THE AUGUST 2007 HEAT WAVE IN NORTH CAROLINA: METEOROLOGICAL FACTORS AND LOCAL VARIABILITY

Christopher M. Fuhrmann, Charles E. Konrad II,
Margaret M. Kovach, and D.J. Perkins
Southeast Regional Climate Center
Department of Geography
Saunders Hall CB #3220
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599-3220

Abstract: August 2007 was an exceptionally warm month across North Carolina. Hundreds of daily maximum and daily high minimum temperature records, as well as numerous all-time temperature records, were either tied or broken during the month. At the same time, a drought of historic proportions overspread much of the Southeast United States. A critical aspect of the August 2007 heat wave was the observed variability in heat and humidity across the different geographic regions of North Carolina. The highest maximum temperatures occurred most frequently in the Piedmont and Sandhills regions, while minimum temperatures were exceptionally high along the coast. The broad-scale pattern of heat can be tied to adiabatic warming associated with subsidence downstream of a persistent upper-level ridge centered over the Mississippi River Valley. Regional to local variations in the heat and humidity across North Carolina are linked to upwind sensible heat fluxes associated with major soil moisture deficits, adiabatic warming connected with downsloping winds off the Appalachian Mountains, and the depth of the mixing layer. Along the coast, the pattern of heat and humidity was tied to the positioning of a mesoscale thermal trough and the presence and strength of the sea-breeze circulation. [Keywords: heat wave, North Carolina, back-trajectories, air mass, drought, thermal trough, vertical mixing.]

INTRODUCTION

The calendar year 2007 was recorded as one of the warmest on record across the contiguous United States (Heim et al., 2008). In particular, the month of August was exceptionally warm compared to climatology (third warmest August on record). Nine states, including five in the Southeast region (North Carolina, South Carolina, Georgia, Florida, and Alabama), experienced record warmth for the month (Fig. 1A). The anomalous warmth in August also coincided with a drought of historic proportions across the Southeast region (Heim et al., 2008) that reached peak intensity in November (Maxwell and Soulé, 2009). For the state of North Carolina, August 2007 was the all-time warmest (Fig. 1A) and second driest (in terms of precipitation) August on record (Fig. 1B). Over 30 all-time daily maximum and minimum temperature records were tied or broken across North Carolina during the month (NCDC, 2007).

The cumulative effects of the heat and drought resulted in numerous societal impacts across the state, including agricultural losses, severe water shortages, and

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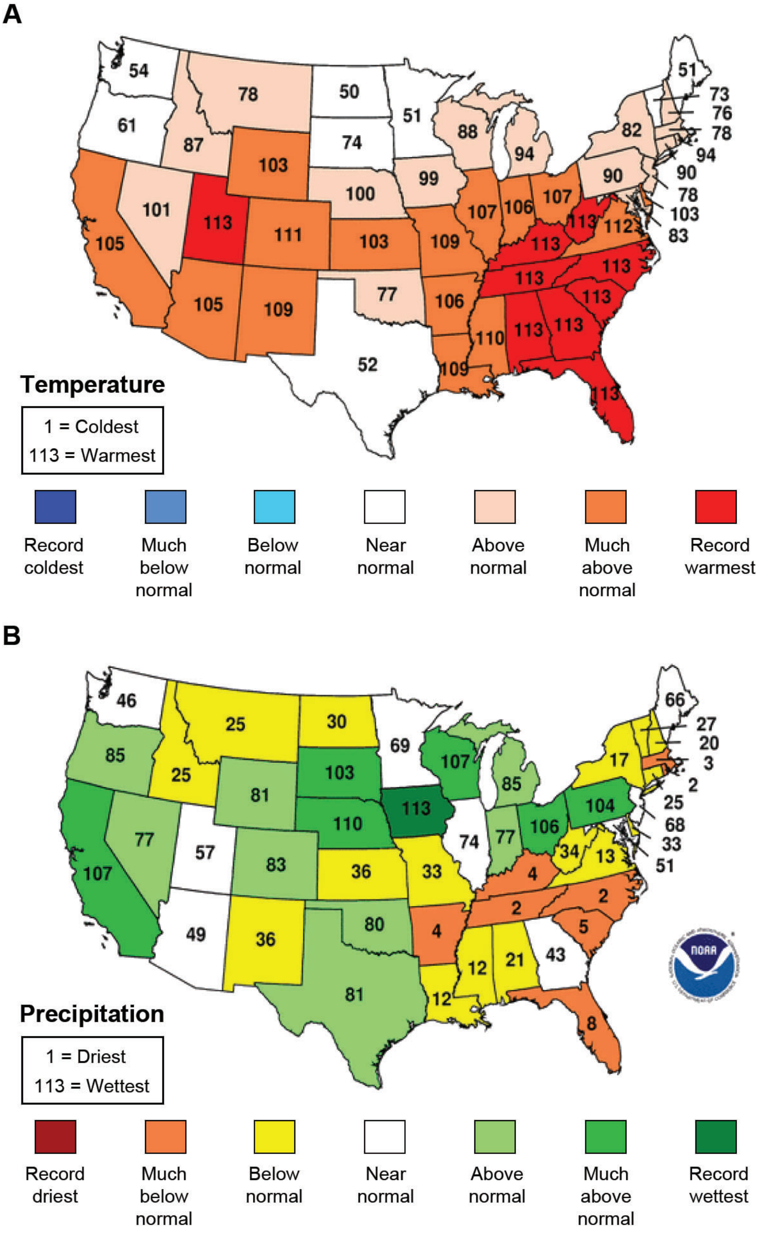

