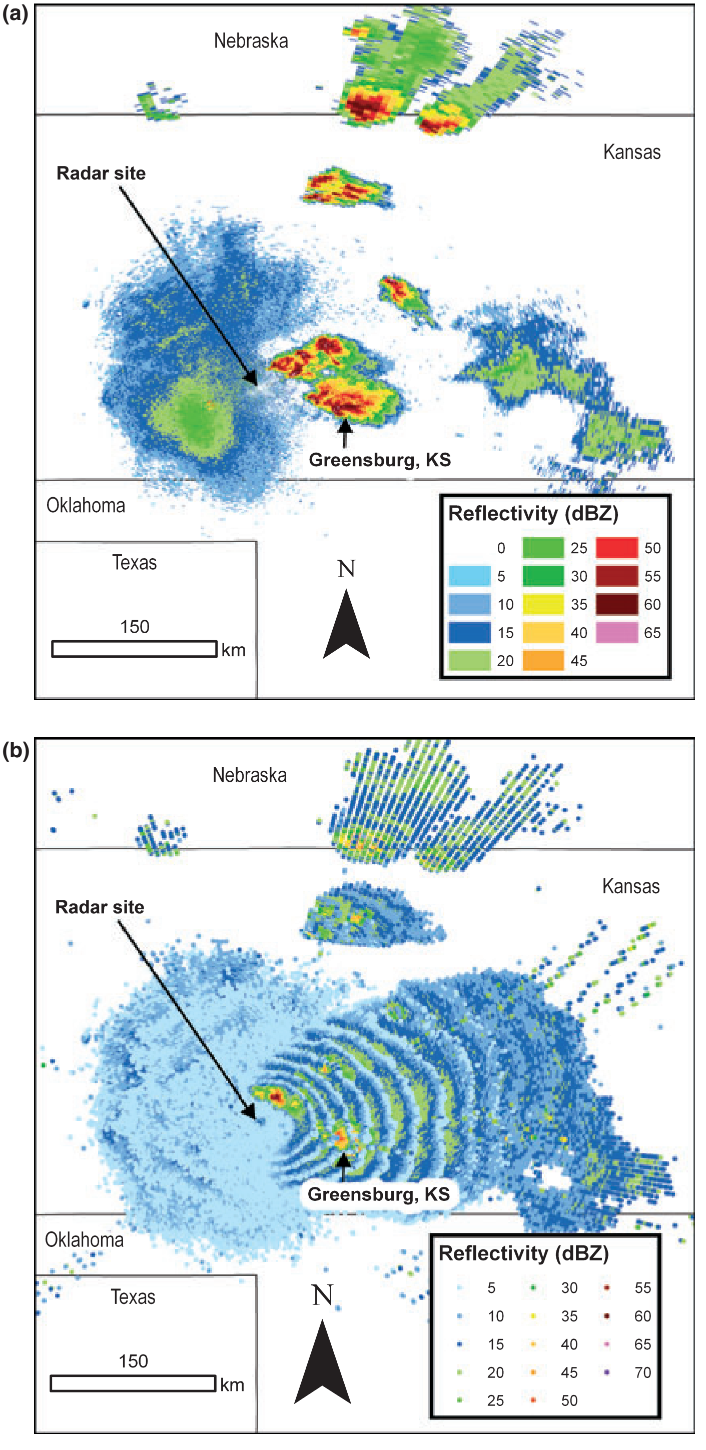

Fig. 2. Reflectivity values detected by the 0.5° tilt, or base scan (a), and complete volume of Level II data (b), from the radar located in Dodge City, Kansas (KDDC) at the time of the Greensburg, Kansas tornado (5 May 2007, 0241 UTC). Higher reflectivity values correspond to larger rainfall rates.

