

The Breath home three days after Camille, August 20, 1969. Moving surge debris and replacing roof, minus Queen Anne dormer that was blown off. (Photo courtesy of the Hancock County Historical Society, Bay Saint Louis, MS.)

A REANALYSIS OF HURRICANE CAMILLE

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A modern look at one of the United States' most destructive hurricanes indicates that it was deeper than, but not quite as intense as, originally estimated.

The pressure gradient must have been tremendously steep. Because of this...I think of Camille as a giant, well-organized tornado rather than as a small, very intense hurricane.

—Dr. Luis R. Rivas in a letter to Leonard G. Pardue of the National Hurricane Center

With the passage of almost 50 years and the recent memory of a number of major hurricane landfalls along the northern Gulf Coast of Louisiana, Mississippi, Alabama, and the Florida Panhandle, including Dennis and Ivan in 2004, and Katrina and Rita in 2005, and, further back, Andrew in 1992, Elena in 1985, and Frederick in 1979, Hurricane Camille in 1969 may not come readily to mind, except for those who lived through it. But for tropical meteorologists, Hurricane Camille holds a continuing fascination as one of the most intense U.S.-landfalling hurricanes on record and for a number of mysteries associated with its meteorological statistics and best-track record.

The African easterly wave that spawned Hurricane Camille traveled across the Atlantic main development region with very little associated convection or organization. However, after entering the Caribbean, the wave amplified and split into two areas of disturbed weather, one in the Bahamas and another near the Cayman Islands. The National Hurricane Center (NHC) sent weather reconnaissance flights to both areas on 14 August 1969, expecting the northern area would be the one to develop but finding that the area in the Caribbean had already developed into a tropical storm. Camille continued to develop rapidly before making landfall at 2200 UTC 15 August over the extreme western edge of Cuba at just under major hurricane strength. A few hours later, Camille moved into the Gulf of Mexico at the onset of the diurnal convective maximum and began rapidly intensifying, achieving category 5 status at 150 knots (kt; $1 \text{ kt} = 0.51 \text{ m s}^{-1}$) and a pressure reading of 908 mb ($1 \text{ mb} = 1 \text{ hPa}$) by 1800 UTC 16 August. Six hours later, the pressure had dropped to 905 mb. At this time, early Saturday evening local

time, Camille was about 290 n mi (1 n mi = 1.852 km) south-southwest of the mouth of the Mississippi River. The hurricane began to significantly affect the Mississippi Gulf Coast on Sunday evening, with the eye making landfall near midnight Sunday local time (0400 UTC 18 August). The bathymetry of the coastline enabled the hurricane to generate a tremendous storm surge that devastated the coastal communities on and near the western Mississippi coast and that would not be approached or eclipsed until Hurricane Katrina in 2005. Camille then moved northward through the Tennessee Valley and eastward through the mid-Atlantic states, where it produced record rainfall over the Appalachians. It subsequently redeveloped into a tropical storm in the Atlantic, after which it underwent extratropical transition and dissipated.

A reanalysis of the NHC's second-generation North Atlantic hurricane database (HURDAT2; Landsea and Franklin 2013) now covers the period from 1851 to the mid-twentieth century (e.g., Hagen et al. 2012). The reassessment of the existing database is necessary to correct random and systematic errors; to incorporate current understanding of tropical cyclones (TCs) upon previously collected raw observations; to include explicit analyses of the time, position, and intensity at landfall; and to add previously unrecognized TCs. Because previous reanalysis results had already addressed the three other category 5 hurricanes on the Saffir–Simpson hurricane wind scale to have impacted the United States during the twentieth century, NHC management requested an expedited reanalysis of Camille because of the need to answer a simple question: which is the strongest hurricane to have struck the United States?

In the context of modern understanding of TC intensity, tropical meteorologists have long held

some skepticism about Camille's landfall intensity, for several reasons. An extraordinary wind speed of 180 kt was reported by the last reconnaissance flight into Camille near 1800 UTC 17 August based on visual estimation of surface wind speeds observed from the surface sea state and an observed dropsonde 901-mb surface pressure. This resulted in a forecast intensity and accepted landfall intensity (10 h later) of 1-min winds of 165 kt, which is near the upper bound for globally known TC intensity in the combined NHC and Joint Typhoon Warning Center best-track data. The 901-mb mean sea level pressure (MSLP) that was noted in real time and in earlier reports (e.g., NHC *Preliminary Report, Climatological Data* monthly summary) disappeared from later reports (e.g., *Monthly Weather Review's* Atlantic hurricane season summary, *Climatological Data* yearly summary), and the earlier 905-mb pressure was identified as the lowest measured pressure (Simpson et al. 1970). In addition, Camille's MSLP and intensity at landfall were at odds with the two other category 5 mainland-U.S.-landfalling hurricanes—the 1935 Labor Day hurricane and Andrew in 1992. Particularly when compared to the Labor Day hurricane, Camille's landfall intensity appeared too high in relation to the MSLP (interestingly, MSLP readings in all three of these category 5 landfalls were taken by private individuals and the barometers were confirmed for accuracy). In addition, the original best track shows Camille gradually strengthening as a category 5 hurricane for more than 24 h before landfall—that contrasts with many other major hurricanes that have made landfall along the northern Gulf Coast, which weakened prior to landfall. All 11 hurricanes—most notably Hurricane Katrina in 2005—during the period from 1985 to 2005 having a central pressure less than 973 mb 12 h before landfall in the northern Gulf of Mexico weakened during these last 12 h (Rappaport et al. 2010).

After almost 50 years, can we answer these questions: During the Gulf of Mexico transit, did any weakening occur? How strong was Camille at landfall in Mississippi? A reanalysis of Hurricane Camille has enabled us to answer these questions to the extent the data will allow.

The official revisions for Hurricane Camille, which have been approved by the Best-Track Change Committee, are summarized below:

Generally, very small (0.3° latitude–longitude or less) changes were introduced to the center positions of Camille throughout its lifetime based upon a combination of ship, station, aircraft penetration, aircraft radar, land-based radar, and satellite observations

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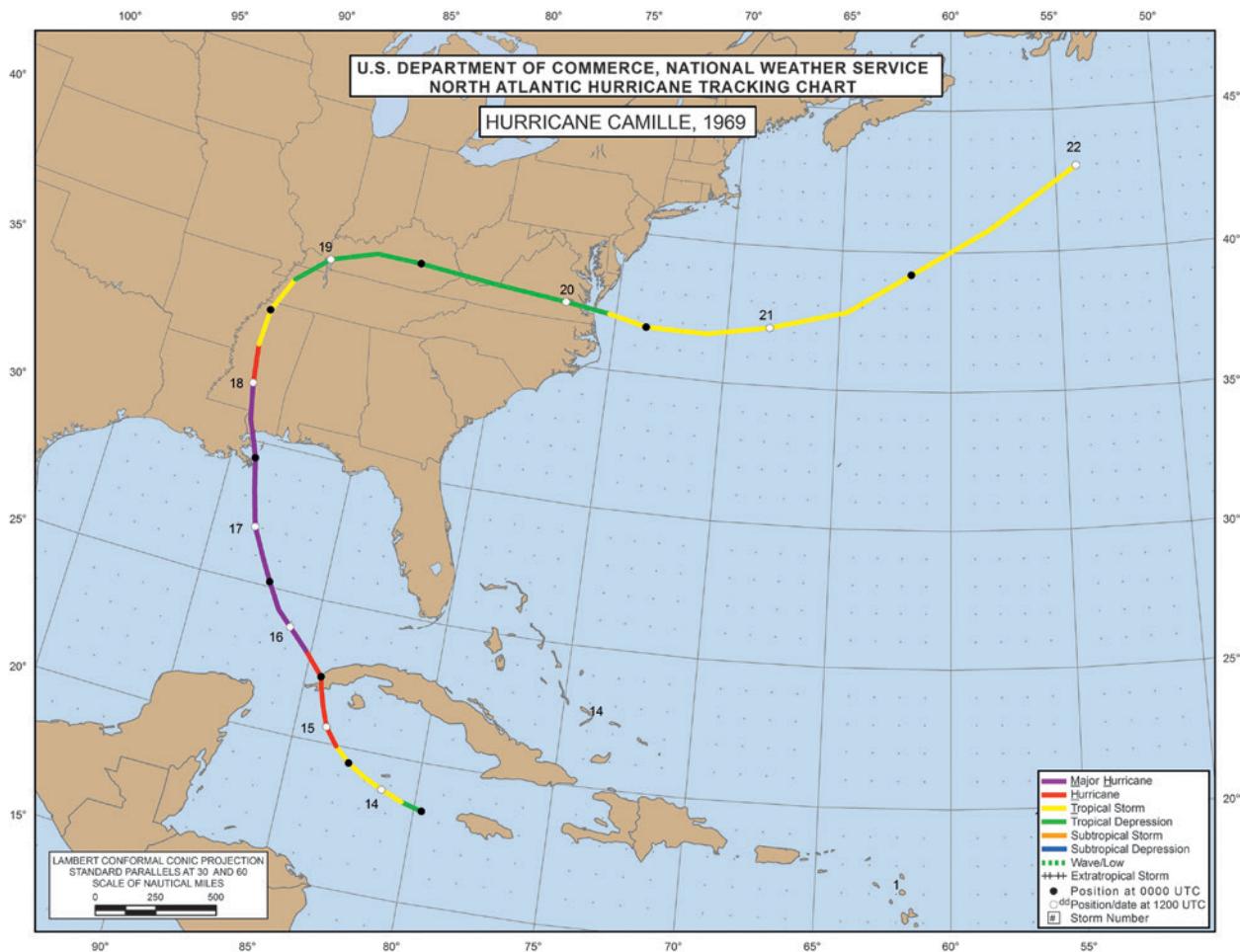