Fig. 1. Statewide ranks of (A) temperature and (B) precipitation for August 2007. The number within the state represents that state's ranking for the given period, compared with all other such periods for that state for the 1895–2007 period of record (113 years). A ranking of 113 equals the warmest or wettest August, while a ranking of 1 equals the coolest or driest August. Figures were constructed by the National Climatic Data Center as part of their monthly State of the Climate report (http://www.ncdc.noaa.gov/sotc/).

record energy consumption. Major reductions in pasture and hay production made it difficult for farmers to feed their livestock, and this forced as many as 85 counties in North Carolina to apply for national disaster relief (USDA, 2007). As reservoir levels and stream discharges were reduced, many localities were forced to implement restrictions to conserve water resources for industry and power generation (Maxwell and Soulé, 2009). Moreover, increases in water temperature in the Catawba River in the western part of the state forced Duke Energy to severely curtail power generation at coal and hydro-electric plants along the river (Beahears, 2007). During the afternoon of 9 August, the hottest period of the month, both Progress Energy and Duke Energy, the two largest power suppliers for the state, recorded all-time record daily megawatt hours consumed (Staff Writers, 2007a). Unfortunately, the increased demand for energy proved deadly in some cases. A 10 month-old child in Lincoln County outside Charlotte died in a house fire caused by an overheated extension cord that was attempting to power a large air conditioning unit (Bright, 2007). Though cooling shelters were opened across the state to accommodate those without power or air conditioning, many individuals required treatment for heat-related illness during the month of August (Bloom, 2007). One of the more publicized stories was that of a high school cross-country runner who collapsed due to heat exhaustion during a meet in Raleigh (Staff Writers, 2007b). The runner spent numerous days recovering in the hospital and the story of the hazard faced by athletes when performing in warm weather brought almost unprecedented attention to the region.

Despite its proximity to the Atlantic Ocean, Gulf of Mexico, and prevailing southwesterly winds around the Bermuda High, only about half of all summer days in North Carolina are dominated by a maritime tropical weather regime, or air mass (i.e., an "MT" designation in the Spatial Synoptic Classification; see Sheridan, 2002). Therefore, any given summer day can yield one of several combinations of temperature (e.g., warm or hot) and humidity (e.g., humid or dry) (Table 1). Despite this variability, there has been relatively little research conducted on the variations in the intensity and duration of high temperatures and high humidity or on the combination of atmospheric and surface conditions that contribute to periods of excessive heat and humidity. Chen and Konrad (2006) conducted a synoptic climatology of summer temperatures in central North Carolina and identified the large-scale circulation and boundary layer conditions that distinguish summer days on the basis of temperature extremes and humidity. However, it is unclear whether these results could be applied to other regions of the state (i.e., mountains, coast).

In this study, we analyze the meteorological characteristics of the August 2007 heat wave and their variability across North Carolina and focus on the following research questions: (1) How did the intensity of the heat and humidity vary throughout the month and across the state (from the mountains to the coast)? (2) What were the atmospheric features, meteorological processes, and surface conditions that mediated the pattern of the heat and humidity across the state? Because the objective of this study is to examine the local-scale character of extreme heat and humidity, we chose to focus our analysis on a single state with geographically diverse regions.

Table 1. Number of Days in August 2007 Classified into Each Air Mass Type Compared to August Climatology of 1948–2000

Air mass[a]	Asheville		Raleigh-Durham		Wilmington	
	Climatology	Aug 2007	Climatology	Aug 2007	Climatology	Aug 2007
DM	8	23	6	1	3	10
DP	2	0	< 1	0	< 1	0
DT	< 1	0	2	20	< 1	0
MM	9	0	6	0	10	0
MP	< 1	0	< 1	0	< 1	0
MT	10	8	13	9	17	18
TR	1	0	3	1	< 1	3

[a]Air mass abbreviations: DM = dry moderate; DP = dry polar; DT = dry tropical; MM = moist moderate; MP = moist polar; MT = maritime tropical; TR = transition.