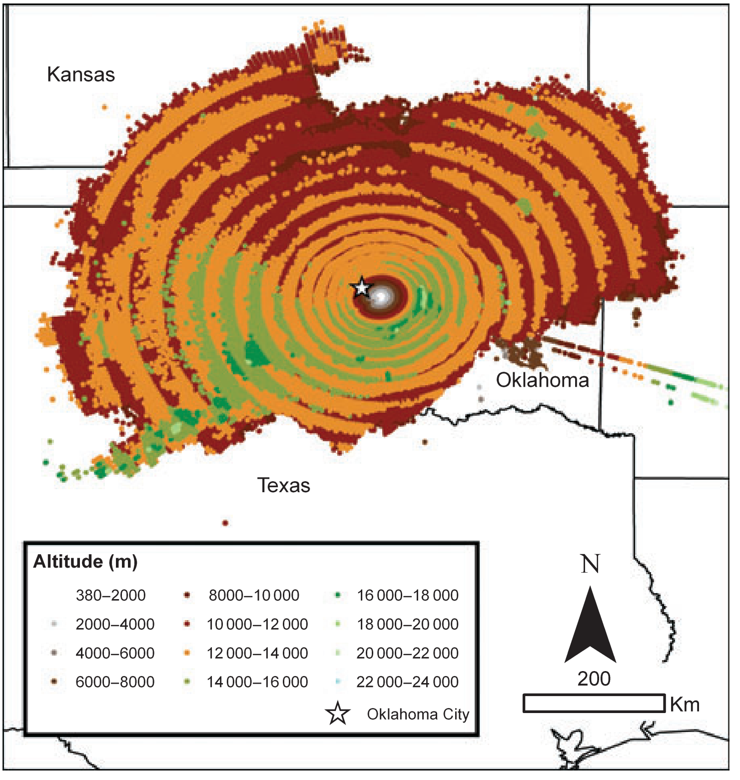

Fig. 3. The altitude of the reflectivity returns detected during a volume scan of the atmosphere by the radar located in Oklahoma City, Oklahoma (KTLX) during a severe thunderstorm event on 20 June 2007.

echoes from fixed objects are relatively easy to distinguish (Collier 2009; Doviak and Zrnic 1993; Fulton et al. 1998).

When the radar's beam intersects a layer of melting precipitation, reflectivity values are higher than normal as melting snowflakes reflect the same amount of energy as very large rain drops. This layer of melting precipitation that occurs just below the freezing level is termed the bright band (Gray et al. 2001; Gourley and Calvert 2003). Converting erroneously high reflectivity values from the bright band into rainfall rates causes rainfall totals to be overestimated (Bechini et al. 2008; Gourley and Calvert 2003; Smith 1986). Also, identification of the bright band is important when composite radar reflectivity data are utilized (e.g. Matyas 2009) as the composite data feature the maximum reflectivity value found at any altitude for each data bin (Zhang et al. 2008). Algorithms implemented to remove these regions from rainfall calculations have proven effective (Gourley and Calvert 2003; Legates 2000).

Creating a Mosaic of NEXRAD Data

To gain a complete understanding of the changes in a single storm as it passes within range of several radar sites, or to analyze synoptic-scale weather systems in their entirety (e.g. Figure 6), it is necessary to combine data from neighboring radar sites into a single mosaic. Creating a mosaic that is spatially and temporally accurate presents numerous

