Radar and Rain Gauge Analysis of the Extreme Rainfall during Hurricane Danny's (1997) Landfall

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ABSTRACT

As a minimal hurricane, Danny moved over Mobile Bay around 0900 UTC 19 July 1997 and became stationary by midmorning, while situated within a synoptic col. Danny then evolved into an asymmetric storm with an intensely convective rainband that produced torrential rainfall through 1200 UTC 20 July 1997. Danny's center remained <100 km from the National Weather Service (NWS) Weather Surveillance Radar-1988 Doppler (WSR-88D) in Mobile, Alabama, for over 48 h, allowing long-term surveillance of the storm's inner core. This event marked the first time the tropical Z–R relationship was employed on an operational WSR-88D system during tropical cyclone landfall. A radar-estimated maximum rainfall accumulation of 1097 mm (43.2 in.) was analyzed over southwestern Mobile Bay. A NWS cooperative rain gauge located on Dauphin Island, Alabama, measured 896 mm (35.28 in.). An adjacent standard rain gauge measured the highest rainfall amount of 932 mm (36.71 in.). This paper investigates the spatial and temporal distribution and potential magnitude of Danny's torrential rainfall episode over coastal Alabama. It is shown that both gauges and radar seriously underestimated event rainfall. An estimate is given for what could have been the true event rainfall amount. In the case of the radar, the WSR-88D Algorithm Testing and Display System is used to obtain a better estimate of rainfall using higher dBZ caps than the operational 50 dBZ. In the case of the tipping-bucket rain gauge, wind and mechanical error estimates were applied in order to quantify rainfall underestimation.

1. Introduction

Landfalling tropical cyclones (TCs) often produce heavy rainfall and disastrous flooding. Over the last 30 yr, flooding associated with heavy rainfall from landfalling TCs has been responsible for at least half of all associated deaths (Rappaport 1999). Structural changes in a storm at landfall may result in spatial redistributions of the strongest winds and heaviest rainfall. Because most damage occurs in the coastal zone, the specific structure and organization of the storm during landfall is of great meteorological importance. Unfortunately, a lack of data often precludes a detailed description and analysis of the surface mesoscale structure at landfall (Powell 1987, 1990; Powell et al. 1996).

In certain situations, radars can provide frequent observations for landfalling TCs. Specifically, the Weather Surveillance Radar-1988 Doppler (WSR-88D) provides mesoscale details of the wind and reflectivity factor (Z) structures within the inner core and rainbands. Therefore, a prolonged structural evolution of boundary layer winds and low-level precipitation are available only if the system moves 1) close enough to the radar (<100 km) for low-level sampling, and 2) slowly enough to remain within radar range for many hours. Hurricane Danny's (1997) center remained <100 km from Mobile, Alabama (KMOB), for over 48 h. This situation provided ideal conditions for continuous high-quality sampling of the inner-core evolution through various structural stages. Additionally, this event marked the first time the tropical Z–R relationship ($Z = 250R^{1.2}$; Rosenfeld et al. 1993) was employed in real time on an operational WSR-88D system during TC landfall.

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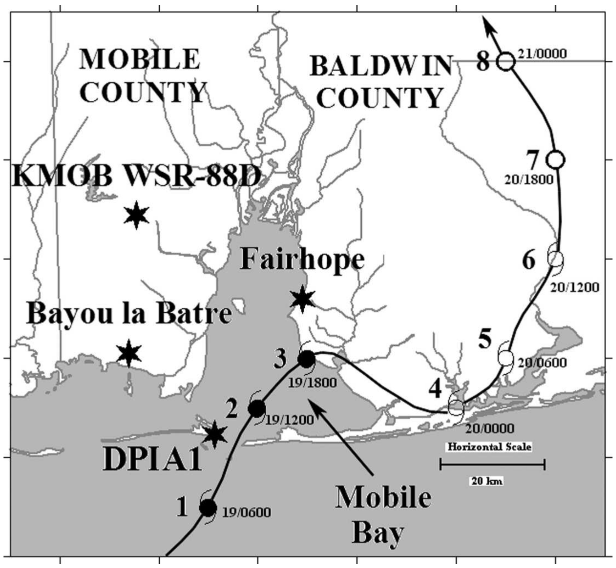

FIG. 1. Danny's track from 0600 UTC 19 Jul to 0000 UTC 21 Jul 1997. Solid circles indicate hurricane status, while open circles indicate tropical storm or tropical depression status. Symbols are shown every 6 h.

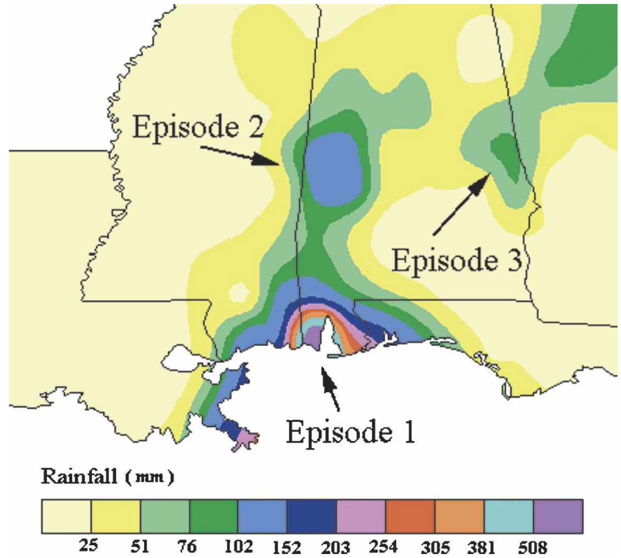

FIG. 2. An isohyetal rain gauge analysis showing three individual heavy rainfall episodes in association with Hurricane Danny between 1200 UTC 17 Jul and 1200 UTC 23 Jul 1997 over portions of AL, FL, LA, and MS (modified from the NCDC source graphic).

Consistent with a slow-moving hurricane, rainfall accumulations over Alabama were extreme. A close-up of Danny's track over a 36-h period is shown in Fig. 1. Shortly before the storm reached position 1, heavy bands of precipitation arrived at the coast. Position 7 marks the time torrential rainfall began to cease. Figure 2 shows three individual heavy precipitation episodes as Danny moved across Alabama. The coastal landfall episode (labeled episode 1 in Fig. 2) occurred between 0000 UTC 19 July and 1200 UTC 20 July 1997. An inner-core asymmetry began to form around 1200 UTC 19 July 1997 near point 2 in Fig. 1. Subsequently, the asymmetric Z field containing 25 mm h^{-1} precipitation rates expanded in areal coverage from 200 to 1400 km^2. Extreme rainfall rates of >100 mm h^{-1} (>4 in. h^{-1}) persisted for nine consecutive hours, resulting in major flooding of bayous and rivers adjacent to Mobile Bay (Blackwell 2000). When the rainfall ceased, radar estimated a maximum of 1097 mm (43.2 in.) over Mobile Bay (Fig. 3) during a 101-h period ending 1219 UTC 21 July 1997. A National Weather Service (NWS) cooperative rain gauge located at the Dauphin Island Sea Laboratory (DISL), measured 897 mm (35.31 in.). A second rain gauge, located directly adjacent to the latter, recorded the highest event accumulation of 932 mm (36.71 in.).

This paper documents the spatial and temporal characteristics of Danny's extreme heavy rainfall event during landfall (see episode 1 in Fig. 2). Possible physical causal mechanisms are discussed. Danny's local impact is documented and a historical perspective is provided that compares the storm to past heavy rainfall producing TCs. The inaccuracies of both the rain gauge– and radar-estimated rainfall totals are examined. Finally, the tropical Z–R relationship, in combination with various Z caps, is used to explore the precise location and potential magnitude of the true rainfall maximum.

2. Data types and analysis procedures

Danny's structural features, heavy rainfall, and asymmetric evolution are described using observations from 1) archive level-II WSR-88D reflectivity and velocity data, 2) U.S. Air Force Reserve C-130 aircraft reconnaissance, 3) rawinsondes, 4) satellites, and 5) surface platforms. The latter includes 1) the Dauphin Island Coastal-Marine Automated Network site (DPIA1), 2) nearby NWS and Federal Aviation Administration Automated Surface Observing System (ASOS) sites, and 3) privately owned observations from the Agricultural Weather Information Service.

The KMOB WSR-88D is located in the hills west of Mobile and has a station elevation of 64 m above mean sea level (MSL). The antenna is mounted on a 24-m tower. The radar possesses the following characteristics: a wavelength of 11.1 cm, a beamwidth of 0.95°, a pulse length of ~470 m, and a pulse duration of 1.57 μs. Data were collected using a volume coverage pattern scan strategy that covers 14 elevation slices every 5 min.

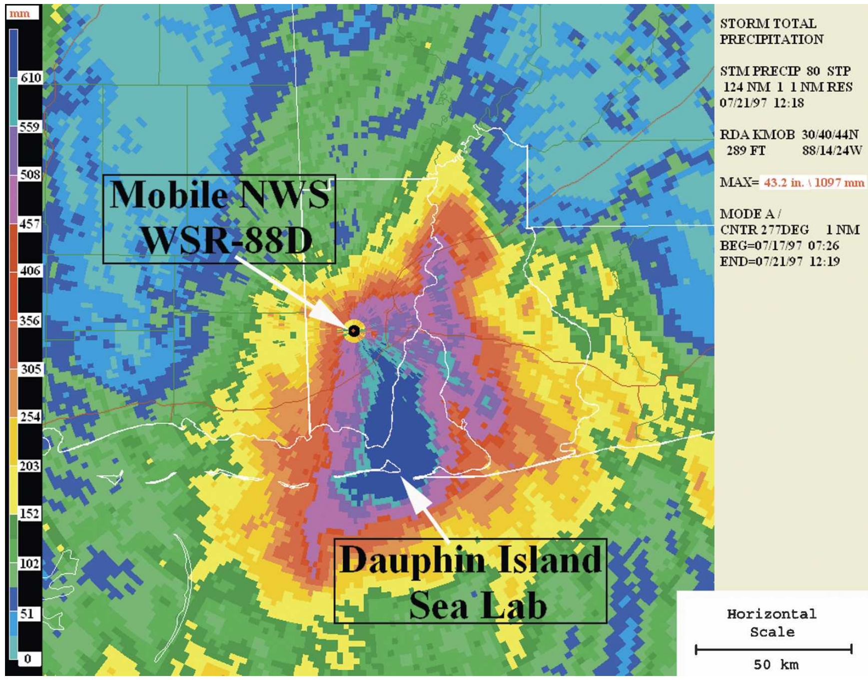

FIG. 3. KMOB WSR-88D storm total precipitation product estimated rainfall between 0726 UTC 17 Jul and 1219 UTC 21 Jul 1997. Note the area of >635 mm (25 in.) over southeast Mobile County, AL, and western Mobile Bay. A maximum of 1097.3 mm (43.2 in.) was estimated over southwestern Mobile Bay.