DATA AND METHODS

Daily values of maximum and minimum temperature from a sample of weather stations in the Cooperative Observer network (Fig. 2) were used to identify the spatial and temporal patterns of heat and humidity across North Carolina. Because average temperatures vary considerably across the state, the percentile values were calculated on a station-by-station basis so that comparisons could be made across physiographic regions. Past studies have identified heat waves on the basis of percentiles (e.g., Hajat et al., 2002; Beniston, 2004; Gosling et al., 2007; Gershunov et al., 2009). Because of the extraordinary nature of daily maximum and minimum temperatures observed across North Carolina in August 2007, we focused our analysis only on days that exceeded the 95th, 99th, and 99.5th percentiles. Minimum temperatures and nighttime dew point temperatures are highly correlated; therefore, minimum temperatures provide a reasonable estimate of humidity near the surface. The selected stations have sufficiently long periods of record and provide good spatial coverage of the major physiographic regions of the state (i.e., mountains, Piedmont, and coast; Fig. 2).

Composites of synoptic-scale features and conditions (i.e., 500 mb geopotential heights, 850 mb air temperatures) were produced using data from the North American Regional Reanalysis (NARR; Mesinger et al., 2006). The NARR is a long-term, dynamically consistent, data assimilation–based collection of climate data for North America and provides analysis beginning in 1979. It is an improvement over earlier global reanalysis datasets in terms of accuracy and has a horizontal resolution (i.e., grid spacing) of 32 km. Anomalies in the synoptic fields were calculated from a 23-year baseline period (1979–2001).

The variability in heat and humidity across North Carolina was also assessed using air mass type data from the Spatial Synoptic Classification (SSC; Sheridan, 2002). The SSC utilizes temperature, dew point, cloud cover, and wind observations from

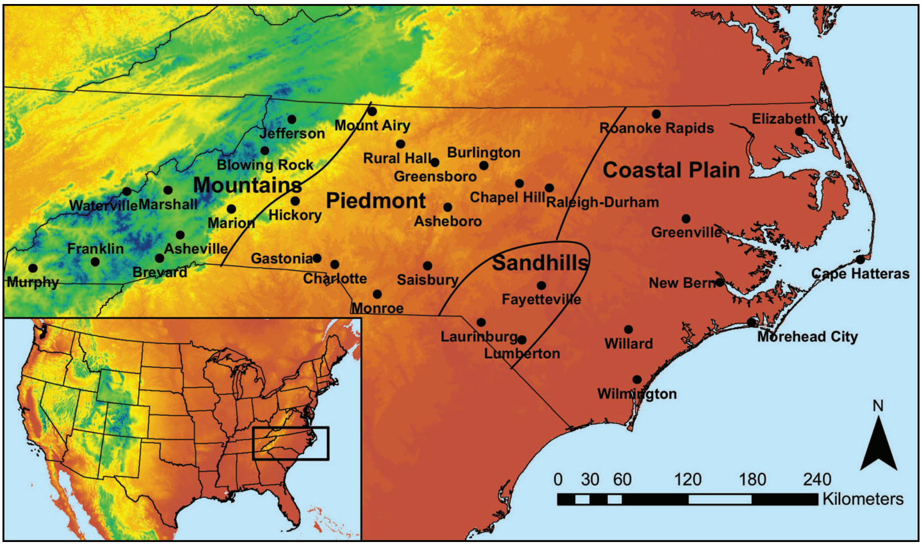

Fig. 2. Map of the study area with locations of selected weather stations.

first-order weather stations to classify days into one of six air mass types: dry polar (DP; synonymous with traditional continental polar air), dry tropical (DT; synonymous with traditional continental tropical air), moist polar (MP; synonymous with traditional maritime polar air), maritime tropical (MT), dry moderate (DM; cooler than DT air), and moist moderate (MM; cooler than MT air). A seventh category, transitional (TR), is applied to days during a period of transition between two air masses. Air mass data were retrieved from the first-order stations at Asheville, NC (mountains), Raleigh-Durham, NC (Piedmont), and Wilmington, NC (coast).

Three-day (72-hour) back trajectories of air parcels arriving into North Carolina were calculated using the NOAA–Air Resources Laboratory Hybrid Single-Particle Lagrangian Integrated Trajectory tool (HYSPLIT; Draxler and Rolph, 2010). Trajectory analysis is a common method for examining three-dimensional atmospheric flow patterns (i.e., horizontal advection and vertical motion). Details on the HYSPLIT tool can be found in Draxler and Hess (2004), while a comprehensive discussion of trajectory analysis and its limitations can be found in Stohl (1998). A version of the Eta Data Assimilation System was utilized to calculate trajectories in HYSPLIT.