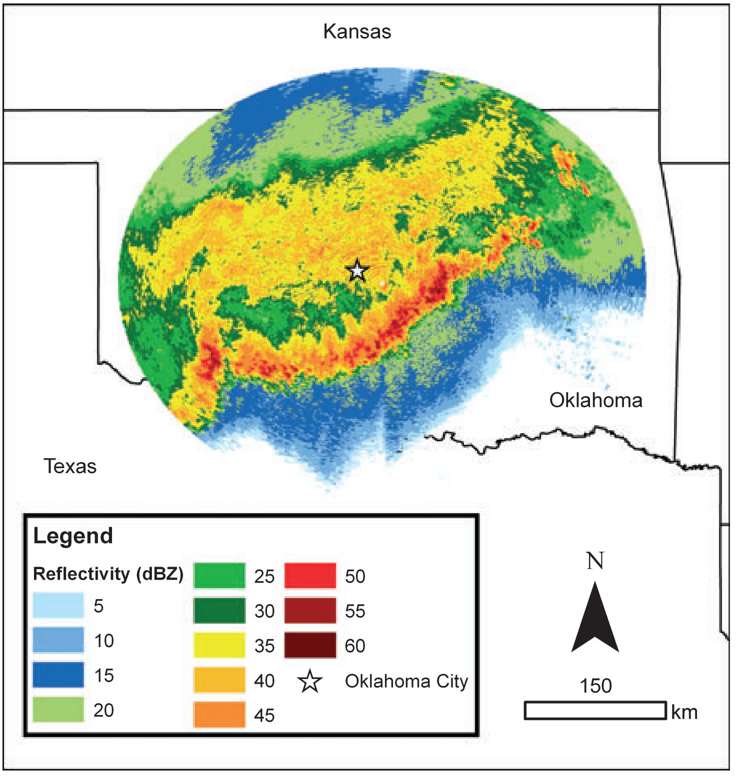

Fig. 4. Composite reflectivity data from the radar located in Oklahoma City, Oklahoma during a severe weather event on 20 June, 2007. These data are from the same time as those depicted in Figure 3.

challenges. NEXRAD coverage (Figure 1) is such that some locations are sampled by as many as eight radars at an altitude of 8 km, while other locations are only sampled by one radar (Basara et al. 2007; Maddox et al. 2002; Zhang et al. 2005). Scanning by multiple radars improves data quality by facilitating the identification of ground clutter and anomalous propagation, and providing additional data along the vertical scale to fill in the 'cone of silence' immediately above the radar (Figure 2b) where scanning is not possible (Lakshmanan et al. 2006; Maddox et al. 1999). Unfortunately, there are locations within the USA, particularly in the intermountain west, where radar coverage is not available due to beam blocking by the elevated terrain (Gourley et al. 2002; Legates 2000). As the elevation of each radar varies across the USA, the lowest-level scan in regions of high terrain will be hundreds of meters above the base-level scan of a radar located near sea level (Maddox et al. 2002; Wood et al. 2003). Thus, differences in elevation must be considered when creating a mosaic.

Further complicating the process of creating a mosaic is that each WSR-88D unit may be calibrated differently, causing it to over or underestimate reflectivity values (Basara et al. 2007; Delobbe and Holleman 2006; Xu et al. 2008). Cold, or under-calibrated radars, may underestimate the intensity of rainfall and the overall severity of the weather event, while a hot, or over-calibrated radar, may overestimate rainfall rates. Differences in reflectivity values of two to more than five decibels are common amongst radars in the WSR-88D network (Zhang et al. 2005). When reflectivity data from miscalibrated radars are