A detailed description of the hybrid scan and the precipitation processing system (PPS) is provided in Federal Meteorological Handbook 11-Part C (Office of the Federal Coordinator for Meteorology 1992). Archive level-II digital data were manipulated and simulations were produced using the WSR-88D Algorithm Testing and Display System (WATADS; National Severe Storms Laboratory 1997). These data are nearly complete for the entire period of study with the exception of 0904–1029 UTC 19 July 1997.

The WSR-88D precipitation rate algorithm converts previously quality-controlled reflectivity data obtained from the sectorized hybrid scan into a rainfall rate using the relationship:

$$Z = aR^b \tag{1}$$

(Marshall and Palmer 1948), where Z is the observed reflectivity factor [dBZ = $10\log_{10}(Z/Z_0)$, where Z_0= 1 mm^6 m^{-3}], R is the rainfall rate (mm h^{-1}), and a and b are constants chosen according to rainfall type and climatic conditions. Currently, several Z–R relationships can be operationally employed on WSR-88D systems. The default relationship (hereafter referred to as "default Z–R") is given by

$$Z = 300R^{1.4}. \tag{2}$$

Although radars measure return power, they cannot measure drop size distribution. As a brief background leading to the development of a second type of Z–R, Eq. (3),

$$Z = \int_0^\infty N(D)D^6\,dD, \tag{3}$$

demonstrates the dependence of Z on drop size diameter D. Here $N(D)$ is the drop size distribution, defined as the number of drops per dD interval (from D to D + dD). Reflectivity varies according to the individual droplet diameters raised to the sixth power and is summed for all diameters in the unit volume. In the case of estimating rainfall by radar in tropical air masses, lesser amounts of returned power due to smaller droplet diameters may cause underestimation. Many studies have been conducted to determine drop size distribution in convective versus stratiform precipitation and for different airmass types (Battan 1973; Jorgensen and Willis 1982; Rosenfeld et al. 1993). The Z–R conversion error depends on the variability in the distribution of rainfall drop sizes, which can vary significantly (Chumchean et al. 2003). Two storms may have different drop size distributions and rainfall rates, but

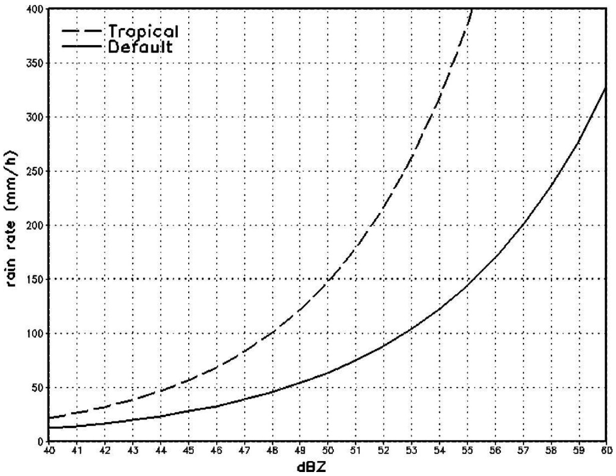

FIG. 4. A plot of the default and tropical Z–R relationships (see text for formulas) vs hourly rainfall rate for reflectivity values >39 dBZ.

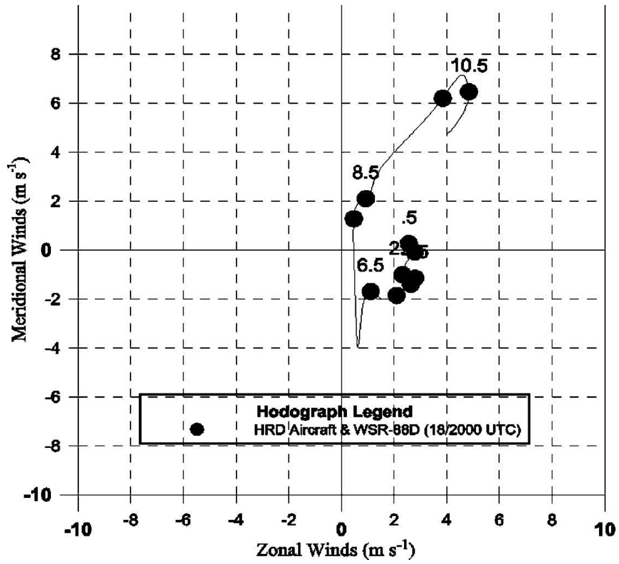

FIG. 5. Storm-centered hodograph generated near Danny. The hurricane's circulation is subtracted out. Environmental winds from airborne Doppler and coastal WSR-88Ds are averaged in a 90-km circle around Danny over multiple layers for 1915–2006 UTC 18 Jul 1997, toward the end of the Hurricane Research Division's (HRD's) Hurricanes at Landfall Experiment. (Data courtesy of P. Dodge and F. Marks, National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory/HRD.)

the radar may measure the same Z for both. Therefore, different Z–R relationships are required to obtain the correct rainfall rates. The Tropical Rainfall Measuring Mission has initiated an extensive ground validation program and promoted the idea of using different Z–R relationships for different rain categories to improve radar-estimated rainfall (Amitai 2000; Liao et al. 2001). Rosenfeld et al. (1993) developed probability-matched relations between Z and R using observations in Darwin, Australia, for four different rainfall regimes. For a convective maritime air mass, the Z–R relation they found roughly follows a power law of the form given by Eq. (4) (hereafter referred to as the "tropical Z–R"),

$$Z = 250R^{1.2}. \tag{4}$$

The tropical and default Z–R relationships are plotted in Fig. 4. The same dBZ values are converted to higher rainfall rates in the tropical case. In the WSR-88D PPS, a maximum precipitation rate (MXPRA) threshold is set to mitigate hail contamination. The MXPRA value for any given situation depends upon existing atmospheric conditions. If the MXPRA is too low, intense rainfall may be underestimated. If the MXPRA is too high, contamination from hail or wet ice will cause rainfall overestimation. Currently, the NWS Radar Operations Center recommends 150 mm h^{-1} as an MXPRA value for U.S. Gulf Coast summer conditions (dotted line in Fig. 4). This value corresponds to a Z "cap" of 55 (50) dBZ for the default (tropical) Z–R relationships. During Danny, the tropical Z–R was continuously employed.

Apart from uncertainties in Z–R relationships and reflectivity caps, Chumchean et al. (2003) listed other sources of inaccuracy in radar-estimated rainfall. These include 1) variability in the vertical profile of reflectivity (Z), 2) errors in measuring radar reflectivity (Z), 3) errors in radar rainfall calibration due to using point measures (i.e., rain gauges) to represent mean rainfall over an area corresponding to the size of a radar pixel, and 4) the use of imperfect rain gauge measurements to calibrate radar observations. The inaccuracies of operational tipping-bucket rain gauges (TBR) will be discussed in section 4.

3. The prestorm environment and significant storm structural changes

Molinari et al. (2004) describes Danny originating from a series of mesoscale convective systems in a moderately sheared environment. After the storm was classified a tropical storm (TS), a weak upper-tropospheric trough to the north steered Danny slowly northeastward from its origin south of the Louisiana coast on 16 July. As a small storm, Danny developed an axisymmetric inner-core cloud pattern on 18 July within weak 0–10-km vertical wind shear of 6.2 m s^{-1} (Fig. 5). Slow strengthening continued and the well-organized storm developed concentric eyewalls later that day (not shown) as weak (0.5–3 m s^{-1}) westerly mean winds between 5 and 9 km above MSL steered Danny slowly into the Alabama coastal waters.

Early on 19 July, the upper-tropospheric trough to the north split. As the western portion of the trough retrograded, deep-layer mean wind flow became more southerly and moved the storm northward toward Mobile Bay. During this time, Danny experienced an eyewall replacement cycle (Blackwell 2000), which temporarily weakened the storm. Danny entered Mobile Bay around 0900 UTC 19 July 1997 as the contraction of the outer eyewall coincided with renewed pressure falls and a highly symmetric single-eyewall storm. At this time, the steering flow weakened as the storm moved into a mid- and upper-tropospheric col.

Blackwell (2000) thoroughly documents the development of a dramatic asymmetry in Danny's wind and precipitation pattern as the character changed from one of stratiform precipitation to one containing persistent convection after entering Mobile Bay. The convective asymmetry persisted well after landfall. The structural evolution during landfall is depicted in Fig. 6 and is discussed in section 5. As the asymmetric transition began, surface wind observations and WSR-88D base velocities indicated the development of a pronounced band of confluence extending from the northeast quadrant and wrapping cyclonically into the west and southwest eyewall. The confluent pattern persisted throughout the asymmetric portion of the landfall event. Heavy convective activity and associated torrential rainfall persisted along and to the west of this confluence axis.

The cause of this confluence axis and the associated asymmetric storm evolution remains unresolved. Numerous studies (e.g., Frank and Ritchie 1999; Kimball and Evans 2002; Black et al. 2002; Molinari et al. 2004) have shown that storm asymmetry often results from increasing vertical wind shear. Lack of airborne Doppler data on both 19 and 20 July precluded the development of storm-centered hodographs during the landfall event. However, it is doubtful that strengthening vertical shear played a role in Danny's evolution. Circumstantial evidence to support this claim includes 1) the synoptic col in which Danny was embedded, 2) infrared satellite imagery from 1800 UTC 19 July 1997 (Fig. 7) showing an oval cloud pattern whose centroid was shifted only slightly northwestward from the storm's center, and 3) the Geophysical Fluid Dynamics Laboratory model analysis (not shown) from 1200 UTC 19 July and 0000 UTC 20 July 1997, which indicated that 850–250-hPa vertical wind shear was below 10 m s^{-1}. A second hypothesis for this strong confluence is presented by H. E. Willoughby (1999, personal communication; Blackwell 2000). This confluence may be a result of intense convective heating associated with a persistent eyewall convective system on Danny's west side over Mobile Bay and partly in response to elevated sea surface temperatures. In addition, Knupp et al. (2006) found evidence of shallow fronts developing in the boundary layer of landfalling TCs. These fronts separate stable evaporatively cooled regions of offshore flow originating under stratiform precipitation over land from less stable warmer regions of onshore flow originating over water. This pattern seems to be somewhat evident in both surface and radar observations on either side of Danny's confluence axis.