HEAT WAVE CHARACTER AND SYNOPTIC SETTING

The spatial and temporal pattern of heat and humidity showed much variability across North Carolina during the month of August 2007 (Fig. 3). The period from 6–10 August was the most extreme with respect to temperature and duration, and it affected nearly the entire state. Approximately half of the daily maximum and daily high minimum temperature records during the month occurred over this five-day period (NCDC, 2007). Some locations in the Sandhills (i.e., Lumberton, Fayetteville,

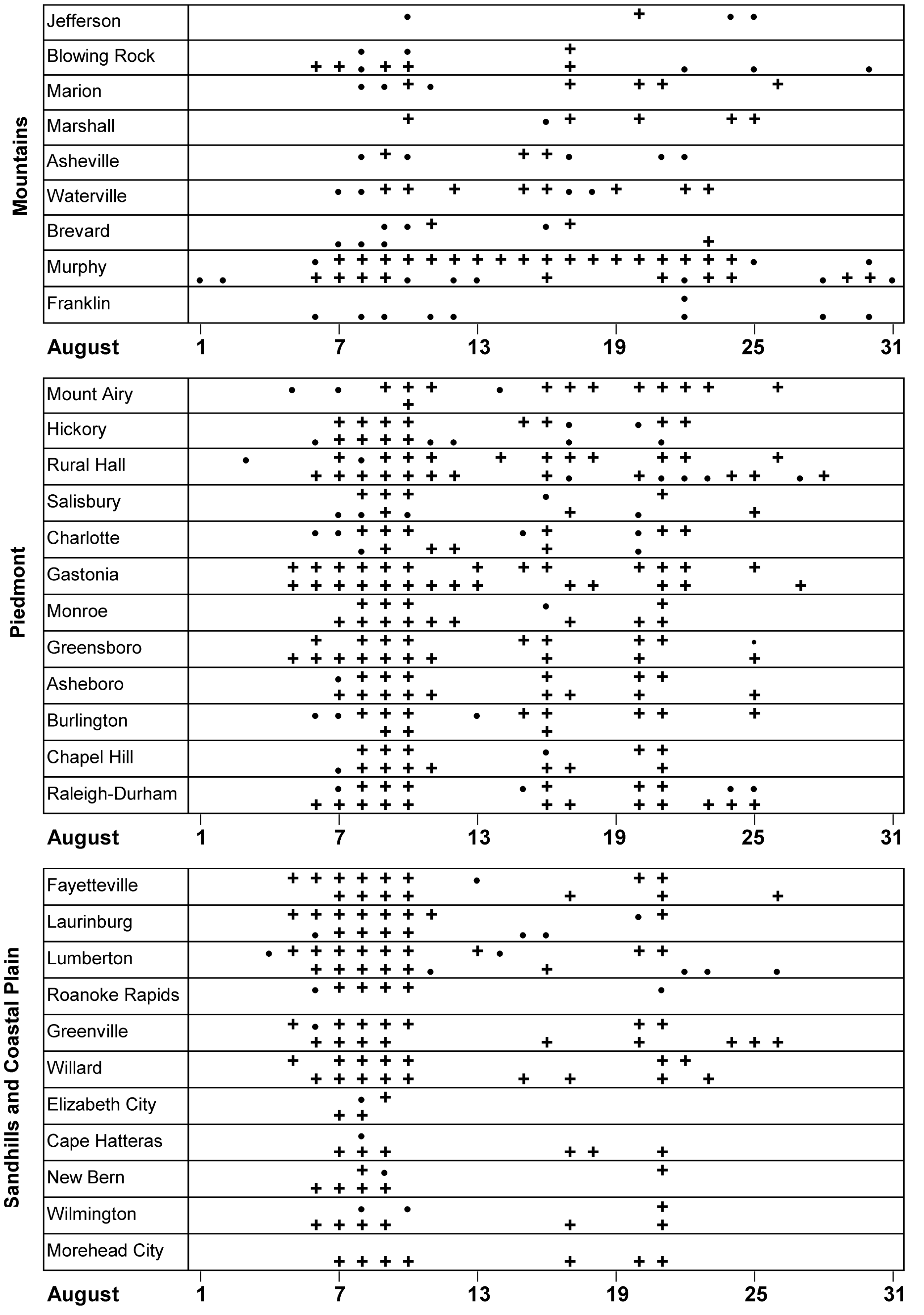

Fig. 3. Temporal distribution of daily maximum and minimum temperature extremes across the major physiographic regions of North Carolina in August 2007. Black dots (crosses) denote daily maximum (top row) or minimum (bottom row) temperatures in the 99th (crosses: 99.5th) percentile of all summer season (June–August) daily maximum or minimum temperatures at each station. Station locations are illustrated in Figure 2.

and Laurinburg) and the inner Coastal Plain observed exceptionally warm daily maximum temperatures as early as 4 August, resulting in a week-long heat event at those locations. The duration of excessively high temperatures during this period was also noteworthy. Remarkably, the first-order station at the Wilmington airport experienced a streak of 77 consecutive hours from 7–10 August in which the heat index equaled or exceeded 32° C. This shattered the previous record of 43 consecutive hours set back in August 1983 and again in August 1998. The passage of a cold front on 11 August moderated daytime temperatures across much of North Carolina, but the associated cloud cover likely contributed to the warm minimum temperatures observed in some Piedmont locations. A second cold front passed through the state on 14 August and resulted in a temporary return to more seasonable temperatures.