FIG. 1. Track map of Hurricane Camille, 14–22 Aug 1969.

(Fig. 1). Such relatively minor changes in the track are typical of systems in this era, as aircraft reconnaissance allowed for fairly accurate determination of the location of the center. The largest alteration to the positions was early on 20 August by about 50 n mi to the east-southeast when Camille was inland as a tropical depression over Kentucky. This adjustment was made to smooth out changes in forward speed as Camille accelerated eastward.

Minor intensity changes were analyzed for the periods around the Cuban landfall and at the end of the life cycle while the cyclone was moving over the mid-Atlantic states into the Atlantic Ocean. Major changes were made to the period Camille transited the northern portion of the Gulf of Mexico from the completion of the period of rapid intensification through an eyewall replacement to the Mississippi landfall, which resulted in modifications to the peak intensity and the timing of the peak intensity. These more substantial changes will be described in detail.

DATASETS AND METHODOLOGY.

Observational capabilities of Atlantic basin TCs in 1969 continued to evolve from those available earlier in the twentieth century. Through the early 1940s, the only measurements available of these primarily oceanic mesoscale cyclones were from unfortunately placed ships at sea and from coastal weather stations (Landsea et al. 2004b, 2008, 2012). These surface observations continued to play a crucial role in the reanalysis of Camille, from measurements obtained via the Comprehensive Ocean–Atmosphere Data Set (Woodruff et al. 1987), original U.S. station observations obtained from the National Climatic Data Center’s EV2 website (www.ncdc.noaa.gov/EdadsV2/), original Cuban station observations provided by the Cuban Meteorological Service, summaries of observations in *Monthly Weather Review* and other articles, microfilmed hand-drawn synoptic maps by the NHC analysts and forecasters in 1969, and the “storm wallet” of observations/analyses made available in real time and postanalysis to the NHC forecasters.



FIG. 2. Aircraft reconnaissance available in Hurricane Camille. (left) Image from ESSA (1969) provides the individual center fixes (small circles and triangles) and the original 6-hourly best-track positions (large circles). (right) Types of aircraft used to provide aircraft reconnaissance into Hurricane Camille.

For this particular reanalysis of Hurricane Camille, special observations and eyewitness accounts were also used, including Hamilton and Steere (1969, oil platform measurements), Breath (2007, personal communication, interviews of survivors), Mississippi Test Facility (1969, MTF observations), and N. C. Roberts Jr. (1969, unpublished manuscript, collection of unofficial observations).

Beginning in the mid-1940s, rudimentary aircraft reconnaissance missions were conducted for TCs (Hagen et al. 2012). These platforms were quite adept at providing center fixes, either by directly penetrating the eye of the storm, by locating the center from the plane's nose radar, or by circumnavigating the cyclone. The aircraft, however, were not able to accurately measure flight-level winds in hurricane conditions, though they were able to provide visual estimates of the surface winds. If the aircraft did obtain a penetration center fix, then they could also provide a central pressure, either via extrapolating the

flight-level pressure to the surface or by dropping a sonde into the eye. These capabilities and limitations continued into the 1969 hurricane season, with a mix of aircraft: the Navy's WC-121s, the Air Force's C-130s, and the Environmental Science Services Administration's [ESSA; the predecessor to the National Oceanic and Atmospheric Administration (NOAA)] DC-6s (Fig. 2).

In addition, the coastal array of Weather Surveillance Radar-57 (WSR-57) radars had been fully deployed during the 1960s and was available to monitor the position of Camille as it made landfall in the United States (Fig. 3). These radars provided a plethora of center fixes from a few locations every 30 min within a couple hundred miles from the coast.

Finally, an emerging capability available operationally at NHC in the 1960s was satellite imagery (Fig. 4). These were visible images from the polar-orbiting ESSA-8, ESSA-9, and *Nimbus-3* satellites, which each provided a snapshot of Camille about once per day.

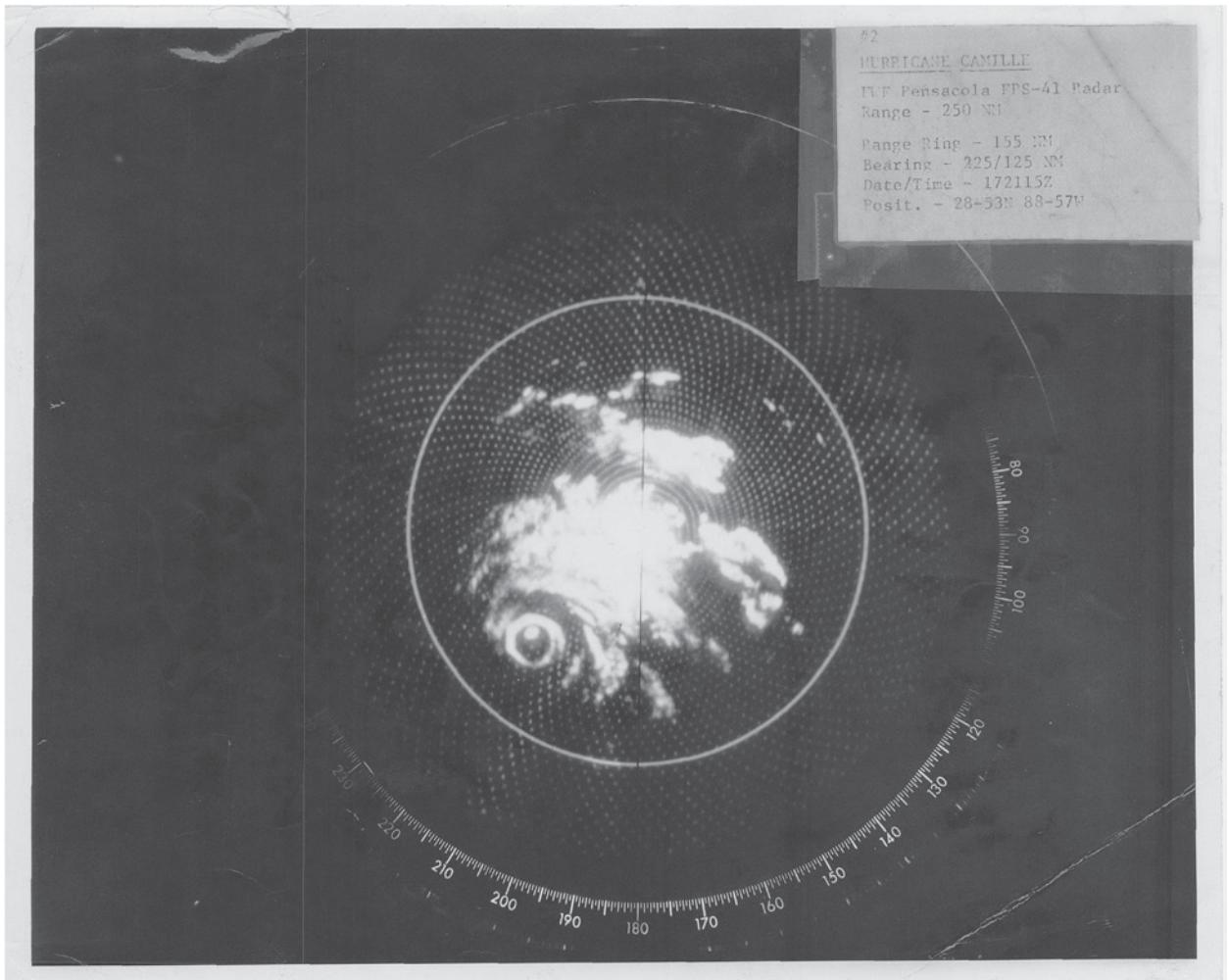


FIG. 3. WSR-57 image of Hurricane Camille at 2115 UTC 17 Aug 1969 from the Fleet Weather Facility Pensacola FPS-41 radar (NHC 1969).