4. Rain gauge observations

a. Rainfall distribution

Because the heavy rainfall accumulations were mostly distributed over the southwest quadrant of Mobile Bay, as opposed to adjacent land areas (Fig. 3), rain gauge coverage of Danny's rainfall maximum was limited. The number of gauges totaled 27. Of these, 7 were official and 20 unofficial. Tables 1 and 2 provide all official and unofficial gauge observations, respectively. An observation is considered official if obtained from either a NWS ASOS or a NWS cooperative observer. An observation is considered unofficial if the quality or standard of measurement is unknown. Most of the unofficial reports were received after the heavy rainfall ended. Unofficial reports were obtained immediately after the cessation of the initial rainfall episode (source NWS Mobile, Alabama). Figure 8 shows the location of rain gauge observations that appear in Tables 1 and 2. The official reports consist of 72-h rainfall accumulations ending 1200 UTC 21 July 1997. Note that very few reports >634 mm (25 in.) lie over land (see annotation of radar-estimated rainfall maximum in Fig. 8).

b. Dauphin Island rainfall

Although removed from the rainfall maximum, an official rain gauge with hourly recording capability was located on the east end of Dauphin Island and recorded the official maximum rainfall accumulation of 896 mm (35.28 in.). It was measured by a Campbell Scientific Model CS-700 TBR (hereafter CS-700) during a 41-h period of consecutive rainfall from 1200 UTC 18 July to 0400 UTC 20 July 1997. A second rain gauge [standard 20.3 cm (8 in.) diameter] was located directly next to the NWS cooperative rain gauge and measured 932 mm (36.71 in.) during the same period. This accumulation represents the highest known event total (see **DISL in Table 2) measured by a rain gauge.

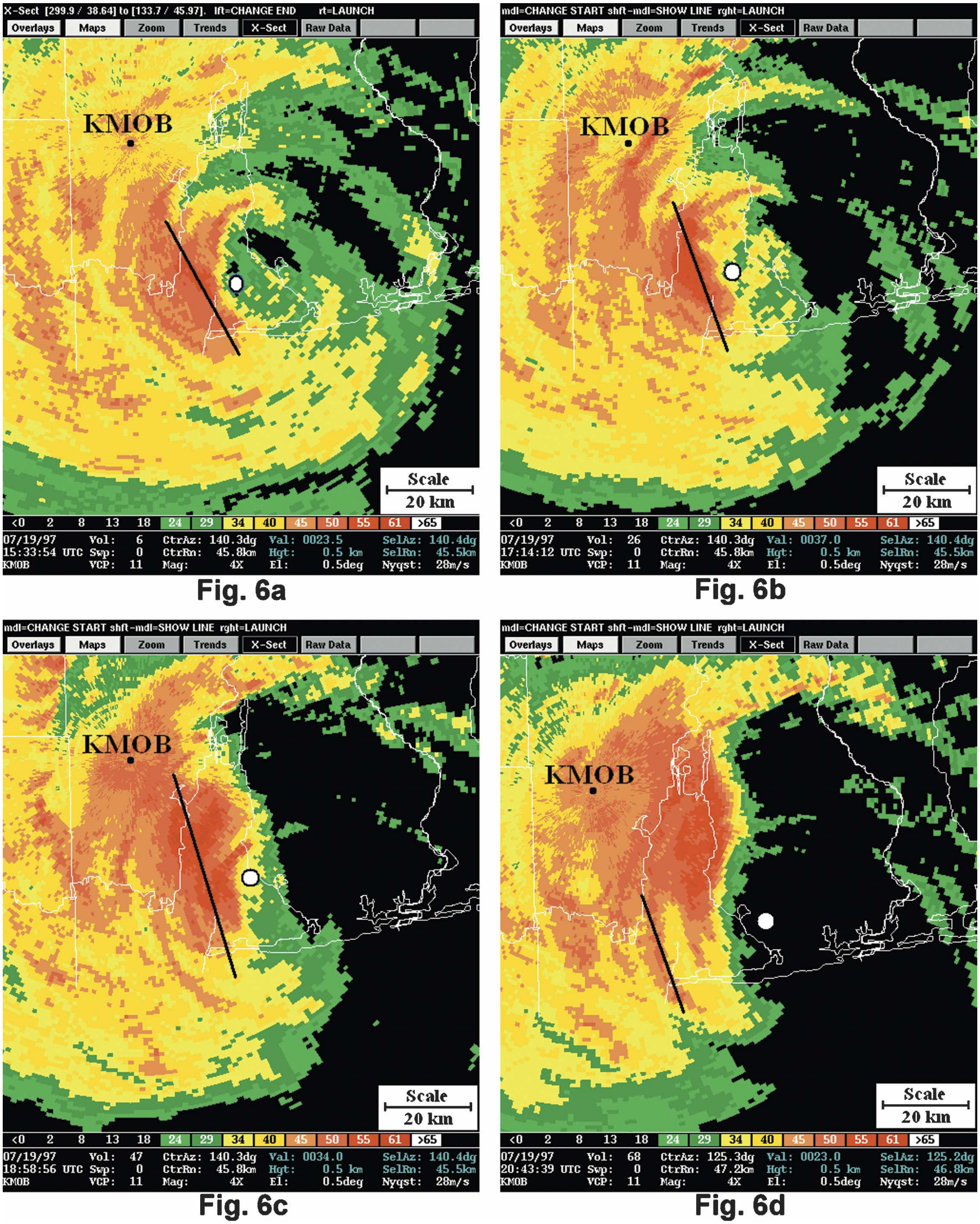

FIG. 6. (a)–(d) Base reflectivity and (e)–(h) corresponding reflectivity vertical cross sections of Hurricane Danny from the KMOB WSR-88D at (a) 1534, (b) 1714, (c) 1859, and (d) 2044 UTC 19 Jul 1997, respectively. The black lines in (a)–(d) correspond to respective cross section locations in (e)–(h), respectively. The upper (lower) end of each line corresponds to the left (right) edge of the respective cross section. Each cross section contains horizontal and vertical distance increments in km, and azimuth (°) and range (km) in brackets depicting the position of each section's end points relative to the KMOB WSR-88D position. A reflectivity scale (dBZ) is depicted at the bottom of each image. Reflectivity factors less than 24 dBZ are not displayed. White dot marks storm center in (a)–(d).

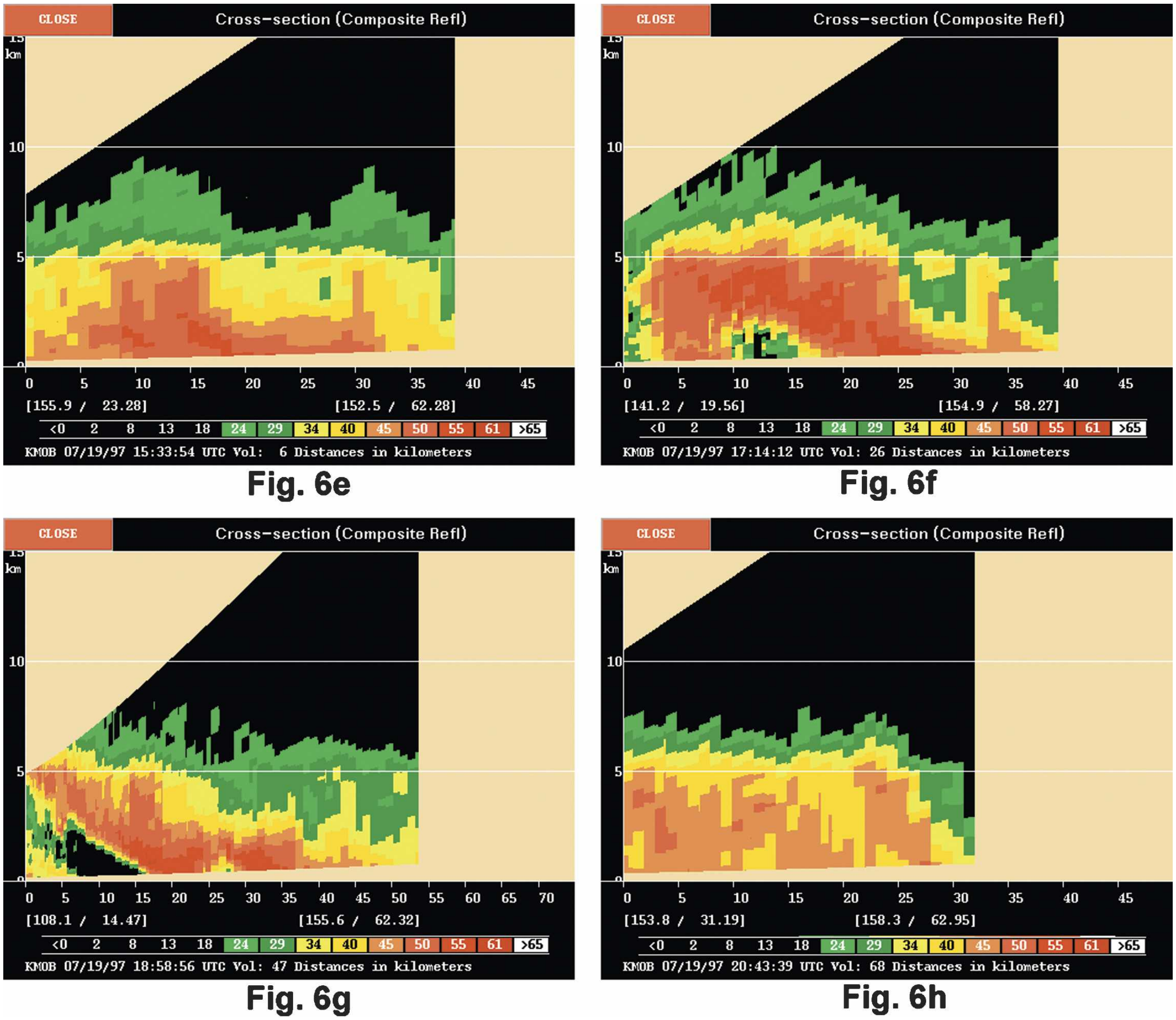

FIG. 6. (*Continued*)

Figure 9a shows a 41-h time series of Dauphin Island CS-700 hourly rainfall accumulations versus 10-m wind direction. Two distinct heavy rainfall periods are seen. The first, from 1500 UTC 18 July to 0900 UTC 19 July 1997, corresponds to a time when Danny was approaching DPIA1 from the southwest and then south. Rainfall accumulations were modest [<25 mm (1 in.)] during this period, with the exception of when 54 mm (2.11 in.) fell from 0400 to 0459 UTC 19 July 1997. A second and more significant period of rainfall occurred from 1100 UTC 19 July to 0300 UTC 20 July 1997 after Danny moved northeast of DPIA1 and became stationary over Mobile Bay (see the distinct wind shift in Fig. 9a from 0800 to 0900 UTC 19 July 1997 as Danny's center passed northeast of DPIA1). The eyewall, where convection was intense, became situated over southwestern Mobile Bay during the period. A 12-h period (1200 UTC 19 July–0000 UTC 20 July 1997) of very heavy rainfall then ensued over the Dauphin Island gauges. The data reveal average hourly rainfall accumulations of 55 mm (2.17 in.) with 4 h receiving hourly accumulations >60 mm (2.36 in.). The maximum hourly accumulation was 80 mm (3.13 in.) from 1200 to 1259 UTC.