The second period of hot weather occurred from 16–17 August and primarily affected the Piedmont and the mountains, though minimum temperatures along the coast (i.e., Wilmington, Cape Hatteras, and Morehead City) were unusually high. The passage of a cold front on 18 August signaled a return to seasonable temperatures for a few days, but this respite quickly gave way to a third period of extreme heat on 20–22 August. This period was more humid in many places; in fact, more daily record high minimum temperatures than record maximum temperatures were measured during the first two days of this heat event (NCDC, 2007). Raleigh-Durham tied its all-time record maximum temperature of 41° C (105° F) on 21 August. There were fewer exceptionally hot days during the final week of the month and these were primarily confined to locations in the Piedmont and the mountains. The final week of August was also humid in places, with minimum temperatures in the 99th percentile at Raleigh-Durham, Rural Hall, Gastonia, Greenville, and Fayetteville.

During the month, locations in the Piedmont and Sandhills experienced the greatest number of days with exceptionally high maximum and minimum temperatures, while coastal locations saw more exceptionally high minimum temperatures than maximum temperatures (Fig. 4). By comparison, most mountain locations saw fewer days with exceptionally warm minimum temperatures. One obvious exception to the general pattern of temperatures observed over the month was at Murphy, located in the southwest corner of North Carolina (Fig. 2), where daily maximum temperatures exceeded the 99th percentile on more than half of the days in August 2007 (Figs. 3 and 4). This was particularly noteworthy during the middle of the month, when temperatures across the rest of the state returned to near normal for a brief period and Murphy remained exceptionally warm. We examine the likely causes of this unusual temperature pattern at Murphy in the next section of the paper. At least part of the variability in daily temperatures exhibited across North Carolina may be due to local-scale effects (e.g., topographic features, land cover, soil types). This is particularly the case in the mountains, where the lack of exceptionally warm overnight temperatures appears to be tied to the valley location of the weather stations (i.e., Jefferson, Marion, Marshall, Asheville, Waterville) and nocturnal cold-air drainage from the higher terrain. The occurrence of exceptionally warm overnight temperatures at Blowing Rock, located on a ridge along the Continental Divide at over 1 km elevation, further supports this notion.

An examination of air mass frequencies at Asheville and Wilmington reveals a greater number of days in August 2007 that were drier compared to climatology,

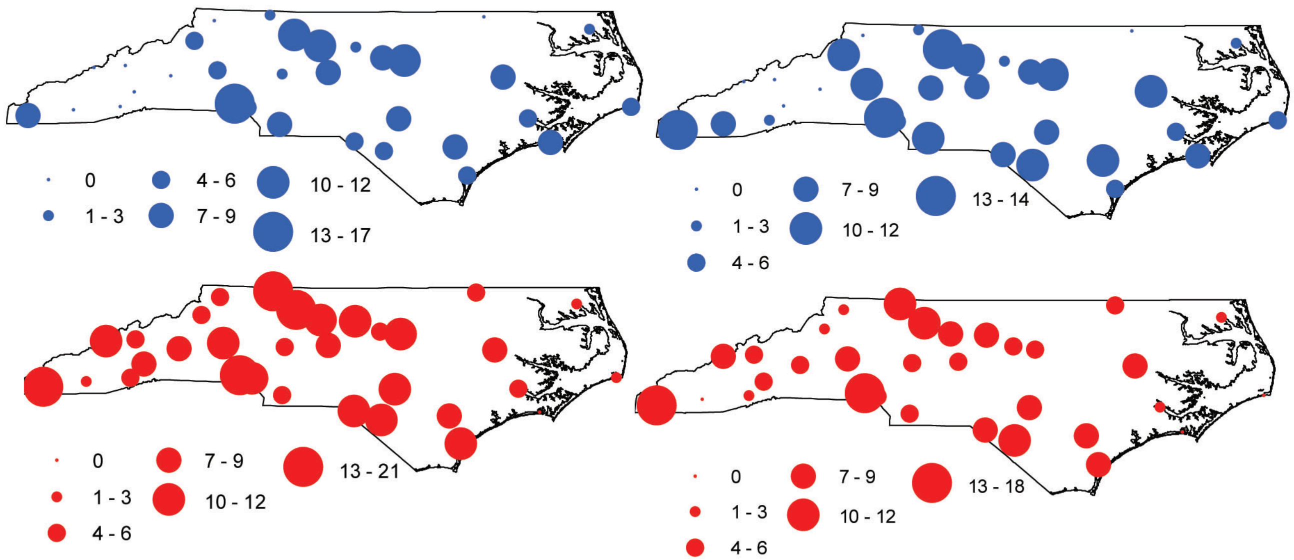

Fig. 4. Graduated circle maps indicating the number of days in August 2007 when daily minimum (top) and daily maximum (bottom) temperatures exceeded the 95th percentile (left panel) and 99th percentile (right panel) of all daily summertime maximum and minimum temperatures.

while at Raleigh-Durham, a greater number of days were both drier and warmer compared to climatology (Table 1). Specifically, in the case of Asheville and Wilmington, days classified as moist-moderate (MM) were replaced by dry-moderate (DM) air masses, while at Raleigh-Durham, the MM and DM air masses were replaced by dry-tropical (DT) air masses. The DT air mass typically represents the hottest and driest conditions at mid-latitude locations (Sheridan, 2002).