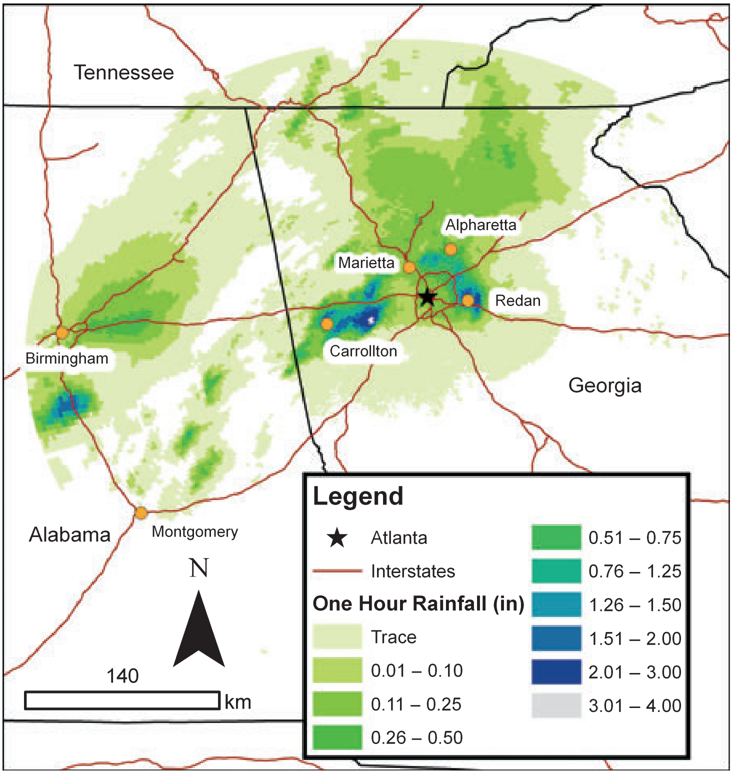

Fig. 5. One hour precipitation totals estimated by the radar located in Peachtree City, Georgia (KFFC) during the rainfall event of 21 September 2009 that led to flooding in and around Atlanta, Georgia.

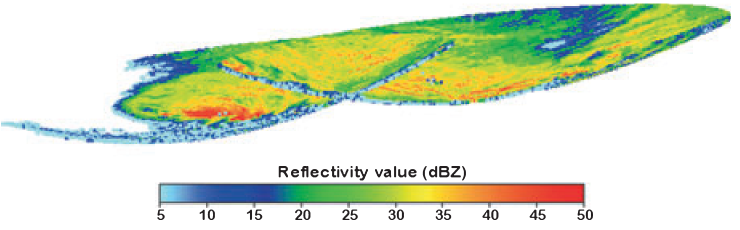

Fig. 6. Side view of base reflectivity data from two adjacent radars during the landfall of Hurricane Floyd (1999) illustrating the overlap of the data in space.

converted to rainfall totals, heavy precipitation events tend to be underestimated, while totals from lighter rainfall events are overestimated (Legates 2000). Williams et al. (2005) found that accurate detection of short-lived convective cells featuring a large gradient in reflectivity suffered the most from radar calibration issues. Fortunately, Parker and Knievel (2005) found that the problem is reduced when examining reflectivity values of 40 dB*Z* or higher, which are generally utilized to delineate convective rainfall (Jorgensen 1984; Matyas 2009).

Issues with the timing of data collection must be considered when data from one radar site are analyzed, but become more challenging when creating a mosaic of data from several radars (Lakshmanan et al. 2006; Yang et al. 2009). When scanning in precipitation mode, each scan takes place over a 5–6 min period (Crum et al. 1998; Klazura and Imy 1993; Yang et al. 2009). As the data collected for the first 1° arc to be sensed are older than the data returned from the last arc of the sweep, these two spatially contiguous arcs do not display temporally continuous data. When data from two overlapping radars are considered, a small and fast-moving cell may appear at two different locations if scan times are greatly offset (Yang et al. 2009). Depending on the type of weather that is occurring, neighboring radars may utilize different VCPs whose scan times range from 4 to 10 min (Yang et al. 2009). Also, as the clocks of the radars are not synchronized (Lakshmanan et al. 2006; Yang et al. 2009), each scan could begin at a different time for each radar that comprises the mosaic.