Figure 9b shows a 41-h time series of Dauphin Island CS-700 hourly rainfall accumulations versus 10-m wind speed and gusts. The highest recorded wind gusts occur simultaneously with periods of peak rainfall intensity. Wind has a serious impact on the collection accuracy of rain gauges. Despite the longtime use of catchment-type rain gauges, few studies are available that quantify the error induced by wind on rain gauge collection ef-

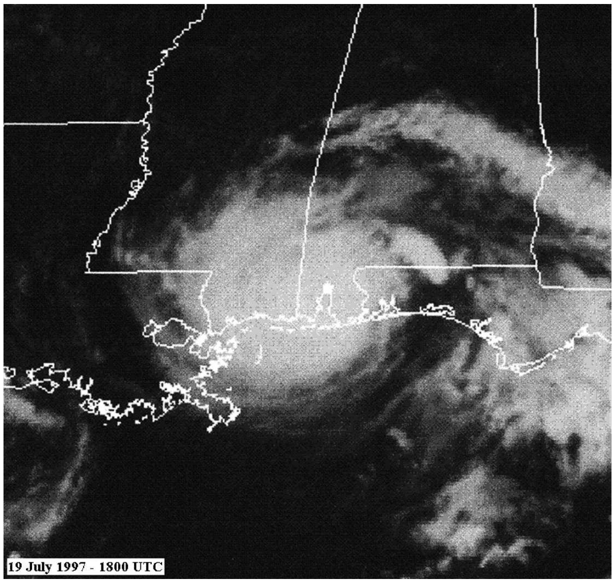

FIG. 7. Geostationary Operational Environmental Satellite infrared image for 1800 UTC 19 Jul 1997. A linear brightness curve is employed. (Image courtesy of NCDC.)

ficiency (Serra et al. 2001). Nespor and Sevruk (1999) found that the blocking effect of a gauge, causes a deviation of the flow, and wind velocities above the gauge orifice are approximately 35% higher than unobstructed flow with the greatest turbulence near the orifice. They also found collection deficiencies increased exponentially for small drop sizes (often associated with lighter rainfall rates), presumably because of being more greatly influenced by sudden flow alterations and turbulence near the gauge orifice. Drops with a significant lateral motion have a higher rate of hitting the side of a gauge instead of entering the orifice (Hassee et al. 1998).

Wilson (1954) found collection deficiencies can range from 10% to 20% with sustained wind speeds of 4.5 m s^{-1} to 50% when speeds are as high as 23.7 m s^{-1}. Koschmieder (1934) found collection deficiencies of 12%–40% (40%–67%) for 5–10 m s^{-1} (10–15 m s^{-1}) winds. Allerup and Madsen (1979; per Hassee et al. 1998) found that rainfall collected in a standard cylindrical gauge was underestimated by 50% (100%) for an 11 m s^{-1} (15 m s^{-1}) wind speed. Deficiencies found by the World Meteorological Organization (1962) ranged from 15%–46% (50%–83%) for 5–10 m s^{-1} (10–15 m s^{-1}) winds. Dunn and Miller (1960) showed rain gauges may catch less than 50% when wind speeds are $>$25 m s^{-1}. Thus, there is no clear consensus on the percentage of undercatchment for various wind speed categories.

In Danny, sustained TS force (17.5–33 m s^{-1}) winds occurred for 26 h and winds gusted to hurricane force ($\geq$33.1 m s^{-1}) at 0500 UTC 19 July 1997, and again during a 4-h period from 1200 to 1600 UTC 19 July 1997. Therefore, appreciable rainfall underestimation certainly occurred. During the 41-h span, the CS-700 measured 896 mm. Ten of the 41 h were characterized by sustained wind speeds $>$25 m s^{-1}. Discounting wind gusts and the using wind-induced rain gauge collection deficiencies displayed in Table 3, an additional 807 mm (26.03 in.) of rain could have been measured, for an event total of 896 mm + 807 mm = 1703 mm (67.06 in.) at this location.

Rain gauge construction also contributes to collection deficiency. A Campbell Scientific (CSI) Model CS-700 tips every time 0.254 mm of rain has been collected (Campbell Scientific, Inc. 2006). This means the bucket tips every 11–12 s with rainfall rates of 80 mm h^{-1} (the highest rate recorded at Dauphin Island during Danny; Fig. 9). The bucket cannot reposition itself fast enough after a tip to collect all of the rainfall entering the outer funnel, which results in undercatchment, especially at high rainfall rates (Humphrey et al. 1997; Nystuen 1999). The CSI manual (Campbell Scientific, Inc. 2006) states that the accuracy of a CS-700 is better than 2% at rain rates of 100 mm h^{-1}. However, Humphrey et al. (1997) assessed the accuracy of five different TBRs by comparing true pump rates with TBR-measured rain-

TABLE 1. Official 24-h rain gauge observations (mm/in.) ending at 1200 UTC each day between 19 and 21 Jul 1997. The 3-day rainfall totals are sorted in descending order in the last column.

Location	Gauge classification	19 Jul 1997 (mm/in.)	20 Jul 1997 (mm/in.)	21 Jul 1997 (mm/in.)	72-h rainfall total (mm/in.)
DISL, AL	NWS cooperative	208/8.2	689/27.12	0.5/0.02	898/35.34
Fairhope, AL	NWS cooperative	146/5.75	369/14.52	94/3.70	608/23.97
Coden, AL	NWS cooperative	186/7.32	309/12.15	5/0.20	500/19.67
Bay Minette, AL	NWS cooperative	68/2.68	396/15.58	31/1.24	495/19.50
Robertsdale (5 NE), AL	NWS cooperative	173/6.80	155/6.10	37/1.47	365/14.37
Mobile, AL (west)	NWS ASOS	73/2.86	212/8.34	27/1.07	312/12.27
Pascagoula (3 NE), MS	NWS cooperative	119/4.67	136/5.37	23/0.90	278/10.94

TABLE 2. Unofficial event total rain gauge observations (mm/in.). If known, rainfall beginning and/or ending times are given in the third column.

Location	Source	Duration	Event rainfall tot (mm/in.)
Dauphin Island, AL	NWS (**DISL)	1200 UTC 18 Jul–0400 UTC 20 Jul	932/36.71
Fowl River, AL	NWS (employee)	Ending 1200 UTC 20 Jul	800/31.5
Montrose, AL	NWS (citizen)	—	699/27.5
Bellefontaine, AL	NWS (citizen)	—	686/27
West Fowl River, AL	NWS (citizen)	—	686/27
Theodore, AL (5 S)	NCDC	1200 UTC 17 Jul–1200 UTC 23 Jul	686/27
Theodore, AL	NCDC	1200 UTC 17 Jul–1200 UTC 23 Jul	622/24.5
Marlow, AL	NWS (citizen)	—	588/24
Spanish Fort, AL	NWS (citizen)	—	548/21.58
Summerdale, AL	NWS (citizen)	—	546/21.5
Tillman's Corner	NCDC	1200 UTC 17 Jul–1200 UTC 23 Jul	498/19.62
Chickasaw, AL	NWS (citizen)	—	486/19.15
St. Elmo, AL	NWS (citizen)	—	483/19
Robertsdale, AL	NWS (citizen)	—	457/18
Mobile, AL (6 SE)	NCDC	—	302/11.99
Grand Bay, AL	NWS (citizen)	—	268/10.53
Mobile, AL (downtown)	NCDC	1200 UTC 17 Jul–1200 UTC 23 Jul	249/9.8
Seminole, AL	NCDC	1200 UTC 17 Jul–1200 UTC 23 Jul	222/8.72
Mobile, AL (4 S)	NCDC	1200 UTC 17 Jul–1200 UTC 23 Jul	213/8.38
Semmes, AL	NWS (employee)	Ending 1200 UTC 20 Jul	182/7.16

fall rates. Undercatchment increased from 5% to 29% as the TBR-measured rainfall rate increased from 6 to 240 mm h^{-1}. Errors depended on the type of TBR and ranged from 5% to 15% at true pump rates ≤ 80 mm h^{-1}. The tested instruments included a CSI TBR with an outer funnel diameter of 152 mm and a resolution of 0.2 mm (i.e., the bucket tips every time 0.2 mm of rainfall is collected), which is close to the CS-700 model specifications (funnel diameter of 200 mm and a resolution of 0.254 mm). Duchon and Essenberg (2001) performed a TBR laboratory calibration using a high, slowly decreasing rain rate and derived the following correction equation:

$$R_c = R + CR^2, \tag{5}$$

where R_c is the corrected rainfall rate, R is the field-observed rainfall rate, and C is a coefficient ranging from 0.000 668 to 0.000 78 h mm^{-1}. The official rain gauge amount of 896 mm in Danny is ~4% higher than the unofficial, non-TBR maximum of 932 mm (see Table 2), despite only being a meter apart. Applying Eq. (5) to the hourly CS-700 rainfall data gives an undercatchment error ranging from 3.2% ($C = 0.000\,668$ h mm^{-1}) to 3.8% ($C = 0.000\,78$ h mm^{-1}), in fairly good agreement with the 4% discrepancy between the TBR and non-TBR gauges rainfall totals (not corrected for wind error). For this reason, Eq. (5) will be used to adjust for tipping-bucket undercatchment errors and the lowest value of C will be used in order to be conservative. The wind and tipping-bucket error corrections will be applied in two different ways. In the first method, each error correction will be applied to the measured hourly rainfall rates. Both error corrections are then added together. In the second method, the hourly wind adjustment will be made first, then Eq. (5) is applied to the new hourly rainfall rates because wind prevented this extra rain from falling into the bucket. The second method will yield a higher adjusted rainfall total. All adjusted rainfall totals are presented in Table 4 and are discussed below.

c. *Comparison to past heavy rainfall–producing TCs*

1) EVENT RAINFALL TOTAL

Danny's 41-h Dauphin Island rain gauge amount of 932 mm (36.71 in.) can be compared to other well-known U.S. heavy rainfall–producing TCs associated with serious flooding. Tropical Storm Allison (2001) yielded a few observations of rainfall accumulations >662 mm (30 in.) over portions of southeastern Texas. The highest accumulation was 940 mm (36.99 in.) measured at the Port of Houston, Texas (source NWS Houston–Galveston, Texas), over a 5-day period. Tropical Storm Alberto (1994) produced an accumulation of 697 mm (27.61 in.) in Americus, Georgia, over a 7-day period. Finally, the Alvin, Texas, rainfall accumulation of 1143 mm (45 in.) in 42 h, associated with TS Claudette (1979), remains the highest-known multiday event rainfall amount associated with any landfalling

FIG. 8. Gauge reports (mm) for the Danny rainfall event over Mobile and Baldwin Counties of AL. Note the location of the radar-derived rainfall maximum (large solid square) over southwest Mobile Bay.