The *Nimbus-3* satellite also had an infrared sensor, which while not available operationally, did show poststorm potential for providing imagery day or night (Allison et al. 1971). The National Aeronautics and Space Administration (NASA) also had an experimental geostationary satellite, the Applications Technology Satellite (ATS), which also provided after-the-fact visible imagery of Camille (Parmenter 1969). These images allowed for some qualitative assessment of Camille, but because of poor navigation, coarse resolution, and spotty temporal coverage, the satellite imagery of 1969 is only marginally of use for knowing Camille's exact position and intensity. For example, the aforementioned issues make it difficult at best to use the Dvorak (1984) technique for estimating TC intensity from satellite imagery. Almost a decade after Camille, *Nimbus* infrared and water vapor imagery and ATS visible imagery were analyzed (Shenk and Rogers 1978).

The methodology for the reanalysis of Camille follows similar steps established in earlier reanalysis efforts: 1) obtain all available raw observational data into a single database, 2) conduct synoptic analysis four times daily, 3) determine genesis changes, 4) determine track changes, 5) determine intensity (maximum sustained surface wind) changes, 6) determine status/dissipation changes, and 7) document all revisions in a metadata file. The track revisions primarily relied on aircraft and radar fixes. The intensity revisions primarily relied on aircraft and coastal central pressure measurements converted to maximum winds via the Brown et al. (2006) and Landsea et al. (2004b) pressure–wind relationships. These intensity values could then be adjusted based on the observed radius of maximum wind (RMW; a measure of inner-core size), radius of the outermost closed isobar (ROCI; a measure of TC size), pressure of the outermost closed isobar (POCI; a measure of

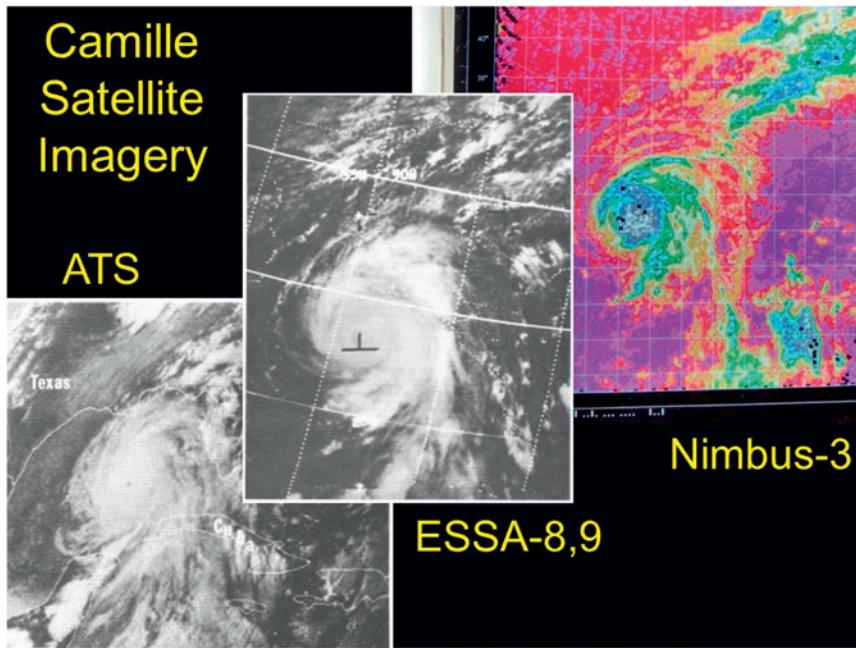


FIG. 4. Satellite imagery of Hurricane Camille. (bottom left) Visible image is from the experimental NASA ATS geostationary satellite at 2340 UTC 16 Aug 1969 (Parmenter 1969). (middle) Visible image is from the ESSA-8 polar-orbiting satellite at 1957 UTC 16 Aug 1969 (ESSA 1969). (top right) Infrared image is from the Nimbus-3 polar-orbiting satellite at 0500 UTC 16 Aug 1969 (Allison et al. 1971).

the environmental pressure), and TC forward motion varied from the climatology of Vickery et al. (2000).

The reanalysis methods documented in Landsea et al. (2004a) have been established in an attempt to provide consistency in the reanalyzed data. Since there is an inherent uncertainty in the wind–pressure

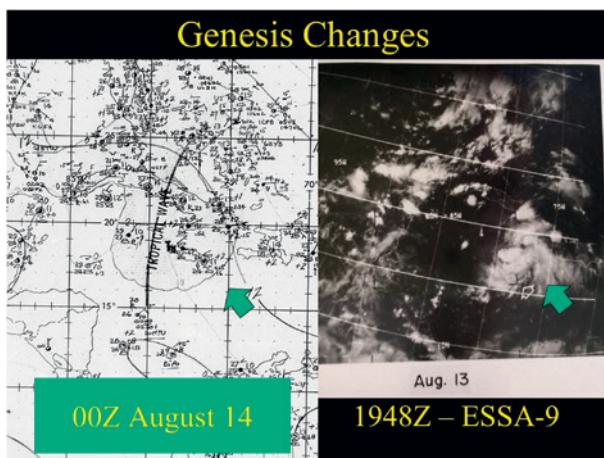


FIG. 5. Observations (0000 UTC 14 Aug 1969; microfilm archives at the NHC library) and satellite imagery (1948 UTC 13 Aug 1969; Weather Bureau 1969) providing evidence for an earlier genesis of Camille than originally indicated.

relationships used in the reanalysis, this translates into uncertainties in the reanalyzed best track intensities. Even using today’s data, the NHC considers their best-track intensities accurate to within about $\pm 10\%$ (Landsea and Franklin 2013). The uncertainty would be higher for storms of the Camille era.

More details on the reanalysis of Hurricane Camille, including data, files, and imagery, are available online. The full metadata, consisting of highlights of daily observations and descriptions about the changes to genesis, track, intensity, landfall, and dissipation, is available on the Atlantic Hurricane Database Reanalysis Project website (www.aoml.noaa.gov/hrd/data_sub/re_anal.html). This also includes the most recent HURDAT2

file, a database of all relevant raw observations, all of the NHC microfilm imagery, and comments from and responses to the Best-Track Change Committee. Additionally, comprehensive “storm wallet” archives maintained at NHC from the late 1950s onward (www.nhc.noaa.gov/archive/storm_wallets/cdmp/) also provide a large source of observations, which have been thoroughly mined for the reanalysis of Camille and other TCs.

GENESIS OF CAMILLE. Camille began as a tropical wave that emerged from the coast of West Africa on 5 August, which did not develop until it reached the western Caribbean Sea. Surface observations in the vicinity of the wave during genesis (Fig. 5) are somewhat sparse and are ambiguous as to when the system had a closed circulation. HURDAT2 originally indicated an “instant” 50-kt TC beginning at 1800 UTC 14 August. A closed circulation was not observed at 1200 UTC 13 August when the system passed over Jamaica; however, a closed circulation of tropical storm strength had developed by 1500 UTC 14 August. Satellite imagery late on 13 August (Fig. 5) indicated the deep convection associated with the wave had organized banding. Given the improved structure seen in the satellite imagery at that time, the

ambiguous surface observations, and the subsequent observations of the system being a moderate tropical storm around midday on 14 August, the best estimate of when genesis occurred is now 0000 UTC 14 August. While this is 18 h earlier than originally indicated, the exact time of genesis is uncertain to ± 6 h.