Analysis of the 500 mb geopotential height and 850 hPa temperature fields during August 2007 reveals significant synoptic-scale anomalies over North Carolina. The first period of hot weather from 6–10 August was tied to an upper-level ridge centered over the lower Mississippi River Valley (Fig. 5B) with positive height anomalies of 30–40 gpm over North Carolina (not shown). Subsidence and adiabatic warming immediately downstream of the ridge resulted in 850 mb temperatures over North Carolina that were 5–6° C above normal (Fig. 6B), or approximately two standard deviations above the climatological mean. The two cold frontal passages around the middle of the month were accompanied by the westward retrogression of a 500 mb trough towards the U.S. East Coast (Fig. 5C). Given its closer proximity to the upstream 500 mb ridge, 850 mb temperatures across western North Carolina remained as much as 4° C above normal (Fig. 6C). A strong upper-level ridge that had developed over the High Plains in the wake of the trough expanded eastward and dominated the large-scale pattern from 16–26 August (Figs. 5D–5E) with positive height anomalies of 40–50 gpm across North Carolina (not shown). These height anomalies over North Carolina were two to three standard deviations above the climatological mean. The lower troposphere remained anomalously warm during this period (2–5° C above normal), though not as warm as earlier in the month (Figs. 6D–6E). The upper-level ridge pattern relaxed slightly toward the end of the month (Fig. 5F), with positive height anomalies of 10–20 gpm over North Carolina (not shown) and near-normal to slightly above normal lower tropospheric temperatures (Fig. 6F).

METEOROLOGICAL PROCESSES

As discussed above, the August 2007 heat wave occurred over a broad region in response to synoptic-scale subsidence and adiabatic warming. Finer-scale variations in the heat and humidity across the state of North Carolina are tied to four meteorological factors, which are discussed in the following sections.

Adiabatic Warming Due to Downslope Winds

The higher frequency of exceptionally warm days in August 2007 across many Piedmont locations, particularly in the western Piedmont (i.e., Hickory, Mount Airy, Rural Hall, Gastonia; Fig. 4) may be tied to the persistence of west-northwesterly flow aloft, which resulted in downsloping winds and adiabatic warming off the Appalachian Mountains. Analysis of 72-hour back-trajectories terminating in the boundary layer (500 m AGL) at these western Piedmont locations reveals a warming of the air by as much as 10° C after it crossed the mountains (Fig. 7). This supports the findings of Chen and Konrad (2006), who determined that as many as 65% of