U.S. TC. However, it will be shown that Claudette's rainfall accumulation was likely less than Danny's, once gauge correction estimates are applied.

Wind speeds were much weaker in Claudette than in Danny and the rain gauge in Alvin was a glass cylinder 24.8 cm (9.75 in.) in diameter [National Climate Data Center (NCDC) 1979a]. Thus, in Claudette there was less wind error and no TBR error. To account for Clau-

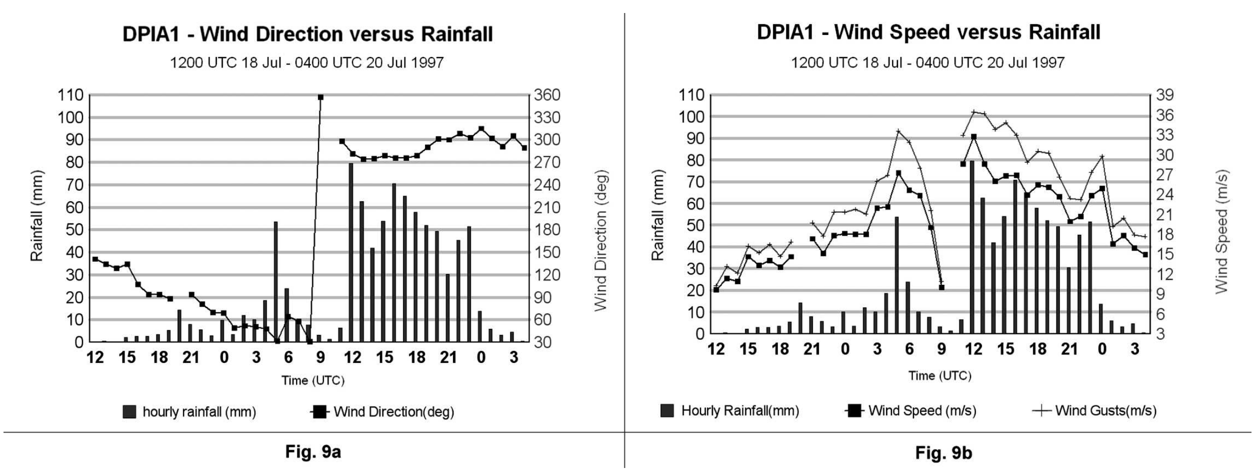

FIG. 9. A 41-h time series of hourly precipitation accumulation (mm) with (a) 10-m wind direction (°) and (b) 10-m wind speed and gusts (m s^{-1}) on the east end of Dauphin Island from 1200 UTC 18 Jul to 0400 UTC 20 Jul 1997. The wind data are from DPIA1, while the rainfall data are from the CSI CS-700 tipping-bucket rain gauge located ~200 m southwest of DPIA1.

TABLE 3. Underestimation error for rain gauges as a function of wind speed for different studies. Errors used for storm comparison purposes are shown in the last column. For the three lowest wind speed categories, the estimated error used for storm comparisons in the present study (last column) is the average (rounded to the nearest 5%) of the published errors shown in columns 2–5. The 80% and 100% comparison errors used for the two highest wind speed categories were subjectively estimated from a combination of errors from extremely limited studies at these higher speeds and error continuity from lower speed categories.

Wind speed ($m\ s^{-1}$)	Koschmieder (1934) (%)	World Meteorological Organization (1962) (%)	Wilson (1954) (%)	Allerup and Madsen (1979) (%)	Dunn and Miller (1960) (%)	Estimated error used for storm comparisons (%)
4–5			10–20			15
5–10	12–40	15–46				30
10–15	40–67	50–83		50		60
15–25	0	0	50	100		80
25–35					50	100

dette's wind error, hourly sustained winds from Houston's Hobby Airport and Ellington Air Force Base (NCDC 1979b; 21 km north and 19 km northeast of the Alvin gauge, respectively) were averaged during the period of Alvin's rainfall (1800 UTC 25 July–1200 UTC 27 July 1979) in order to produce hourly time series of wind speed estimates. Because nearly all of Alvin's rainfall occurred well after Claudette's landfall (while it was a depression centered 100–180 km to the north), these winds at Hobby and Ellington should be fairly representative of those at Alvin (assuming similar exposure). Average hourly wind speeds during this period ranged from 5 to 9 $m\ s^{-1}$ with only 1 h above 10 $m\ s^{-1}$ (11 $m\ s^{-1}$), compared with the Danny event where winds were generally well above 10 $m\ s^{-1}$ for the entire time. Using the wind corrections in Table 3, Claudette's total accumulation of 1143 mm (45 in.) was adjusted upward to 1505 mm (59.25 in.). Applying method 1 to adjust Danny's rainfall for wind and TBR errors, yields a new value of 1732 mm, while method 2 gives 1812 mm (Table 4). Thus, even the more conservative method 1 for wind and gauge adjustments indicates that Danny exceeded Claudette's total maximum accumulation. Like Claudette, Alberto and Allison were weak tropical depressions after landfall, and therefore would not have wind corrections nearly as significant as Danny's. Thus, Danny's adjusted multiday rainfall accumulation likely exceeded all of these events.

Great uncertainty regarding wind corrections surrounds Hurricane Easy's (1950) total rainfall of 1148 mm (45.2 in.) in 72 h in Yankeetown, Florida (Florida Department of Environmental Protection 2006). Easy was a category-3 hurricane when it made landfall and performed a very slow loop in the area over 1–2 days (Norton 1951). The type and exposure of the gauge are unknown and there are no wind measurements from the vicinity of Yankeetown, so wind-estimated error estimates are not possible. However, Easy was much more intense than Danny, and thus may have produced much greater wind-related errors at Yankeetown than was the case at Dauphin Island during Danny. It is fairly safe to say that Danny and Easy likely produced the top two multiday precipitation events in the United States, but it is impossible to tell which is greater.

2) 24-H RAINFALL TOTAL

Danny not only made a historic mark with regard to the multiday rainfall accumulation, but also set a new Alabama 24-h rainfall record of 826 mm (32.52 in.) in the 24-h period from 0100 UTC 19 July to 0059 UTC 20 July 1997 (Fig. 10; source NCDC 1997). This, with uncorrected rain gauge measurements, launched Danny into fourth place for the all-time contiguous U.S. record of this type. Presently, Danny remains behind both Claudette, which produced an unrivaled 1092 mm (43 in.) in Alvin, and Hurricane Easy, which yielded 983 mm (38.7 in.) in Yankeetown. It is worth mentioning that 876 mm (34.5 in.) of rain fell in a 24-h period over Smethport, Pennsylvania, but the event was non-TC related and the rainfall amount was estimated. Also shown in Fig. 10 are the maximum 24-h rainfall records for Georgia, Louisiana, and Mississippi. Interestingly,

TABLE 4. Event and 24-h rainfall totals (mm) for Hurricane Danny (CS-700 tipping-bucket rain gauge) and TS Claudette (glass cylinder). (top row) Measured rainfall, rows below show rainfall adjusted for 1) wind errors, 2) wind plus tipping-bucket (TBR) errors (method 1, see text), and 3) TBR on top of wind errors (method 2, see text).

	Danny (41 h)	Danny (24 h)	Claudette (42 h)	Claudette (24 h)
Measured	896	826	1143	1092
Wind adjustment	1703	1581	1505	1439
TBR plus wind (method 1)	1732	1609	—	—
TBR on top of wind (method 2)	1812	1688	—	—

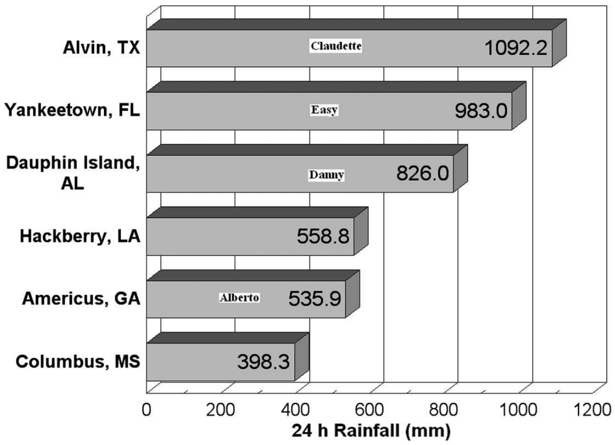

FIG. 10. Record maximum 24-h rainfall (mm) for select U.S. states (source NCDC). Note that the Hackberry, LA, and Columbus, MS, rainfall records did not occur in association with U.S. Gulf Coast TCs.

four of six all-time rainfall records were TC related. Georgia's record was set when the remnants of Alberto became stationary and produced 536 mm (21.10 in.) in 24 h.

In Danny, the average and median wind speeds during the 24 h of heaviest rainfall were both near 24 m s^{-1} with 10 h having winds $\geq$25 m s^{-1}, so there was significant wind-induced rainfall error at the gauge. Using the error methodologies developed in section 4b, the 24-h rainfall total at Dauphin Island was estimated to be 1609 mm (1688 mm) according to method 1 (method 2). Likewise, for Claudette, the average and median wind speeds estimated during the 24 h of heaviest rainfall at Alvin were both 7 m s^{-1}. Thus, with Claudette's less-significant wind-induced errors, the rainfall total at Alvin was estimated to be 1092 mm (gauge) + 347 mm (wind) + 0 mm (TBR) = 1439 mm (56.65 in.). Therefore, Danny may have broken the 24-h rainfall record (previously held by Claudette) by around 170 mm (6.69 in.) or more. It is possible that the 24-h record may actually be held by Hurricane Easy, which produced an uncorrected 24-h rainfall of 983 mm (38.70 in.) at Yankeetown. There is no wind information near this gauge location, so corrections are not possible. However, Easy was a category-3 hurricane on the Saffir–Simpson scale (Simpson and Riehl 1981), with winds >51 m s^{-1} at landfall near Yankeetown (U.S. Climatological Data 1950). The storm maintained hurricane intensity during the 24-h period of record rainfall on 5–6 September 1950. Thus, significant but unknown wind errors likely occurred near the gauge.