The factors previously discussed may lead to multiple reflectivity values being available for the same location (Figure 6). To create an accurate mosaic, researchers have investigated several interpolation strategies for selecting a reflectivity value for each grid cell (Lakshmanan et al. 2006, 2007; Trapp and Doswell 2000; Yang et al. 2009; Zhang et al. 2005). In nearest- neighbor mapping, the reflectivity value from the radar that is closest to the grid cell is utilized. This strategy minimizes problems with low reflectivity values produced by a wide beam that travels far from the radar, but discontinuities along locations that are equidistant between two radar sites are problematic. Thus, differences in calibration and sweep times, as well as bright band sampling appear as straight lines through the reflectivity values. Averaging the reflectivity values can smooth the data, but erroneously low or high reflectivity values among the data that are averaged produce a grid cell whose value is also too high or low. Using the maximum reflectivity value regardless of which radar detected this value assures that higher reflectivity values comprising small-scale features, such as individual convective thunderstorms, are not filtered out by a smoothing strategy, but the grid becomes biased towards 'hot' radars. Calculating a weighted mean such that the closest radar carries the highest weight can provide a method for smoothing data while limiting problems with beam width and lower reflectivity values sensed at far distances. Zhang et al. (2005) and Langston et al. (2007) found this strategy to produce the most accurate mosaic. As the analysis of Langston et al. (2007) also includes a temporal component, they add that a temporal weighting scheme utilizing an exponentially-decaying weighting function improves accuracy over the method employed by Zhang et al. (2005). As geographers utilize many methods for spatial interpolation (e.g. Burrough and McDonnell 1998; Goodchild 1992, 2003; Goodchild et al. 1993; Lam 1983; Miller 2004; Mugglin et al. 1999,), further techniques to interpolate radar data could be developed by geographers.

Using Radar to Estimate Rainfall

To estimate rainfall rates from radar reflectivity values, the *Z–R* relationship is utilized where Z is the radar reflectivity value (mm^6 m^{-3}) and R is the rainfall rate (mm h^{-1}) (Marshall and Palmer 1948). These variables are related via a power function so that Z depends upon the size distribution and raindrop diameter to the sixth power, and R depends upon the raindrop size distribution, the size of the drops to the third power, and the fall velocity of drops of a given diameter. Given the different types of precipitation, storm types, and storm intensities, it is not possible for a single *Z–R* relationship to accurately derive rainfall rates in every given situation (Collier 1996; Hardegree et al. 2008).

Table 3. Five *Z–R* relationships employed at WSR-88D sites

Relationship	Equation	Use	20 dB*Z* rain rate (mm·hr^{-1})	40 dB*Z* rain rate (mm·hr^{-1})
Marshall–Palmer	$Z = 200R^{1.6}$	Stratiform	0.76	11.43
East-Cool Stratiform	$Z = 130R^{2.0}$	Winter stratiform east of continental divide	1.02	8.89
West-Cool Stratiform	$Z = 75R^{2.0}$	Winter stratiform west of continental divide	1.27	11.68
Convective (Default)	$Z = 300R^{1.4}$	Summer deep convection, non-tropical	0.51	12.19
Rosenfeld Tropical	$Z = 250R^{1.2}$	Tropical convection	0.51	21.59

Marshall et al. (1947) suggested $Z = 200R^{1.6}$, and today, the NWS uses $Z = 300\ R^{1.4}$ as the default equation (Fulton et al. 1998). Table 3 lists the variety of Z–R relationships that can be employed at each radar site and the rainfall rates for reflectivity values of 20 dBZ representing accumulating stratiform precipitation, and 40 dBZ representing the higher rain rates of convective precipitation.

Given its ability to collect data over a spatially continuous area covering approximately 166 000 km^2, radar has been an invaluable tool utilized to develop rainfall climatologies. Prior to the establishment of NEXRAD, rain gauges were the primary source of rainfall-related data. However, the spatial coverage of gauge data is inadequate to develop a spatially-accurate rainfall climatology as Habib et al. (2009) estimate that only 1.3 gauges are available per 1000 km^2 across the USA. Too few gauges are present in most regions to detect the majority of small-scale convective rainfall events, and gauges often do not capture the peak rainfall produced by a storm (Allen and DeGaetano 2005; Habib et al. 2009; Li et al. 2008). Additionally, rain gauge measurements may be erroneous due to the effects of turbulence and increased wind flow around the gauge so that undercatch may be 20–40% during a strong thunderstorm (Wilson and Brandes 1979).