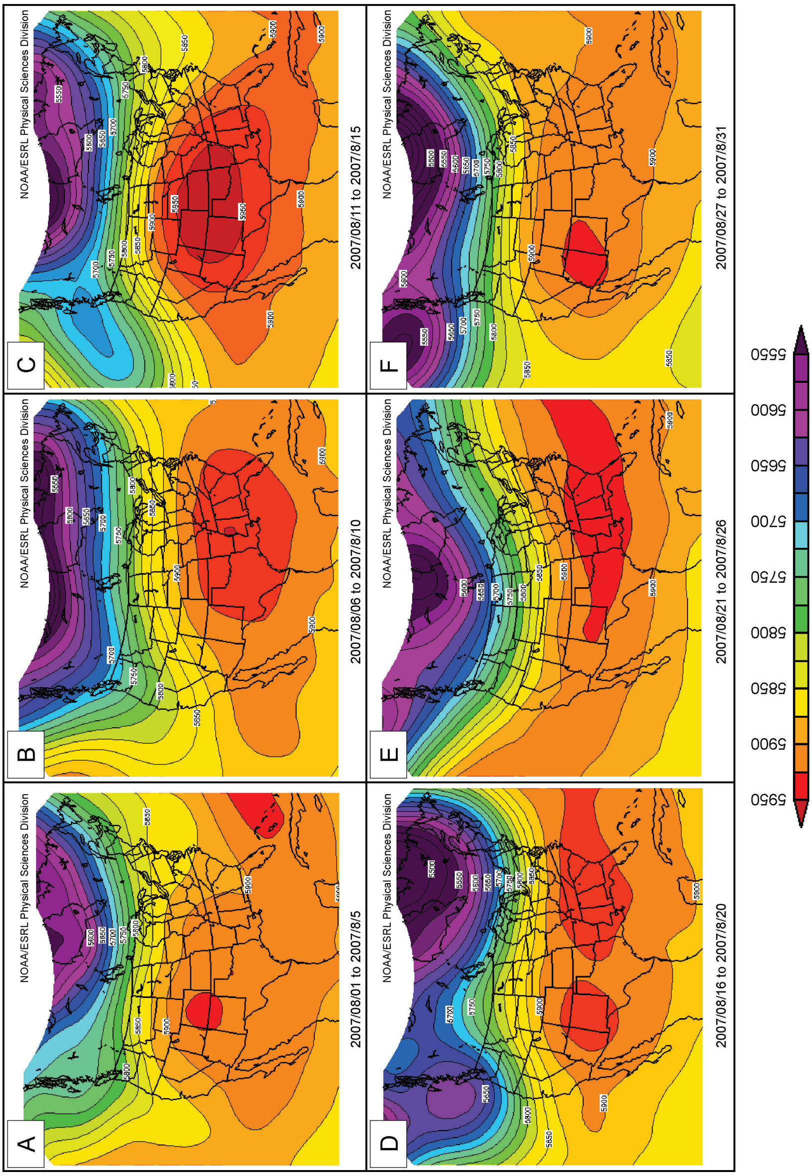

Fig. 5. Composite 500 mb geopotential height fields (m) averaged over five-day periods in August 2007 (except for 21–26 August, which is a six-day composite). Image provided by the NOAA/ESRL Physical Sciences Division, Boulder, CO, from its website at http://www.esrl.noaa.gov/psd/.

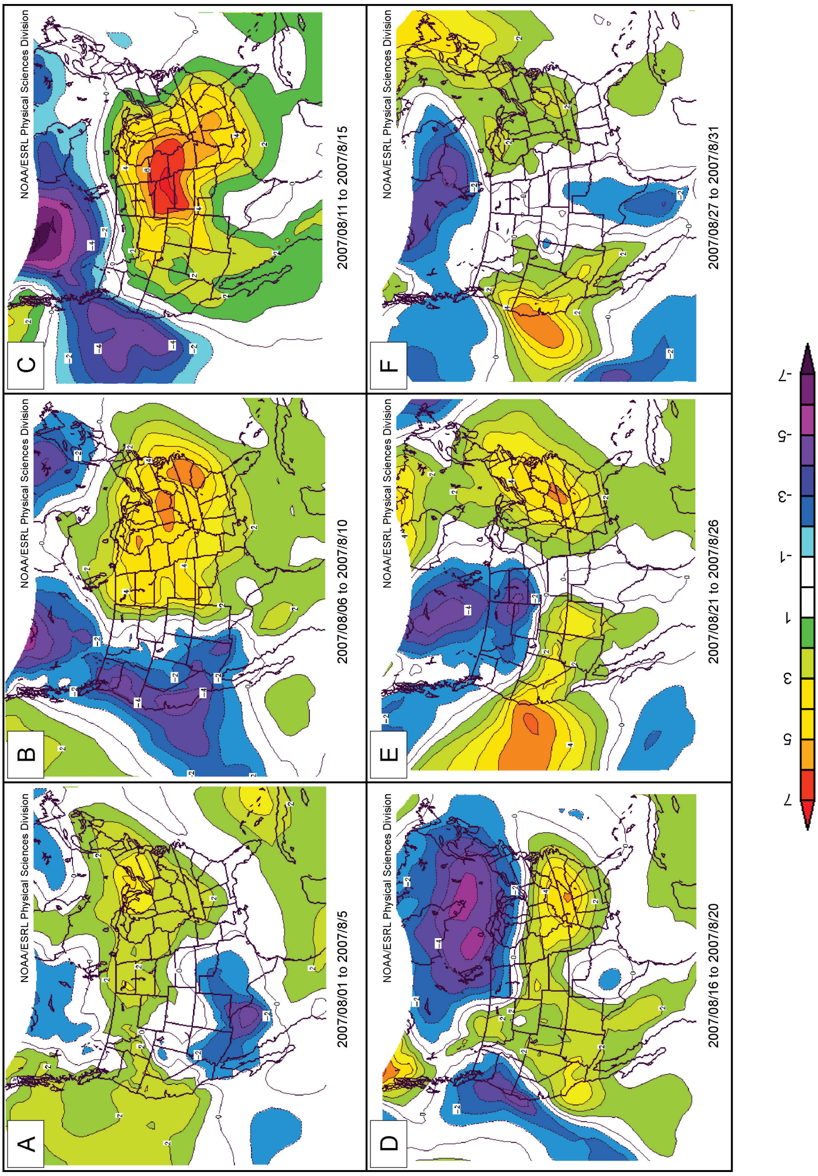

Fig. 6. Composite 850 mb temperature anomaly fields (° C) averaged over five-day periods in August 2007 (except for 21–26 August, which is a six-day composite). Image provided by the NOAA/ESRL Physical Sciences Division, Boulder, CO, from its website at http://www.esrl.noaa.gov/psd/.