Rain gauge exposure and position to storm center are very important when comparing Danny with Easy. During Danny's heaviest rainfall, the gauges on Dauphin Island were located in an exposed area on the east end of a narrow barrier island within the eyewall and inner core of a hurricane (<30 km from the center). Likewise, Yankeetown received its heaviest rainfall within the core of Hurricane Easy. However, Yankeetown is roughly 3 km inland and gauge exposure is unknown. By contrast, the 24 h of heaviest rainfall at Alvin on 25–26 July 1979 occurred at a location 40 km inland and also 100–180 km from a tropical depression's center well after landfall. Therefore, Alvin's rainfall accumulation would have been subject to much less wind-induced error than the other two events. It is likely that Hurricanes Danny and Easy produced the greatest 24-h rainfalls in U.S. history, but the one producing the greater amount will likely remain unknown.

5. Temporal evolution of heavy rainfall patterns

Danny's asymmetric transition during its prolonged landfall near Mobile Bay is well documented by Blackwell (2000). During this time, rainfall rates and distributions vary significantly. Figures 11a–f show a series of KMOB 6-h radar-integrated rainfall products valid at 0000 UTC 19 July–1200 UTC 20 July 1997. Initially (Fig. 11a), the precipitation is most predominant in Danny's northern and eastern semicircles with 6-h amounts exceeding 152 mm (6 in.).

Between 0600 and 1200 UTC (Fig. 11b), the precipitation pattern becomes more symmetric about the storm center with a maximum 6-h amount of over 76 mm (3 in.). By 1200 UTC Danny acquires its greatest axial symmetry, but is dominated by stratiform precipitation (Blackwell 2000).

After 1200 UTC, a dramatic asymmetric transition takes place while the storm is situated in Mobile Bay. As the system evolves from a stratiform to more convective mode, precipitation in Danny's western eyewall exceeds 305 mm (12 in.) in the 1200–1800 UTC period (Fig. 11c) before shifting northward during the 1800–2400 UTC period (Fig. 11d).

The transition to a more convective mode of precipitation is also indicated in the hourly rate of lightning strikes within a 55-km radius of Danny's center between 1200 and 2200 UTC (Fig. 12). Lightning activity was nonexistent in the storm's core prior to 1600 UTC, then increased afterward during the time of Danny's greatest hourly rainfall rates and Z values (Figs. 6a–c). This west-side precipitation asymmetry persists through the remainder of the storm's inland trek across southwestern Alabama.

Early in the development of Danny's west-side asymmetry, composite Z values increased to >55 dBZ (Fig. 6a) at the beginning of the multihour period of maxi-

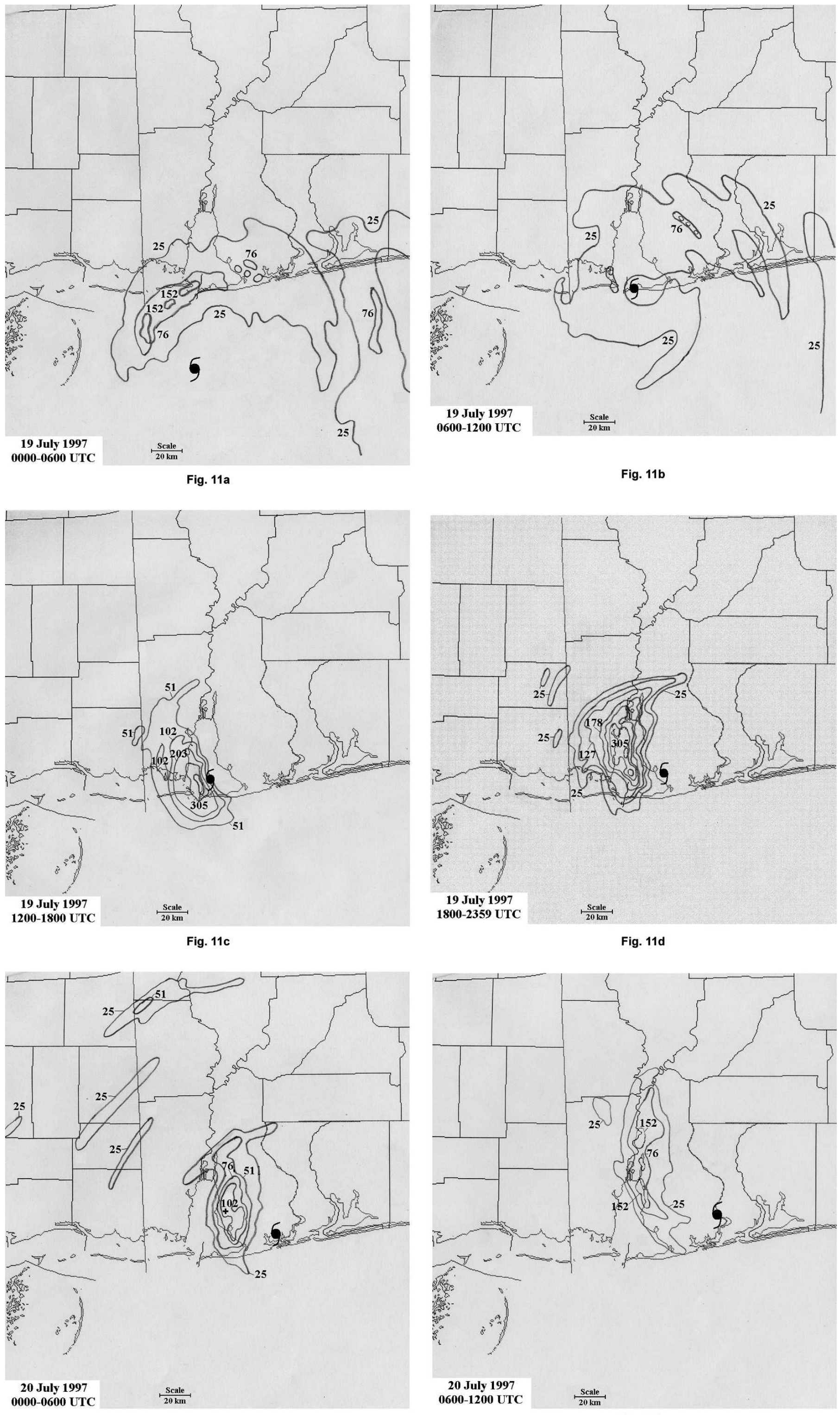

FIG. 11. The 6-h KMOB WSR-88D user selected radar-derived precipitation totals for (a) 0000–0600 UTC 19 Jul, (b) 0600–1200 UTC 19 Jul, (c) 1200–1800 UTC 19 Jul, (d) 1800 UTC 19 Jul–0000 UTC 20 Jul, (e) 0000–0600 UTC 20 Jul, and (f) 0600–1200 UTC 20 Jul 1997. Contours are labeled 1 in. (25 mm), 2 in. (51 mm), 3 in. (76 mm), 4 in. (102 mm), 5 in. (127 mm), 6 in. (152 mm), 7 in. (178 mm), 8 in. (203 mm), and 12 in. (305 mm).

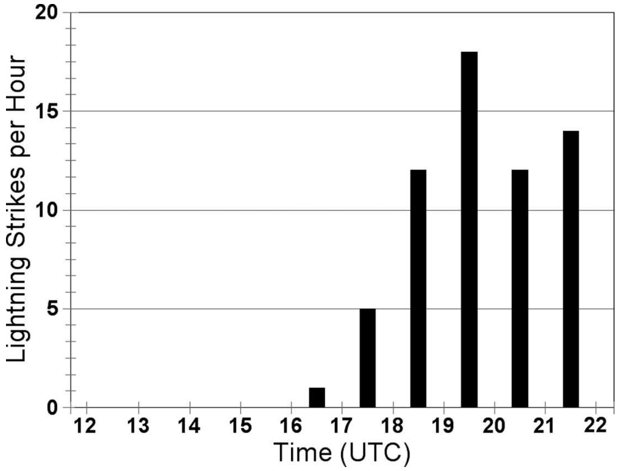

FIG. 12. Hourly frequency of lightning strikes between 1200 and 2200 UTC 19 Jul 1997 within a 55-km radius of Danny's center. (Data courtesy of S. Goodman and W. Peterson at the National Aeronautics and Space Administration Global Hydrology and Climate Center and Vaisala Corporation.)

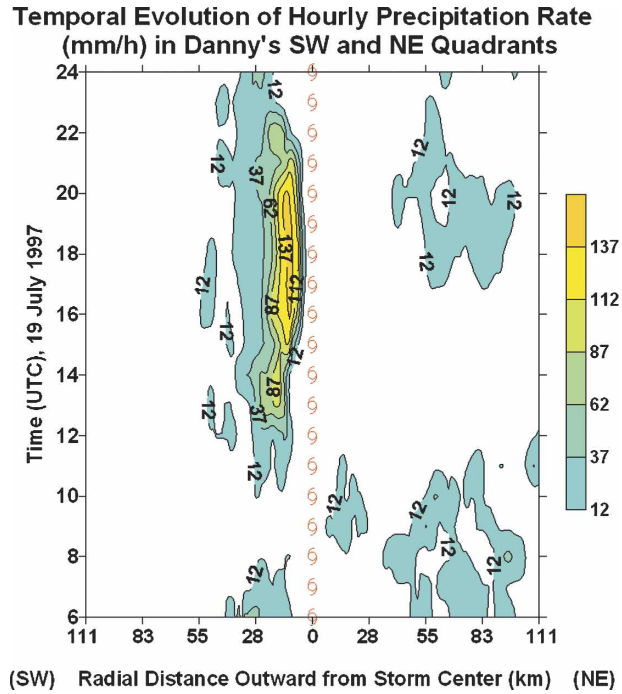

FIG. 13. Temporal evolution of KMOB WSR-88D one-hour precipitation (OHP) product maxima (mm h^{-1}) from 0600 UTC 19 Jul to 0000 UTC 20 Jul 1997. The OHP maxima are plotted as a function of radial distance southwest and northeast from the storm center (km). The storm center is denoted by TC symbols.

mum 1-h rainfall rates (Fig. 13, discussed later), but a cross section along the length of this west-side convection (Fig. 6e) shows that maximum Z values are confined to levels below 2.5 km and well below the melting level (located above 4.7 km) and associated bright band. By 1714 UTC, the area of Z values >55 dBZ to the west of Danny's center dramatically expanded both in horizontal (Fig. 6b) and vertical extent (Fig. 6f) and now extends from the near-surface to near-melting level. A region of Z values <24 dBZ, situated below elevated Z values >55 dBZ, represents a low-level inflow notch and shallow weak echo region below 2-km altitude associated with the nose of a low-level jet wrapping cyclonically around the east and north sides of Danny (Blackwell 2000); the absence of lightning within 23 min on either side of this time indicates these very large Z values are probably not associated with melting hail.