Despite their limitations, rain gauge data provide a ground truth to which radar-derived data can be compared (DeGaetano and Wilks 2009; Hardegree et al. 2008; Trapero et al. 2009). Data from rain gauges have been utilized to determine that 15 dBZ reflectivity values do not produce rainfall that accumulates on the ground, thus most studies utilize 20 dBZ as a threshold for stratiform clouds that produce rainfall (Allen and DeGaetano 2005; Gorokhovich and Villarini 2005; Matyas 2007). At the NWS River Forecast Centers, rain gauge data are combined with radar data to create an hourly precipitation map with a spatial resolution of 16 km^2 on a national polar grid known as the Hydrologic Rainfall Analysis Project grid (Fulton et al. 1998; Habib et al. 2009; Hardegree et al. 2008). Data from the HRAP grid are utilized by River Forecast Centers for river modeling activities and flood forecasting, and Vieux (2001) describes the relative ease with which HRAP data are imported into a GIS, thus making them suitable for analysis by geographers.

Radar-based Climatologies of Hazardous Weather Events and Opportunities for Geographic Research

Climatological-scale studies of lake effect snow that incorporate radar reflectivity data have been published for the Great Salt Lake (Steenburgh et al. 2000), the Finger Lakes of New York (Laird et al. 2009a), and Lake Champlain in Vermont (Laird et al. 2009b). The use of reflectivity data allows the quantification of the spatial coverage and orientation of cloud bands, and estimation of snowfall totals (Laird et al. 2009a; Rodriguez et al.

2007). As the analysis of radar reflectivity returns allows to calculation of statistics such as mean and median reflectivity, the percentage of time that reflectivity values equal or exceed threshold values, and the spatial coverage of each threshold value, it is possible for other researchers, including geographers, to utilize NEXRAD data to construct snowfall climatologies for other lakes. As conventional surface data are not of a high enough spatial or temporal resolution to identify local convergence zones, land and lake breezes, and roll convective patterns that are precursors to lake effect snow events (Kristovich et al. 1999; Steenburgh et al. 2000), these features may also be observed by radar to improve the prediction of lake effect snowfall events.

The appearance of a critical reflectivity threshold has helped researchers identify cold season weather events such as bow echoes, freezing drizzle, and thundersnow. Reflectivity data were essential to characterize changes during the life cycles of 51 cold season bow echoes examined by Burke and Schultz (2004). Bow echoes can produce widespread damaging winds and are identified in radar images by their curved shape that expands over time with a tight reflectivity gradient on their leading edge. Burke and Schultz (2004) utilized the appearance of a 40 dBZ echo within the squall line to denote the start of a bow echo, and then calculated its duration. Recently, Ikeda et al. (2009) developed a method to identify radar reflectivity patterns that are associated with freezing drizzle, which is a hazard for aircraft both in-flight and on the ground. Their detection scheme correctly classified freezing drizzle events 70% of the time due to the presence of reflectivity values under 5 dBZ and uniform echo fields in the horizontal direction. According to Steiger et al. (2009), more than 20% of lake effect snow events in western New York produce lightning. They utilized a radar reflectivity threshold of 35 dBZ to confirm the possibility of thunderstorm activity as their primary accounts of lightning were from storm spotters. They suggest that future researchers utilize reflectivity data to examine the structure of these storms, and the analysis of spatial patterns described in all three of these papers could be performed by geographer-climatologists.

Climatological studies utilizing WSR-88D data of thunderstorms that produce hail have improved hail prediction and detection algorithms (Basara et al. 2007; Billet et al. 1997; Mallafre et al. 2009). It can be difficult to distinguish a small number of large hailstones from a large number of small hailstones as reflectivity values are dependent on both the size and number of hydrometeors (Delobbe and Holleman 2006). Thus, reflectivity values greater than or equal to 55 dBZ are generally assumed to contain hail (Delobbe and Holleman 2006; Fulton et al. 1998), and researchers have related the probability that a storm will produce large hail to the vertically integrated liquid (VIL) product produced from Level II radar data (Billet et al. 1997; Edwards and Thompson 1998; Holleman et al. 2000; Lopez and Sanchez 2009). In addition to using VIL, the probability of hail has also been determined utilizing the 45 dBZ echo top height (Delobbe and Holleman 2006; Waldvogel et al. 1979). Hail climatologies utilizing radar data, as well as data from atmospheric soundings and ground observations, have been developed for the southern plains (Basara et al. 2007), the Washington DC area (Billet et al. 1997; Donavon and Jungbluth 2007), and Oklahoma (Witt and Nelson 1991). However, more research examining various radar-based prediction thresholds for hail size is needed for other regions of the country as atmospheric dynamics and thermodynamics exhibit regional variability (Edwards and Thompson 1998).