PEAK INTENSITY IN THE GULF OF MEXICO. Near the end of 3 days of rapid intensification, resulting in an intensity increase of 120 kt from its inception as a tropical depression, Camille reached its initial peak intensity of 150 kt from 1800 UTC 16 August to 0000 UTC 17 August. At 1835 UTC 16 August, an Air Force reconnaissance aircraft measured 908-mb central pressures from two separate dropwindsondes inside a circular eye of 10 n mi diameter. This eye size yields an approximate 8 n mi RMW using Kimball and Mulekar (2004). This pressure suggests maximum winds of 151 kt based on the Brown et al. (2006) pressure–wind relationship for intensifying storms south of 25°N latitude. Given a near-average environmental pressure from the 1010-mb outer closed isobar, a slow forward speed of 9 kt, and a tiny RMW of 8 n mi versus the 12 n mi climatology for this latitude and central pressure (Vickery et al. 2000), the intensity is analyzed at 150 kt. This is a 20-kt major increase from the previous best track value for 1800 UTC 16 August.

A similar methodology is used at the subsequent 0000 UTC 17 August best-track time. The same aircraft sortie observed a 905-mb central pressure at 0016 UTC 17 August with no change in eye size. As the cyclone was now straddling the 25°N latitude line, the 905-mb pressure suggests an intensity of 151 and 154 kt based on the Brown et al. (2006)

pressure–wind relationships for intensifying storms both north and south of 25°N latitude, respectively. An intensity of 150 kt at 0000 UTC 17 August is analyzed from these values, an increase of 10 kt from the previous best-track value.

INTERNAL STORM STRUCTURE OF CAMILLE IN THE GULF OF MEXICO. When environmental conditions are very favorable for TC development (low shear, warm SSTs, and deep warm water of the northwestern Caribbean and the Gulf of Mexico Loop Current) and the intensity has reached major hurricane status, hurricanes are likely to begin an eyewall replacement cycle (ERC),

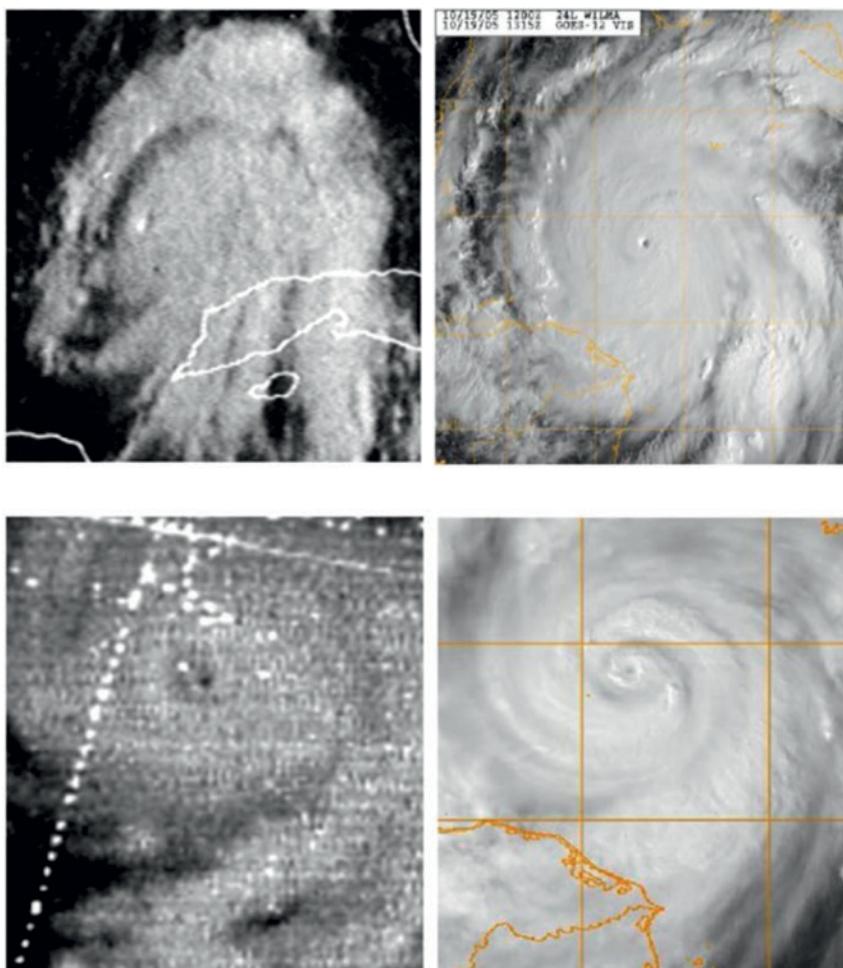


FIG. 6. (top left) Visible satellite image of Hurricane Camille at 1311 UTC 16 Aug 1969 near initial peak intensity and 5 h before 1800 UTC 908-mb pressure and 150-kt intensity. (top right) Visible satellite image of Hurricane Wilma at 1315 UTC 19 Oct 2005 near peak intensity of 882 mb and 160 kt. (bottom left) Visible satellite image of Hurricane Camille suggestive of a double eyewall at 1953 UTC 17 Aug 1969 at 919-mb pressure and 135-kt intensity. (bottom right) Visible satellite image of Hurricane Wilma showing the double eyewall confirmed by aircraft data at 1915 UTC 19 Oct 2005 at 892-mb pressure and 140-kt intensity.

CAMILLE'S 901-MB DROPSONDE

During the penetration of the eye of Camille near 1815 UTC 17 August, an Air Force dropsonde in the eye recorded a 901-mb pressure. For a short time, this was documented in the operational advisories, the *Preliminary Report* (Weather Bureau 1969), the *Climatological Data* (DeAngelis and Nelson 1969), and the *Mariners Weather Log* (DeAngelis 1970) to be Camille's deepest sea level pressure as well as the lowest pressure of record ever recorded by aircraft reconnaissance. Some months later in the *Monthly Weather Review* article on the 1969 hurricane season (Simpson et al. 1970), the 905-mb figure from an earlier drop was identified as the lowest sea level pressure for Camille. A footnote in Simpson et al. (1970, p. 295) said only, "Preliminary reports and other publications indicated a lowest pressure of 901 mb. Recently, a check of the raw data indicates this should be corrected to the 905-mb value given here." This footnote was ambiguous and could have meant two things: either that the earlier drop yielding a 905-mb pressure became the lowest pressure when the 901-mb reading was thrown out, or that the 901-mb reading was recalibrated to achieve a 905-mb reading. It appears that the decision was the former one, to use the 905-mb pressure from the aircraft reconnaissance flight 20 h earlier. There is no documentation on why the 901-mb sea

level pressure was rejected, nor was the decision clarified after contacting the surviving NHC hurricane forecasters from the 1969 hurricane season.

A review of the sonde data (Fig. SBI) indicates that the 850-mb geopotential height was 692 m. This is inconsistent with a 901-mb surface pressure based on comparison to other aircraft data and dropsondes. For example, an aircraft in the eye of 2005's Hurricane Wilma extrapolated a sea level pressure of 901 mb from an 850-mb height of 516 m—176 m lower than the height on the Camille sonde. Two other eye sondes from Camille reported 905- and 908-mb central pressures along with 850-mb heights of 551 and 586 m, respectively. The 850-mb heights from the Camille 905- and 908-mb sondes and the Wilma 901-mb extrapolation are all consistent, while the 850-mb height on the Camille "901-mb" sonde is an outlier.

Several methods were tried to better estimate the central pressure at the time of the 1815 UTC 17 Aug fix. These methods are summarized here.

Method 1.

A rule of thumb used at the NHC is that a 10-m change in the aircraft-reported 850-mb height roughly corresponds to a 1-mb change in the surface pressure. The 692-m height

of the "901-mb" dropsonde is 141 m higher than that of the 905-mb sonde and 106 m higher than that of the 908-mb sonde. This suggests a pressure of 918–919 mb as a first rough estimate.

Method 2.

Inside the eye, the aircraft reported a 700-mb geopotential height of 2390 m and a temperature of 16.6°C. Using standardized tables previously employed at NHC (OFCM 1997) for extrapolating the sea level pressure from these data using the standard environmental lapse rate yield an estimated minimum sea level pressure of 920 mb. It is notable that at the time of the 905-mb sonde, the aircraft reported a 700-mb height of 2240 m and a temperature of 22°C. Using the tables, these numbers yield an extrapolated pressure near 902 mb.

Method 3.