Lightning activity begins to slowly increase after 1743 UTC as the area of Z values encompassed by >55 dBZ continues to expand over Danny's western semicircle through 1858 UTC (Fig. 6c). But this activity remains minimal compared with many convective events (Molinari et al. 1994, 1999, 2004) and likely indicates weakly buoyant (1–4 m s^{-1}) updrafts in the hurricane core's low levels (Black et al. 1996) and generally <10 m s^{-1} updrafts at higher levels (Marks and Houze 1987), that is, updrafts too weak for significant lightning generation. Cecil and Zipser (2002) showed that lightning is accompanied by large Z values reaching well above the melting level, indicative of updrafts >10 m s^{-1}. However, the greatest Z values (>55 dBZ) are concentrated below 2 km along the cross section through the western portions of Mobile Bay (Fig. 6g), thus indicating weaker updrafts. By 2043 UTC, the heaviest precipitation has shifted into northern sections of Mobile Bay (Fig. 6d) with Z values significantly diminishing over southwestern sections of the bay (Fig. 6h).

Bright bands are common near the 4.5-km elevation in vertical cross sections through stratiform precipitation regions of tropical cyclones (Jorgensen 1984; Black et al. 1996; Corbosiero and Molinari 2002). The lack of a distinct bright band in Danny during the heaviest periods of rainfall over southern Mobile Bay is a good indicator of Danny's convective nature during this time.

Figure 13 further quantifies the asymmetric evolution of Danny by comparing 1-h rainfall accumulations in the western and eastern semicircles. From 1039 to 1100 UTC, the symmetric storm exhibits a closed, single eyewall. Shortly after 1100 UTC, however, Z values in the southwest eyewall increase and broaden in radial extent, while the northeast eyewall displays a reduction. Hourly rainfall accumulations in the northeast quadrant drop below 13 mm (0.5 in.). Around 1200 UTC, the asymmetry becomes very distinct with Z values (Fig. 6a) and rainfall accumulations concentrated in the southwest portion of the storm. From 1300 to 1500

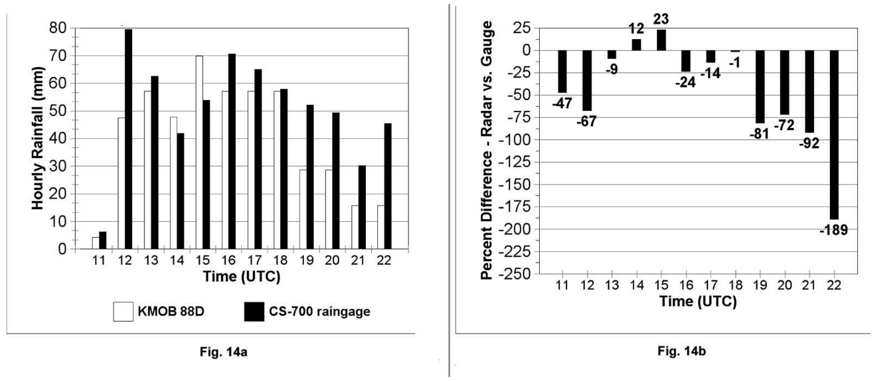

FIG. 14. Graphs displaying (a) hourly precipitation estimates (mm) from KMOB WSR-88D derived from the tropical *Z–R* curve and collocated hourly CS-700 rain gauge measurements (mm) at the Dauphin Island Sea Laboratory on the eastern tip of Dauphin Island, AL, for 1100–2200 UTC 19 Jul 1997; and (b) their hourly (radar–gauge) rainfall differences (mm).

UTC, the radar eye diameter decreases from 18 to 16.5 km, coincident with increases in rainfall and maximum wind speed (Blackwell 2000). Danny intensifies during this period and thereafter maximum *Z* values in the southwestern eyewall increase to 50–55 dB*Z*. By 1600 UTC, maximum *Z* values further increase to 55–60 dB*Z*. Likewise, rainfall accumulations increase from 90 to 140 mm h^{-1} (3.5–5.5 in. h^{-1}). By 2000 UTC, the storm begins to weaken and maximum *Z* values shift northward from the southwestern quadrant into the entire western eyewall (Figs. 6d and 11d). Rainfall accumulations expand farther outward from the TC's center, consistent with the radius of maximum wind expansion noted by Blackwell (2000).

6. Radar-estimated rainfall maximum

a. Radar and rain gauge comparison

In section 4b, it was shown that the Dauphin Island CS-700 rainfall accumulations were underestimated. It will be demonstrated that radar rainfall estimates were also too low. The exact radar bin where the CS-700 lies represents the basis for the comparison. For completeness, the CS-700 lies 13 km to the south-southwest of the radar-estimated rainfall maximum (section 6b) and was the only reliable gauge with hourly recording capability closest to the radar-estimated rainfall maximum (over water). Any further comparison between radar rainfall and event rain gauge accumulations would be scientifically invalid because 1) there is only one recording gauge (i.e., the CS-700) near the actual event rainfall maximum and 2) the exact beginning and ending times of the other event total rainfall data are unknown (Fig. 8).

Rain gauge (*G*) to radar (*R*) comparisons (*G–R*) are shown in Figs. 14a,b. Figure 14a shows the hourly rainfall totals for both platforms. Figure 14b expresses the ratio as a percentage with respect to WSR-88D estimates. Negative (positive) values mean that the radar estimate is lower (higher) than the CS-700 accumulation. Both figures show that for all but 2 h, the WSR-88D estimates are lower than the CS-700 1-h accumulations. On average, the WSR-88D estimates are ~18% lower than the CS-700 accumulations. These values more closely match when Danny's convective eyewall was at its closest point to the east end of Dauphin Island. This is consistent because this is when gauge collection deficiencies are at their highest (strongest winds; Fig. 9b), thus allowing radar estimates and gauge accumulations to more closely match. When the CS-700 hourly accumulations fell below 40 mm h^{-1} and surface wind speeds significantly decreased due to the more intense rainbands moving north of Dauphin Island, WSR-88D estimates became much lower than the CS-700 accumulations. This confirms that WSR-88D rainfall estimates need further adjustments to improve their accuracy, especially with different rates of rainfall possibly due to changes in drop size distribution. In section 6b, multiple radar-only estimates will be produced using the tropical *Z–R* but with different *Z* caps to further assess the radar rainfall estimation.

b. Variations in radar rainfall estimates

It was previously established that the greatest amount of rainfall occurred from 1515 UTC 19 July to 0005 UTC 20 July 1997. During this period, the WSR-88D revealed persistent 51–61-dB*Z* *Z* values, which were greater than the 50-dB*Z* cap used to produce radar rainfall estimates in real time. Figure 15 is a time

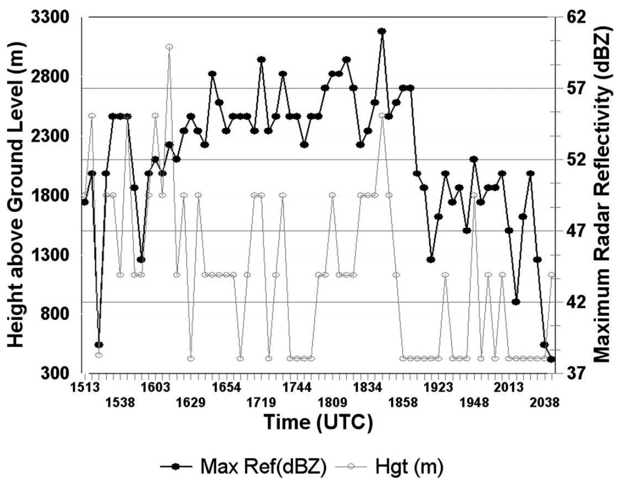

FIG. 15. Time series of observed maximum radar reflectivity (squares, dBZ) and height to which elevated (solid circles, m) over the location of the rainfall maximum, from 1513 to 2043 UTC 19 Jul 1997.

series of maximum Z values and their elevation AGL for 1513–2043 UTC.

Based on five 6-hourly soundings from Slidell, Louisiana, from 0000 UTC 19 July to 0000 UTC 20 July 1997, the observed average freezing level was 4700 m AGL with the freezing level probably much higher in the eyewall of Danny. The highest Z values (51–61 dBZ) were sampled well below the melting level (Fig. 15), but yet, not below the 0.5° radar elevation slice. Given how far a 0.95° beamwidth spreads in the vertical direction over a horizontal distance of 30 km (approximately the distance between KMOB and the rainfall maximum; Fig. 8), we computed the distance between the bottom of the radar beam and the ground to be about 150 m. Because the lowest 150 m of elevation is below the cloud base, where the relative humidity is less than 100%, there would be slight evaporation of water drops. Thus, the rainfall rate below the bottom of the beam is less than that at cloud base (above the bottom of the beam). Therefore, the highest Z values were indeed sampled, so as to prevent rainfall underestimation due to higher Z values existing below the elevation of the lowest radar beam. Nor did wet hail contamination (i.e., causing overestimation) occur. It is uncertain that hail even exists in hurricanes. Black and Hallett (1986) and McFarquhar and Black (2004) found 1-mm-diameter graupel near the freezing level (5.5–6.3 km) in in situ microphysical measurements in hurricanes (including a case over land); they did not mention hail. These smaller ice particles more than likely melted before reaching the levels of maximum reflectivities (Fig. 15). The data show that ~81% of the maximum observed Z values during the time range in Fig. 15 were ≥49 dBZ, ~72% were ≥51 dBZ and over half (~53%) were ≥53 dBZ. The above arguments clearly justify the use of a higher Z cap than 50 dBZ.

Using the operational tropical Z–R, WATADS was used to generate three WSR-88D precipitation estimates during the 1515 UTC 19 July–0005 UTC 20 July 1997 period. Each differs according to the chosen MXPRA values of 50, 53, and 55 dBZ, which allow for maximum hourly rainfall rates (Fig. 4) of 147.2 (5.80), 261.8 (10.31), and 385 mm h^{-1} (15.14 in. h^{-1}), respectively. Unlike any other time during Danny's landfall, this period adequately captures the potential amount of rainfall that was underestimated due to the existence of Z values >50 dBZ that were not factored into the radar-derived rainfall estimates.

Results are shown in Figs. 16a–c. The scale in each is different to highlight the exact location and magnitude of the rainfall maximum. Results confirm the location of the maximum to be very close to the 151° azimuth and 39-km range with respect to the KMOB WSR-88D (i.e., over southwestern Mobile Bay), 13 km to the north-northeast of the CS-700. Maximum radar-derived rainfall estimates during this period range from 718 mm (28.29 in.) using a 50-dBZ Z cap to 1148 mm (45.19 in.) using a 55-dBZ cap (see Figs. 16a,c). The maximum rainfall amount estimated using 55 dBZ represents a 59.7% increase over the 50-dBZ estimate. Although on the high end, if one were to accept the use of a 55-dBZ cap as valid, an additional 430 mm (16.9 in.) of rain could have fallen during this approximate 9-h period. On the low end, the amount of rainfall (718 mm or 28.29 in.) estimated by the 50-dBZ cap is probably too low (suggested by the G–R comparison).