Incorporating lightning data into radar-based thunderstorm climatologies can help to separate stratiform and convective rainfall and indicate the stage of development of a storm cell (Steinacker et al. 2000; Tadesse and Anagnostou 2009). Lightning activity commences when updrafts reach the $-10°C$ isotherm (Gremillion and Orville 1999;

Lhermitte and Krehbiel 1979; Toracinta et al. 1996), and once reflectivity values increase above 35 dB*Z* (Tapia et al. 1998; Toracinta et al. 1996). The greatest flash density occurs in the tallest convective clouds where 40 dB*Z* reflectivity values are present at an altitude above 5 km (Proctor 1991; Steiger et al. 2007; Tapia et al. 1998; Toracinta et al. 1996).Tadesse and Anagnostou (2009) found that a higher density of flashes coincides with a longer duration of the storm. Due to the strong relationship between radar reflectivity and lightning flash occurrence, Tapia et al. (1998) concluded that lightning flash data could be utilized to detect heavy rainfall events associated with convective rainfall in locations where radar data are not available.

Many of the NEXRAD-based studies of tropical cyclones are case studies of the evolution of convective thunderstorms and precipitation within the eyewall or outer spiral rainbands (e.g. Blackwell 2000; Bluestein and Hazen 1989; Lee et al. 2008; Matyas 2009; Medlin et al. 2007; Ulbrich and Lee 2002), tornadoes (e.g. Baker et al. 2009; McCaul et al. 2004), or wind fields (e.g. Arndt et al. 2009; Blackwell 2000; Zhao and Jin 2008). Fewer studies have examined these characteristics through a radar-based analysis across multiple storms. Powell and Houston (1998) examined the wind fields of four hurricanes that made landfall during 1995 utilizing both WSR-88D and airborne Doppler radar, while Gall et al. (1998) examined the spiral rainbands located near the cores of Hurricanes Hugo (1989), Andrew (1992) and Erin (1995). Schroeder et al. (2009) have investigated the precipitation structures of multiple tropical cyclones through combined use of WSR-88D data and mobile instrument towers. Matyas (2006, 2007, 2010a,b) has employed GIS to analyze WSR-88D reflectivity data for multiple tropical cyclones. Reflectivity data from the Level III base scan or lowest scan elevation contained within the Level II data are mosaicked within a GIS and properties of the rain fields including their area, compactness, elongation, fragmentation, extent outwards from the circulation center, and the positions of their centroids are calculated and then compared to the environmental conditions that each storm experiences (e.g. vertical wind shear, relative humidity, etc.). Quantifying the spatial attributes of convective and stratiform regions within tropical cyclones could help to improve the spatial accuracy of rain fields simulated in modeled storms.

Radar Data and GIS

Radar-derived climatologies of weather events such as those described in the previous section could be constructed by geographers employing GIS. As converting radar data into a format suitable for analysis within a GIS was difficult prior to 2005, this could be one explanation as to why analysis with radar data is not routinely conducted by geographers. In 2005, researchers at the NCDC developed the Java NEXRAD Exporter (Ansari and Del Greco 2005) that georeferences the data as a grid of latitudinal and longitudinal coordinates based on a World Geodetic System spheroid (WGS84) model of the earth. The data can then be converted into several formats including polygon shapefiles, GeoTiff, and netCDF. This tool has been utilized by researchers such as Mote et al. (2007) and Matyas (2010b) to convert large volumes of WSR-88D reflectivity data into a GIS-friendly format so that climatological-scale analyses could be performed. Now upgraded and re-titled the Weather and Climate Toolkit, this toolkit is available from the NCDC on their website (NCDC 2009b), which should facilitate the use of these data by geographers.