The sonde data (decoded in Table SBI, along with the calculated water vapor mixing ratio and equivalent temperature) were also used to determine sea level pressure using the hydrostatic equation. The mean equivalent temperature of the layer was taken from a skew *T* analysis to be about 27.0°C, or 300.2 K. The data were entered into the hydrostatic equation below:

$$\begin{aligned} \text{Pressure (sea level)} &= \text{Pressure} \times \exp[(\text{Gravity} \times \text{Geopotential height})/(\text{Gas constant for dry air} \times \text{Mean equivalent temperature})] \\ &= 700 \times \exp[(9.81 \text{ m s}^{-2} \times 2390 \text{ m})/287 \text{ K}^{-1} \times 300.2 \text{ K}] \\ &= 919 \text{ mb} \end{aligned}$$

TABLE SBI. Decoded Camille eye dropsonde data at 2125 UTC 17 Aug 1969.

Pressure (mb)	Temp (°C)	Dewpoint (°C)	Geopotential height (m)	Water vapor mixing ratio (g kg ⁻¹)	Equivalent temp (°C)
700	16.6	16.6	2390	14.3	19.0
732	19.4	18.4	—	17.5	22.3
850	28.0	26.7	692	27.0	32.5
874	29.4	27.8	—	27.0	33.9
901	30.8	28.3	—	28.0	35.9

Based upon the three methods, a central pressure of about 919 mb is estimated for 1800 UTC 17 August for Camille, with a derived intensity of 135 kt.

There are two questions about the "901-mb" sonde that are likely

unanswerable. First, E. Uhlhorn (2015, personal communication) indicates that a combination of a surface pressure of 919 mb, and surface temperature of 30.8°C, and a 28.0 g kg⁻¹ surface mixing ratio yields a surface θ_e of 382 K, which is 8 K warmer than other such

values in recent dropsondes. Was there an instrumentation error, or were these data representative of extreme conditions in Camille's eye? Second, did the sonde actually reach the surface?

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19410 33700 16600 51515 10168 07370

URXX KCHS 172140ZPOST FLIGHT SUMMARY
CAPT ZUBER AND CAPT WADAGNOLO
FIXED EYE 1815Z AT CORDINATES 28 DEGREES 12 MIN N 88 DEGREES 46 MIN W
WELL DEFINED EYE CLOSED WITH FEEDER BAND IN ALL QUADRANTS MAX SFC WINDS
OBSERVED IN SE QUADRANT OF 180 KTS PLUS MAX FL WND OBS SE QUAD AT
95 KTS MISSION ABORT 0000Z FIX DUE TO SHUTDOWN NO. FOUR ENGINE

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FIG. SBI. (top) Dropsonde coded message at 2125 UTC 17 Aug 1969 for the sonde released into the eye of Camille near 1815 UTC that day. (bottom) Postflight summary from the Air Force aircraft reconnaissance mission that launched this dropsonde. Images were obtained from the microfilm archives at the NHC library.

where a new eyewall forms outside the original small eyewall. This new eyewall then contracts as the old inner eyewall dissipates. Satellite imagery near the time of peak intensity on 16 August showed a remarkably distinct pinhole eye, which is often seen in an intense hurricane. However, Camille was still 28 h from landfall on the northern Gulf Coast and climatologically, if the environment remained favorable, an eyewall replacement would likely have occurred during that time. The existence of double/concentric eyewalls was known in 1969, as there is one documented radar fix report of a double eyewall for Camille, in reviewing all hourly radar fixes. However, the importance of the ERC—the cycle of temporary weakening followed by reintensification as the ERC completes and the new outer eyewall contracts—would not be fully understood until Willoughby et al. (1982).

The next and last reconnaissance flight into Camille occurred 18 h after 905 mb was measured. It is unknown if Camille intensified further during that time, which would have included the overnight diurnal convective maximum. It is also unknown when an ERC may have started. But 18 h later, there

was evidence of an ongoing ERC from four different sources: radar, reconnaissance, satellite imagery, and ground observations. In a serendipitous coincidence, on 17 August there are radar images from both Naval Air Station (NAS) Pensacola (2115 UTC) and NWS New Orleans (1732 UTC); a visible satellite image from 1953 UTC; and an aircraft penetration near 1815 UTC. Both radar images show a well-formed symmetric double eyewall (Figs. 3 and SB2a). In the description from the aircraft, “Just as we were near the [eye] wall cloud we suddenly broke into a clear area and could see the sea surface below,” the copilot, Robert Lee Clark, wrote in 1982” (Sheets and Williams 2001, p. 152). The clear area was possibly a moat that separated the inner and outer eyewalls. In addition, although faint, the visible satellite image shows what appears to be a moat (Fig. 6, bottom). Finally, observations from Freeport Sulphur Company at Garden Island Bay, Louisiana (near the mouth of the Mississippi River), at 2255 UTC 17 August noted, “the western eye would have been some ten miles distant [to the east]. However a brief lull was observed, with wind velocities dropping to 30–35 mph” (N. C. Roberts Jr. 1969, unpublished manuscript).

CAMILLE LANDFALL PRESSURES

A key parameter in analyzing tropical cyclones is the central pressure. Unfortunately, for Hurricane Camille, no aircraft reconnaissance flights were in the storm during the last several hours before it made landfall. Several pressure measurements obtained along the Mississippi coast were examined to determine which, if any, could provide a central pressure value for Camille.

Two pressures were measured at or near the time of eye passage in Bay St. Louis, 909 and 904 mb (26.85 and 26.70 in. Hg, respectively), and a pressure in the eyewall was measured in Pass Christian, Mississippi, 919 mb (27.15 in. Hg). The estimated distance between the 909- and 904-mb readings and the center of the eye is 3–4 n mi; that is to say, it was on the eastern edge of the small eye (which had a 10 n mi diameter, suggesting a radius of maximum wind of 6–8 n mi). The estimated distance between the Pass Christian eyewall pressure reading and the center of the eye is 7 n mi.

From NHC (1969) a letter detailing the 919-mb eyewall pressure reading in Pass Christian:

Mr. James Cagle, one of my co-workers here, took barometric readings at his home in Pass Christian during the passage of Camille. His lowest reading was 27.05 at 2330, August 17. I checked his aneroid barometer and found it to have a +0.10 error. Therefore the corrected reading should be 27.15. He also reports that there was no “lull” in his area... my own lowest reading of 29.28, [was]...30 miles east of the eye....

The two documented pressure readings in the eye were taken by Charles Breath, a boat dealer and mariner, who had a marine barometer in his home as well as a wall barometer. He logged pressure readings starting a couple days prior to the arrival of Camille and increased the frequency of the readings to hourly and then to half hourly as the hurricane approached landfall. The first low reading, the 909 mb, was taken just as the roof had partially come off and the family was

awaiting the arrival of the eye in order to evacuate to one of their other (rental) homes on their property farther back from the river bluff. He took the marine barometer with him, and once they had walked back to the rental property, took another reading, which was lower—the 904 mb. He provided the 904-mb reading to the MTF (today it is Stennis Space Center) meteorologists and to Nash and Ep Roberts.

Nash Roberts, a local New Orleans meteorologist, put out a request on-air for weather data, and there was a record that he was contacted by phone by Mr. Breath regarding the 904-mb reading (Loyola University 2001). The barometer and possibly the log were provided to Ep Roberts, Nash’s brother, a meteorologist as well, who had a store that sold meteorological instruments. The barometer was checked and found to be accurate. It is not known how NHC came to obtain the 909-mb measurement and why they did not use the 904 mb, but it could be that they went by the log, which had the 909 mb as the last entry.

A week after the storm, two MTF employees, meteorologists at the weather station there, talked to Mr. Breath while driving around the area observing damage and trying to determine the extent of the eye passage. At that time, he told them of the 904-mb reading and they documented it in their report (Mississippi Test Facility 1969):

Mr. Breath...always religiously kept up with the weather. His home was over 100 years old, but sturdily built of wood. Although most of the roof was blown off, the studs of the roof still stood...During the brief time they had in the “eye,” not more than 10 minutes, they evacuated to a home on higher ground.

He first observed his Aneroid type wall decorative barometer, scaled to 28 inches pressure when the pressure began plunging. He stated the needle just fell off rapidly beyond the 28 inch limit. In the turmoil, he remembered his Marine type barometer and went into another

room and observed it. During some time period when he knew he was in the “eye,” he read 26 point something, and later recalled that it was probably 26.7 inches pressure. He stated that this was a reading in the “eye” but possibly was not the lowest he observed.

An interview was conducted with Mr. Breath in 1979 (Pyle 1984) as part of the University of Southern Mississippi oral history program.

Mr. Pyle: As Hurricane Camille started to come up in the gulf that Sunday afternoon, your wife here has got a panoramic view of the gulf right out in front of you, what did you see? What did it look like, the atmosphere?