Over the rainfall maximum location, the data in Fig. 15 reveal an average maximum Z value of 52.3 dBZ during the approximate 9-h period. Theoretically (Fig. 4), a Z cap of 52.3 dBZ would increase the maximum hourly rainfall rate to 230 mm h^{-1} (9.05 in. h^{-1}). This rate is reasonable and certainly not impossible given a stationary hurricane [for comparison, the world record 1-h rainfall is 305 mm (12 in.), which occurred in Holt, Missouri, in 1947]. Based on an average 52.3-dBZ radar Z value and linearly interpolating between the 50- and 53-dBZ simulations (Figs. 16a,b), the radar-estimated rainfall maximum that occurred from 1515 UTC 19 July to 0005 UTC 20 July 1997 should have been no less than 922 mm (36.3 in.). The maximum rainfall amount estimated using the 50-dBZ cap (Fig. 16a) is 719 mm (28.29 in.). Upon adding the difference between the 9-h 52.3- and 50-dBZ-estimated rainfall values to the overall rainfall maximum of 1097 mm (43.2 in.; see Fig. 3), Danny likely produced at least 1301 mm (51.21 in.) for the event's total rainfall.

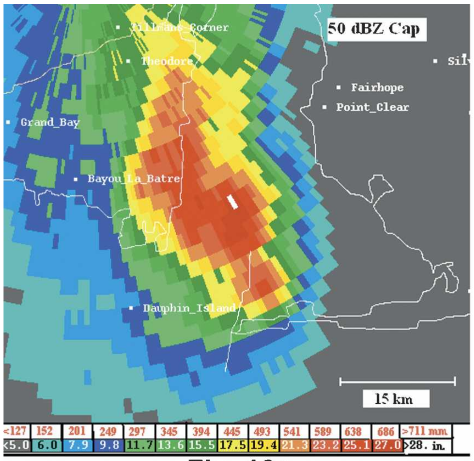

Fig. 16a

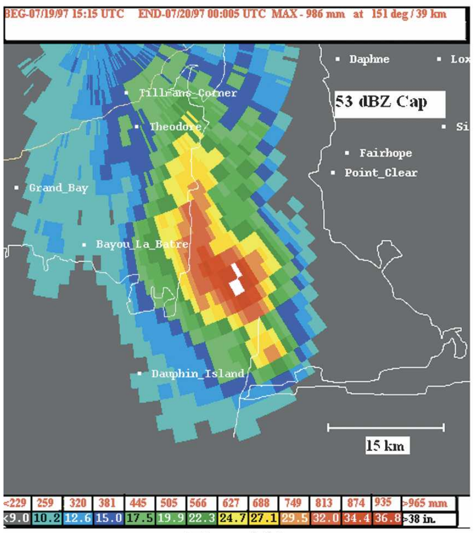

Fig. 16b

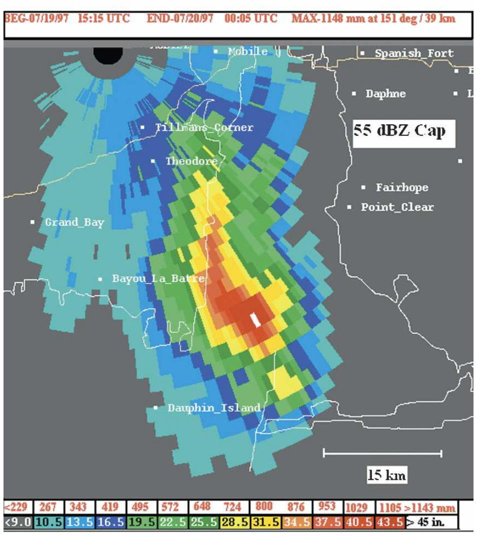

Fig. 16c

7. Summary and conclusions

Hurricane Danny produced an historic heavy rainfall episode during its landfall along the Alabama coast. The center remained <100 km from the KMOB WSR-88D for over 48 h and the event marked the first time the tropical Z–R relationship ($Z = 250R^{1.2}$) was employed on an operational WSR-88D system during TC landfall.

This research has documented the temporal and spatial characteristics of extremely heavy rainfall occurring in association with Danny's convective western eyewall. Blackwell (2000) used numerous radar observations prior to, during, and after Danny's landfall to identify the evolutionary characteristics of the wind field (and its maximum) during the asymmetric transition. The current investigation discovered the following.

1) After having a rather uniform circular precipitation pattern with rainfall rates generally between 25 and 76 mm h^{-1} (1–3 in. h^{-1}) during the predawn hours, radar-derived rainfall rates became extreme [$\geq$405 mm (6 h)$^{-1}$ or $\geq$16 in. (6 h)$^{-1}$] shortly after 1200 UTC 19 July 1997 when Danny became asymmetric and intensely convective over Mobile Bay. Excessive rainfall rates persisted through 0000 UTC 20 July 1997 with a general tapering thereafter.
2) Results confirm the location of the true rainfall maximum to be over southwestern Mobile Bay (151° azimuth and 39-km range with respect to the KMOB WSR-88D). This location is of great importance because it establishes that the maximum was not over land (previously unknown from the real-time operational output; Fig. 3) and most definitely exceeds the 896 mm (35.28 in.) measured by the CS-700 on the east end of Dauphin Island (located 13 km to the south-southwest of the true rainfall maximum).
3) A new Alabama maximum 24-h rainfall record of 826 mm (32.52 in.) was set from 0100 UTC 19 July to 0059 UTC 20 July 1997. This launched Danny into fourth place for the all-time contiguous U.S. record of this type. As of this paper's publication, Danny

←

FIG. 16. Radar-derived rainfall estimates (mm and in.) from 1515 UTC 19 Jul to 0005 UTC 20 Jul 1997 using reflectivity caps of (a) 50 dBZ, which corresponds to a maximum allowable hourly rainfall rate of 147.2 mm h^{-1} (5.80 in. h^{-1}); (b) 53 dBZ, which corresponds to 261.8 mm h^{-1} (10.31 in. h^{-1}); and (c) 55 dBZ, which corresponds to a 384.6 mm h^{-1} (15.14 in. h^{-1}). Note that the scale is different in each panel in order to highlight the precise location and exact magnitude of the maximum.

officially remains behind both TS Claudette, which previously produced 1092 mm (43 in.) in Alvin, Texas, and Hurricane Easy, which yielded 983 mm (38.7 in.) in Yankeetown, Florida.

4) The highest recorded wind gusts occurred simultaneously with a period of peak rainfall intensity over Dauphin Island. Thus, large underestimation could have occurred due to both high wind and tipping-bucket errors. Ten of the 41 h were characterized by sustained wind speeds >25 m s^{-1} and occasional wind gusts to hurricane force. Discounting wind gusts and using two different methods of applying wind adjustment factors and a variable tipping-bucket error, a total of 1732 or 1811 mm of rain may have occurred over this location (which is well removed from the landfall maximum over southwestern Mobile Bay).
5) Danny's 41-h rainfall amount of 932 mm (36.71 in.) at Dauphin Island, Alabama (non-TBR reading) compares to other extreme U.S. rainfall totals from TS Allison (2001) in Texas, TS Alberto (1994) in Georgia, Hurricane Easy (1950) in Florida, and TS Claudette (1979) in Texas. Claudette, with 1143 mm (45.00 in.) in 42 h at Alvin, Texas, is the highest known multiday event associated with any U.S. landfalling TC. But, when wind and gauge errors are estimated using the most conservative of two methods, corrected rainfall estimates for Danny (1732 mm or 68.19 in.) exceed corrected estimates for Claudette (1505 mm or 59.25 in.). Hurricane Easy, a category-3 hurricane at landfall near Yankeetown, Florida, produced a 72-h total of 1148 mm (45.2 in.) there; but, the actual amount, if corrected for severe wind errors, was likely much higher. Unfortunately, rainfall error estimates at Yankeetown are not possible in Easy as a result of a lack of wind data. If wind and gauge corrections could be applied to Easy, like in Danny, it is likely that rainfall estimates for Easy would also exceed Claudette's corrected estimate. Thus, Hurricanes Danny and Easy likely produced the top two multiday precipitation events in the United States, but it is impossible to tell which one produced the greatest total.
6) Results show the WSR-88D rainfall estimates produced by the operational 50-dBZ Z cap were likely too low. Using 52.3 dBZ as a cap, Danny likely produced an additional 204 mm (8.01 in.) during a 9-h period, which brings the estimated rainfall maximum over southwestern Mobile Bay to 1301 mm (51.21 in.) compared with the previously estimated 1097 mm (43.2 in.) using the operational 50-dBZ Z cap.
7) Reliable gauges near Danny's rainfall maximum were unavailable and the only *G–R* comparison that could be performed, was performed. The *G–R* (of unadjusted rainfall data) at Dauphin Island showed that the radar-estimated hourly rainfall values were less than the gauge-collected accumulations, except for two highly convective hours. The gauge-collected rainfall at Dauphin Island was conservatively (method 1) estimated to be undermeasured by 836 mm (or 93%) for a new total of 1732 mm. A radar adjustment at this location would not be useful because Z values did not exceed 50 dBZ at this location for any significant length of time (Fig. 6). It is therefore concluded that the radar severely underestimated rainfall at Dauphin Island and likely also near the rainfall maximum over southwestern Mobile Bay. At this location, the radar-estimated rainfall may be underestimated by more than 204 mm (18.6%), for a new total of 1301 mm. Since the adjusted gauge measurement of 1732 mm is not at the location of the rainfall maximum over the Bay and because it seems likely that radar severely underestimated rainfall everywhere, the rainfall at the maximum location in Danny likely exceeded 1732 mm. Therefore, the radar underestimation at the location of the rainfall maximum would be more serious than at Dauphin Island.

Blackwell (2000) points out that a small diameter storm may maintain or even increase in intensity for several hours over a tidal estuary as long as the convective portion of the eyewall experiences latent heat fluxes from the underlying water surface. It is ironic that Danny was so small compared with most hurricanes, but yet, achieved incredible convective intensity over such a confined space. Had it not been for the synoptic col in which Danny was embedded and/or the exact location and orientation of Mobile Bay relative to the storm's position, this catastrophic rainfall event may not have occurred. More research is needed to document the variability in the drop size distribution of landfalling TCs. The impending dual-polarization upgrade to NWS WSR-88Ds should significantly enhance rainfall estimation capabilities.

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