The recent increase in the use of GIS by scientists who are not geographers suggests that it is becoming an accepted tool for use atmospheric research. In 2005, *Meteorological Applications*, a journal published by the Royal Meteorological Society, dedicated a special issue to the use of GIS in atmospheric research (Thornes 2005). However, only four coauthors out of the 49 who contributed to manuscripts in this issue of *Meteorological Applications* were affiliated with a Geography department (Dyras et al. 2005; Madelin and Beltrando 2005; Thornes et al. 2005). Also in 2005, the *Bulletin of the American Meteorological Society* published five short articles that featured the use of GIS for atmospheric science research. Yuan (2005) described her research on tornado damage tracks, and Shipley (2005) reported that the NWS Office of Science and Technology/Systems Engineering Center began converting WSR-88D data into a shapefile format for utilization in a GIS. Three other articles (Habermann 2005; Kruger et al. 2005; Wilhelmi and Betancourt 2005) discussed how the University Corporation for Atmospheric Research (UCAR) and the National Center for Atmospheric Research (NCAR) aim to incorporate GIS into their data dissemination and analysis plans. Thus, opportunities exist for geographers who utilize GIS to contribute more frequently to atmospheric research.

Several geographers have described the problems inherent in the analysis of temporal data within a GIS (Egenhofer et al. 1999; Galton 2001; O'Sullivan 2005; Peuquet 2001), and this could be the primary reason why relatively few geographers employ it to analyze radar data. Most temporal database models utilize snapshots to determine changes over time, but this does not allow an explicit representation of an event occurrence (Worboys 2005). However, researchers are developing tools capable of temporal analysis of spatial data. For example, Edsall et al. (2000) demonstrate their tool for temporal Fourier analysis with data from rain gauges collected over 180 days; it is reasonable to assume that radar-estimated rainfall data could be analyzed using their technique. If temporal analysis tools could be incorporated into widely-available GIS software, perhaps geographers could perfect GIS-based techniques for accurate spatial and temporal analyses of weather phenomenon detected by radar data.

Geographers specialize in modeling spatial phenomenon (e.g. Wilmott and Gaile 1992). If many non-geographers are utilizing GIS and radar data in their work, then more geographers should also begin to perform the GIS-based analysis of radar reflectivity data and rainfall estimates. As a GIS facilitates the geospatial analysis of large volumes of data, it has become more widely used for precipitation mapping and hydrologic modeling (Dyras and Serafin-Rek 2005; Fang et al. 2008; Knebl et al. 2005; Whiteaker et al. 2006; Xie et al. 2005). The collaboration of geographers specializing in geospatial techniques with those pursuing research in climatology and hydrology could provide specialized tools for the geovisualization and analysis of radar reflectivity and velocity data within a GIS. Utilizing the high temporal and spatial resolution provided by radar data, geographers, with their expertise in spatial modeling, have the potential to make important contributions to our understanding of weather systems.

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Short Biography

Corene Matyas is an Assistant Professor at the University of Florida, Gainesville, Florida, USA. Her primary research focuses on the GIS-based analysis of tropical cyclones. In much of her work, she utilizes GIS to spatially analyze radar reflectivity data. Her work has been published in The Professional Geographer, Journal of Applied Meteorology and Climatology, Theoretical and Applied Climatology, Meteorology and Atmospheric Physics, and International Journal of Applied Geospatial Research. She received a Teacher of the Year Award from the College of Liberal Arts and Sciences at the University of Florida in 2009. She holds a B.S. in Environmental Geoscience from Clarion University of Pennsylvania, M.A. in Geography from Arizona State University, and Ph.D. in Geography from Pennsylvania State University.

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