Mr. Breath: I have had through the years a habit of watching the barometer. I go more by the barometer than anything else. And I started taking hourly checks on it. And then when the barometer really started to fall, regardless of what we saw out in the gulf or whatever, we started really getting ready to leave. We knew something bad was coming up.

...

Mr. Pyle: How aware were you of the time you were in the house before you left?

Mr. Breath: Oh, I was watching closely because I was keeping this log, see. I was watching it close. I had a log in the beginning at every hour. And then as it would start falling more, I’d have it every half hour and make a recording of it.

...

Mr. Pyle: When you saw the barometer, when you could actually see it dropping, what were your thoughts? It might be hard to recall. I was just wondering if you were thinking about your family, your house—

Mr. Breath: Well, I just couldn't believe what I was seeing. Actually, I just [couldn't believe it].

Mr. Pyle: Did you ever question if your barometer was right?

Mr. Breath: Nash Roberts, who is a weather report man, had one of his men come over and interview me. He asked permission to take the barometer to have it checked in New Orleans to see if they were actually accurate, or whether I had made a mistake, or what. And I certainly agreed to it. They brought it back in a couple of weeks, and said that it was within a tenth of a point of being right, and that could be the difference between the sea level here and the sea level in New Orleans.

...

Mr. Pyle: And then, you took your last reading and left about what time?

Mr. Breath: Oh, probably about eleven-fifteen.

Mr. Pyle: And the reading then, for the record, was how low?

Mr. Breath: 26.85!

Mr. Pyle: Inches of mercury, that's terrifically [low]! [laughter]

Mr. Breath: And I feel sure that it dropped a little bit more than that, but that's what I actually have a record of.

In the University of Southern Mississippi interview, Mr. Breath states again that he obtained a lower reading but that he was not able to document it (probably not having brought the log back with him to the other property). It sounds like he meant the 26.70 in. Hg reading, as he says he "felt sure" the barometer fell lower than 26.85 in. Hg.

These 904-, 909-, and 919-mb pressure measurements are crucial for the assessment of a 900-mb central pressure analysis for Camille's landfall as described in the main text. They do highlight the importance of unofficial meteorological observations, even for a hurricane like Camille in a relatively recent era.

An ERC was in progress, but what could this mean for Camille's intensity at this time? Because the plane had radar and their observations focused on the inner eye, this suggests that radar reflectivity of the outer eye was weaker compared to the inner eye and that the inner eye was still the prominent feature. This suggests that the ERC was not complete.

A comparison of Camille to 2005's Hurricane Wilma (Pasch et al. 2006) is instructive, as it appears that the central pressures and inner-core structures may be quite similar. Figure 6 (top) shows Camille's and Wilma's satellite appearance when both storms were near peak intensity. The similarities between the satellite images of the two hurricanes include a very well-defined pinhole eye, smooth central dense overcast (CDO) with subsidence around the CDO, and similar CDO size. Figure 6 (bottom) shows both Camille and Wilma undergoing an eyewall replacement, likely at a similar stage of an eyewall replacement cycle. Both images show a moat between an outer eyewall and the still-well-defined inner eyewall. Wilma's pressure between the peak and the ongoing ERC had increased 10 mb from 882 to 892 mb. Therefore, it is logical for Camille's pressure at this time to have risen about 10 mb from the minimum of 905 mb. An analysis of the "901"-mb dropsonde suggests a central pressure of about 919 mb (see the sidebar "Camille's 901-mb dropsonde"). This is a rise in pressure of about 14 mb and is close

to the expected 10-mb rise in the comparison with Wilma.

Wilma's intensity decreased modestly from 160 to 140 kt at this stage of the ERC. Thus, it is logical for Camille's intensity to also have weakened slightly from its estimated 150-kt peak intensity. The re-analyzed central pressure of 919 mb, which is newly added into the 1800 UTC 17 August best-track time, suggests an intensity of 133 kt. Because of the intensity decrease from the ERC followed by reintensification, both the normal and weakening subsets of the Brown et al. (2006) pressure-wind relationships for north of 25°N latitude were used, with values of 133 and 127 kt, respectively. With the concentric eyewall structure, a low environmental pressure of 1008 mb for the outer closed isobar, a somewhat faster forward speed of 12 kt, and a continued tiny inner RMW, the best-track intensities for Camille are reduced to 135 kt at 1800 UTC 17 August and 140 kt at 0000 UTC 18 August. These are major changes downward from the original 165 kt. Unfortunately, no further aircraft reconnaissance fixes were available before landfall in the United States.

LANDFALL OF CAMILLE IN MISSISSIPPI.

Camille made landfall near Waveland, Mississippi, at 30.3°N, 89.4°W at 0400 UTC 18 August, based on radar fixes and pressure measurements at the coast (Fig. 1). The hurricane displayed a concentric eyewall

CAMILLE RADAR ANIMATION

For the first time, a radar loop of Hurricane Camille was constructed from archived radar imagery.

In the 1960s, U.S. Weather Bureau radar imagery could only be viewed in real time by the on-site radar operators. A radar coded message containing a center fix and a rough description of precipitative features was transmitted hourly to the NHC. This meant that with the exception of hurricanes within range of the collocated local Miami, Florida, radar, no real-time radar imagery of hurricanes was available to the hurricane specialists. Also, there was no real-time animation of radar data available, even to the radar operators. This is much different from modern-day radar data availability.

The WSR-57 radar had an archive capability with a camera automatically recording the radar image once per minute onto 16-mm film, independent of operator-controlled gain and other radar controls, and not including the transparency overlay of the surface map that the radar operator would change when changing the range of the radar. In August 1969, Camille was at different times within the range of a number of radars at Key West, Florida; Pensacola, Florida; Mobile, Alabama; Jackson, Mississippi; New Orleans, Louisiana; Baton Rouge, Louisiana; and Lake Charles, Louisiana. The best available archive images were from New Orleans, which fortunately was in a position to record imagery of the approach to the coast and the Mississippi landfall. These images were obtained from the National Climate Data Center (NCDC). Sets of two consecutive images, every 10 min, were photocopied from the plan position indicator (PPI) scope image, from 1630 UTC 17 August 1969 through 0730 UTC 18 August (Fig. SB2, top).

To utilize the radar images, the 1969 radar location needed to be determined, and a surface map was created based on the 50 n mi range rings available in the radar data. This map was then precisely overlaid on each radar image (Fig. SB2, bottom), which were subsequently incorporated into a GIF animation.

The entire loop can be viewed in the provided supplemental material.

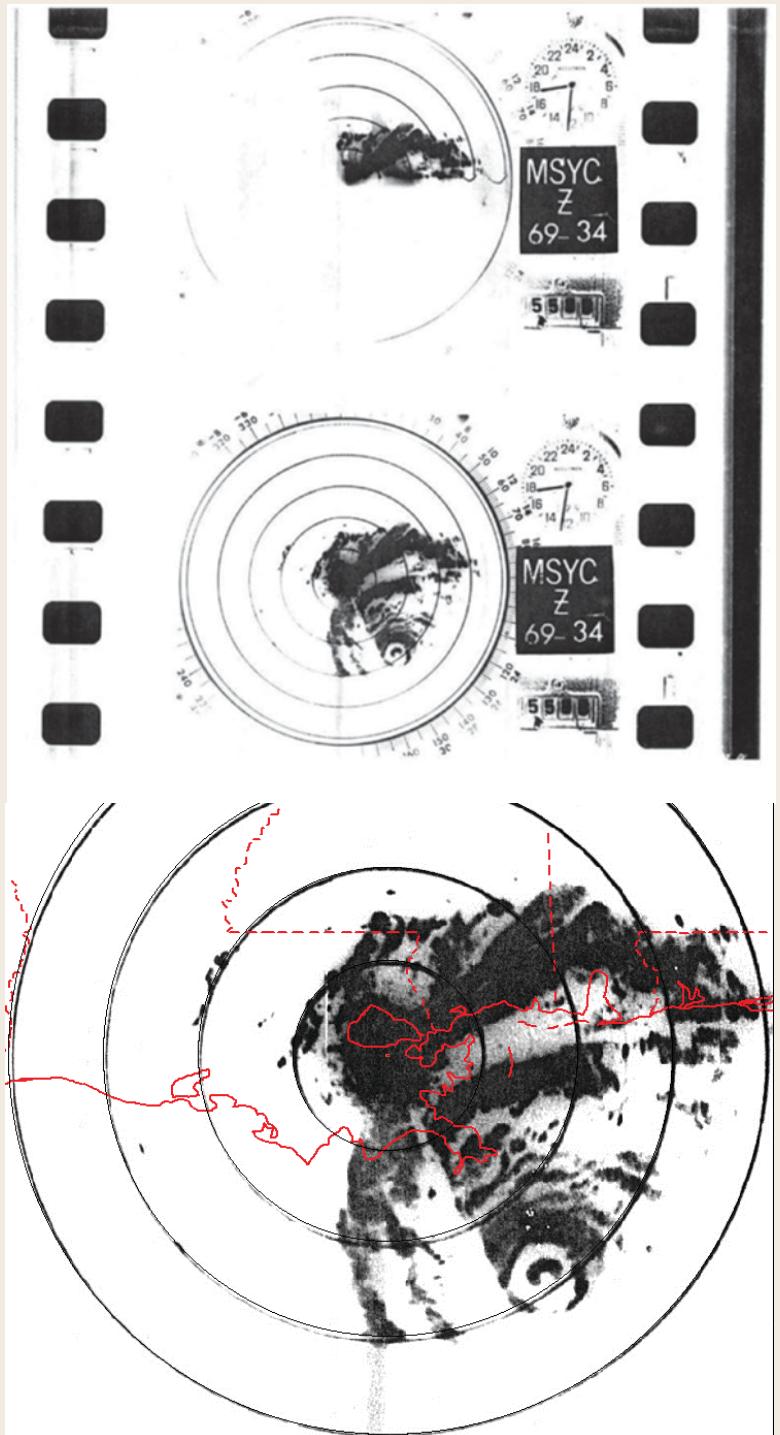


FIG. SB2. (top) Sample of the photocopy of the PPI scope WSR-57 radar from New Orleans of Hurricane Camille at 1732 UTC 17 Aug 1969. (bottom) Subsequent radar image with the map overlay and scaling.

structure with circular eyes with diameters of 10 and 30 n mi with some additional prominent banding at larger radii. The inner eye near the time of landfall could be considered elliptical with a major axis of 12 n mi oriented northwest–southeast and a minor axis of 8 n mi (N. C. Roberts Jr. 1969, unpublished manuscript). The POCI at landfall was a very low 1004 mb, but the hurricane was also quite tiny with an ROCI of 150 n mi. Camille’s forward speed had increased to about 15 kt at the time of landfall.

The discovery of additional landfall pressures and radar imagery from the New Orleans Weather Bureau Office aided analysis of the Mississippi landfall. There were three pressure values of interest near the point of landfall. A pressure of 909 mb was measured by Mr. Charles Breath at the onset of the eye in his home just west of the bridge in Bay St. Louis, Mississippi, which was about 3–4 n mi east of the landfall point. This marine aneroid barometer was subsequently tested and determined to be accurately calibrated. The 909-mb value had been the accepted central pressure value at landfall originally as shown in HURDAT2 and discussed in Simpson et al. (1970). However, Mr. Breath also measured a 904-mb pressure at a later point in the eye passage a short distance west of the first measurement (see the sidebar “Camille landfall pressures” for additional discussion about this 904-mb measurement), in one of his rental properties behind his damaged house, as reported by N. C. Roberts Jr. (1969, unpublished manuscript) and confirmed in interviews of the Breath family (Breath 2007). In addition, N. C. Roberts Jr. (1969, unpublished manuscript) documents an even lower value of 897-mb pressure reading, also in Bay St. Louis, with additional details on its location and time from the Loyola University archives of Roberts’s records. However, there is no documentation on the accuracy of the instrument and this barometer could not be located today. Moreover, the value provided in inches of mercury—26.50 in.—appears to be rounded to the nearest 0.5 in. Thus, this value cannot be assumed to be completely accurate. Given that the 904-mb pressure reading was taken near the eastern edge of the eye, a 900-mb central pressure is analyzed at landfall. It is of interest that this corresponds closely to the 901 mb that N. C. Roberts Jr. (1969, unpublished manuscript) analyzed as the central pressure, taking a mix of the Waveland–Lakeshore–Bay St. Louis observations.

This central pressure of 900 mb—a roughly 20-mb decrease in the 10 h since the last aircraft data—shows Camille was strengthening at landfall, possibly because of the end of the ERC. Brown et al. (2006) suggest maximum sustained winds at landfall

of 148 kt using the standard relationship or 155 kt using the intensifying subset north of 25°N. Given the competing factors of a tiny RMW of approximately 6–8 n mi and a moderate forward speed of 15 kt, but a very low pressure of the outer closed isobar of 1004 mb, an intensity of 150 kt is reanalyzed for the time of landfall (a graph of the previous and reanalyzed best-track intensities is provided in Fig. 7). The 150 kt at landfall show Camille as a category 5 hurricane at landfall in Mississippi. This intensity assessment confirms the original indication of Camille as a category 5 striking the United States (Hebert and Taylor 1978).

The intensity changes of Camille on 16 and 17 August appear similar to those of 1992’s Hurricane Andrew on 23 and 24 August. Andrew reached an initial peak intensity of 150 kt with a 922-mb central pressure near 1800 UTC 23 August (Landsea et al. 2004a). After this, an ERC commenced with the winds decreasing to 125 kt and the pressure rising to 941 mb early on 24 August.¹ As the ERC completed, Andrew rapidly reintensified to an intensity of 145 kt and a central pressure of 922 mb as it made landfall in southern Florida near 0900 UTC 24 August.

Additional indirect support for the landfall intensity comes from inland observations and use of

¹ Aircraft data documenting the ERC available online (http://verif.rap.ucar.edu/jntweb/tcdata/vortex/sources/raw_VDMs_v1.000/1992/vortex_AL041992_ANDREW.txt).

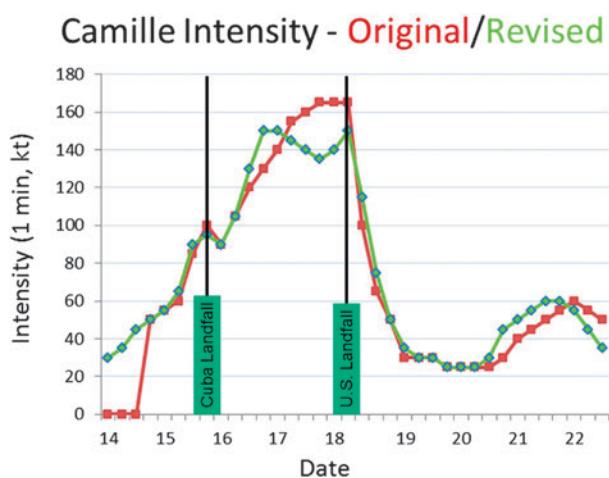


FIG. 7. Original (red) and revised (light green) intensity of Camille. Intensity is the analyzed maximum 1-min surface wind associated with the circulation of the TC. Camille’s landfalls in Cuba and in the United States are indicated with the black vertical lines.

TABLE 1. The official revisions for Hurricane Camille in the 6-hourly HURDAT2, 14–22 Aug 1969, which have been approved by the Best-Track Change Committee. Changes are listed in boldface with the original best-track value, if existing, in parentheses. Three new best-track entries were added at the beginning, and two new nonsynoptic-time landfall entries were added for the Cuba and Mississippi landfalls. There were no significant position changes.

Time and date	Lat (°N)	Lon (°W)	Max wind speed (kt)	Central pressure (mb)	Storm status
0000 UTC 14 Aug	18.3	79.7	30	—	Tropical depression
0600 UTC 14 Aug	18.5	80.5	35	—	Tropical storm
1200 UTC 14 Aug	18.8	81.3	45	—	Tropical storm
1800 UTC 14 Aug	19.1 (19.4)	82.0	50	991	Tropical storm
0000 UTC 15 Aug	19.5 (19.7)	82.7	55	991	Tropical storm
0600 UTC 15 Aug	20.0 (20.1)	83.3	65 (60)	—	Hurricane
1200 UTC 15 Aug	20.6 (20.7)	83.8	90 (85)	969 (970)	Hurricane
1800 UTC 15 Aug	21.3 (21.2)	84.1	95 (100)	966 (964)	Hurricane
2200 UTC 15 Aug	21.9	84.3	95	—	Landfall over western Cuba
0000 UTC 16 Aug	22.3	84.4	90	—	Hurricane
0600 UTC 16 Aug	23.1	85.2	105	—	Hurricane
1200 UTC 16 Aug	23.8 (23.7)	86.0 (85.9)	130 (120)	—	Hurricane
1800 UTC 16 Aug	24.3 (24.2)	86.6 (86.5)	150 (130)	908	Hurricane
0000 UTC 17 Aug	25.2	87.2	150 (140)	905	Hurricane
0600 UTC 17 Aug	26.0	87.7	145 (155)	—	Hurricane
1200 UTC 17 Aug	27.0	88.3 (88.2)	140 (160)	—	Hurricane
1800 UTC 17 Aug	28.2 (28.3)	88.7	135 (165)	919	Hurricane
0000 UTC 18 Aug	29.4	89.0 (89.1)	140 (165)	909	Hurricane
0400 UTC 18 Aug	30.3	89.4	150	900	Landfall near Waveland, MS
0600 UTC 18 Aug	30.7	89.6	115 (100)	—	Hurricane
1200 UTC 18 Aug	32.0 (32.2)	89.9 (90.0)	75 (65)	—	Hurricane
1800 UTC 18 Aug	33.4	90.1	50	—	Tropical storm
0000 UTC 19 Aug	34.7	90.0	35 (30)	—	Tropical storm
0600 UTC 19 Aug	36.0	89.3	30	—	Tropical depression
1200 UTC 19 Aug	37.0	88.0	30	—	Tropical depression
1800 UTC 19 Aug	37.6 (37.7)	86.0	25	—	Tropical depression
0000 UTC 20 Aug	37.6 (38.0)	84.0 (84.8)	25	—	Tropical depression

TABLE I. Continued.

Time and date	Lat (°N)	Lon (°W)	Max wind speed (kt)	Central pressure (mb)	Storm status
0600 UTC 20 Aug	37.4	80.6 (80.2)	25	—	Tropical depression
1200 UTC 20 Aug	37.2 (37.3)	77.3 (77.0)	30 (25)	—	Tropical depression
1800 UTC 20 Aug	37.0	75.3 (75.1)	45 (30)	1000	Tropical storm
0000 UTC 21 Aug	36.7 (36.6)	73.6 (73.4)	50 (40)	—	Tropical storm
0600 UTC 21 Aug	36.7	70.9	55 (45)	—	Tropical storm
1200 UTC 21 Aug	37.1 (37.3)	68.1 (68.4)	60 (50)	—	Tropical storm
1800 UTC 21 Aug	37.8 (38.0)	64.7 (64.9)	60 (55)	—	Tropical storm
0000 UTC 22 Aug	39.2	61.8 (61.4)	55 (60)	—	Tropical storm
0600 UTC 22 Aug	40.8	58.2	45 (55)	—	Tropical storm
1200 UTC 22 Aug	43.0	54.0	35 (50)	—	Extratropical storm

the Kaplan and DeMaria (1995) inland decay model for TCs. Columbia, Mississippi, reported a “fastest mile” sustained wind of 104 kt about 4 h after landfall in or near the RMW. This value adjusts to 99 kt in converting to a peak 1-min wind (Powell et al. 1996). Application of the Kaplan–DeMaria model with a landfall intensity of 150 kt yields a value of 101 kt, which is close to the Columbia observation.

Other than the observation in Columbia, no anemometer measurement recorded extreme winds near the RMW, mainly because of the lack of anemometers in the landfall area. The highest observed sustained (roughly 10 min) winds in Camille were 113 kt, at which point the anemometer failed, at the Transworld drilling rig block 92 about halfway between the mouth of the Mississippi River and the Mississippi coast, at some point during the eye passage to the east. This measurement was almost certainly higher than 10 m above the ocean, but its exact altitude is unknown.

With the movement of Camille across the marshlands of northeastern St. Bernard Parish, Louisiana, category 5 winds are assessed to have occurred in Louisiana as well as Mississippi. Runs of the Schwerdt et al. (1979) parametric hurricane wind model suggest maximum sustained winds of 75–80 kt in far southwestern Alabama. Category 1 winds for Alabama would be consistent with the impacts observed just west of there in Pascagoula, Mississippi.

The original best track showed a brief landfall in southeastern Louisiana near the mouth of the Mississippi River just before 0000 UTC 18 August (Table 1). However, the numerous radar fixes available indicated that the center of the hurricane remained just offshore, which is consistent with the radar-based track shown in the *Preliminary Report* (Weather Bureau 1969). Camille passed over the marshy regions of northeastern St. Bernard Parish around 0230–0330 UTC 18 August, but no landfall point is indicated here because of the lack of dry land in the vicinity.

It should be noted that the original HURDAT format did not allow for nonsynoptic best-track points. The new HURDAT2 format allows for this, so that position and intensity at landfall can be accurately documented.

EXTRATROPICAL TRANSITION AND DISSIPATION OF CAMILLE.

The original best track did not indicate an extratropical stage occurred in Camille; however, Simpson et al. (1970) stated that extratropical transition (ET) did occur. Data examined during the reanalysis show that Camille became embedded within a frontal boundary by 1200 UTC 22 August and ET occurred at that time. The best track has been updated to clarify this by indicating ET at 1200 UTC 22 August. No change was introduced to the timing of Camille’s dissipation, which occurred just after extratropical transition.

COMPARISONS OF CAMILLE WITH OTHER U.S. CATEGORY 5 HURRICANES.

Three other category 5 Atlantic basin hurricanes are known to have struck the United States: the 1928 “San Felipe” hurricane in Puerto Rico, the 1935 “Labor Day” hurricane in the Florida Keys, and 1992’s Hurricane Andrew in southeast Florida. This record of U.S. category 5 hurricanes is likely complete since 1900. However, before that time, coastal U.S. populations were quite sparse—especially in parts of Florida, Louisiana, and Texas—and a category 5 could have struck the coast but not been recognized as such, or may have even been missed completely as one goes farther back in time. In comparing the MSLP and landfall intensity of these category 5 hurricanes, Camille, at 900 mb and 150 kt, ranks in intensity for U.S. hurricanes just below the 1935 Labor Day hurricane, at 892 mb and 160 kt (Landsea et al. 2014); however, it is slightly stronger than Andrew in 1992, at 922 mb and 145 kt (Landsea et al. 2004a), and the 1928 San Felipe hurricane in Puerto Rico, at 931 mb and 140 kt (Landsea et al. 2012), for strongest hurricanes at landfall.

SUMMARY. A reassessment of Hurricane Camille has introduced a number of significant changes into the best-track database:

Genesis time changed to 18 h earlier than originally indicated, at 0000 UTC 14 August.

Major intensity changes of least 20 kt from the original best-track values were introduced for Camille’s intensity at these time periods:

- an increase from 130 to 150 kt at 1800 UTC 16 August;
- a decrease from 160 to 140 kt at 1200 UTC 17 August;
- a decrease from 165 to 135 kt at 1800 UTC 17 August; and
- a decrease from 165 to 140 kt at 0000 UTC 18 August.

Additional intensity changes include reductions in the peak intensity of Camille from 165 to 150 kt and the timing of the peak intensity:

- previous peak intensity of 165 kt was just prior to the Mississippi landfall, at best-track points 1800 UTC 17 August and 0000 UTC 18 August;
- new peak intensity of 150 kt in the Gulf of Mexico at the time of the 908- and 905-mb readings, at 1800 UTC 16 August and 0000 UTC 17 August; and

- the peak intensity of 150 kt was reached again at the time of the Mississippi landfall at 0400 UTC 18 August.

At U.S. landfall at Waveland, Mississippi, at 0400 UTC 18 August, Camille is assessed to have struck with a central pressure of around 900 mb and an intensity of 150 kt. This is deeper but slightly weaker than the original 909-mb and 165-kt landfall intensity implied by the last entry in HURDAT2 before landfall at 0000 UTC 18 August.

A brief extratropical cyclone stage was formally documented at the last point in Camille’s life cycle at 1200 UTC 22 August, but no change to the dissipation timing was indicated.

No major changes were introduced for the track of Camille.

The reanalysis of Camille reconfirms that the devastating hurricane came ashore as a category 5 on the Saffir–Simpson hurricane wind scale, but it is now considered to be the second-most-intense hurricane in the United States’ record. After Camille’s revision, it is not anticipated that any other single storm will be reassessed out of sequence, as this completes analysis of all category 5 U.S.-landfalling hurricanes. The Atlantic Hurricane Database Reanalysis Project will continue to revise the HURDAT2 database through the end of the twentieth century and provide official updates to the database’s roughly 10 hurricane seasons every calendar year.

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