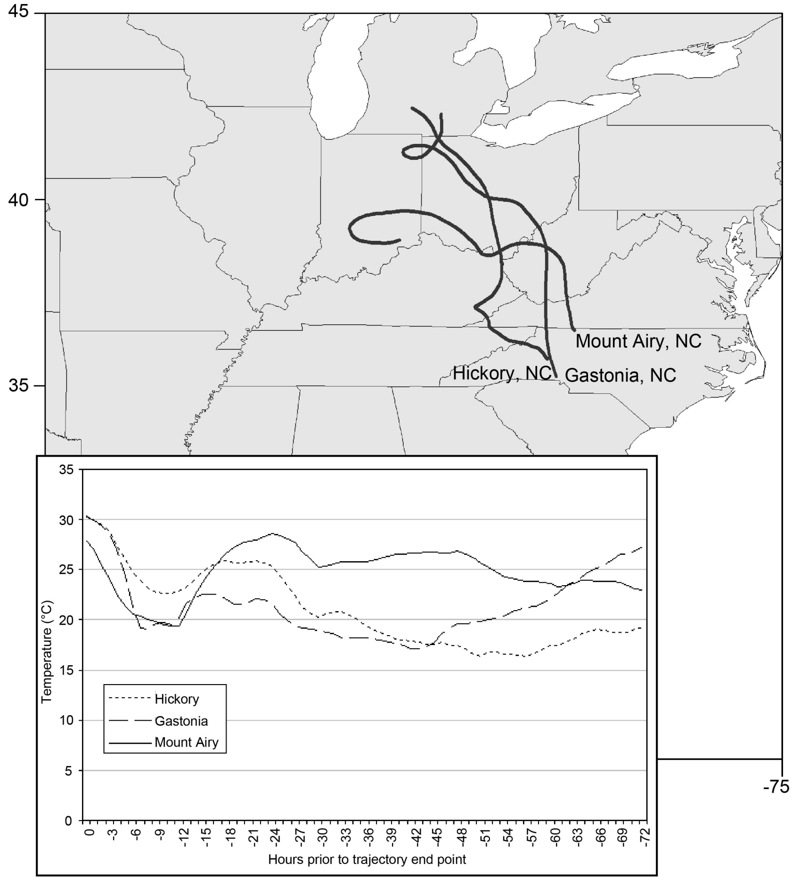

Fig. 7. Horizontal component of 72-hourr back-trajectories and air temperature (K) at each six-hour trajectory segment terminating in the boundary layer (500 m AGL) at 21 UTC at Gastonia, NC (13 August 2007), Hickory, NC (15 August 2007), and Mount Airy, NC (4 August 2007).

the warmest days in the North Carolina Piedmont from 1951 to 1993 displayed a sufficiently strong westerly wind component to cross the mountains and warm adiabatically on the lee side. Adiabatic warming due to downsloping winds likely contributed to the temperature pattern at Murphy as well, where daily maximum temperatures exceeded the 99.5th percentile on more than half of the days in August 2007. This was particularly noteworthy during the middle of the month when temperatures across the rest of North Carolina returned to near normal for a brief period and Murphy remained exceptionally warm (Fig. 3). Examination of the 500 mb geopotential height anomalies and 72-hour back-trajectories reveals that the interaction of the large-scale circulation and the local topography likely contributed to the temperature pattern at Murphy. During the middle of the month, western North Carolina remained under the influence of the upper-level ridge (Fig. 5C) and therefore was subject to subsidence warming. Low-level northerly winds beneath the eastern

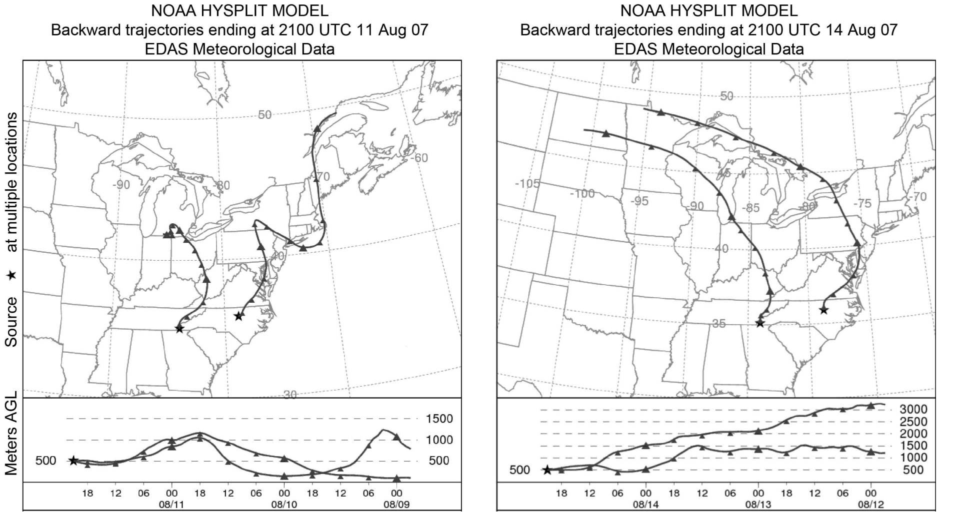

Fig. 8. Horizontal and vertical components of 72-hourr back-trajectories terminating in the boundary layer (500 m AGL) at Murphy (west) and Raleigh-Durham, NC (further east) on 11 August (left panel) and 14 August, 2007 (right panel).

periphery of the ridge prevailed over western North Carolina, creating downslope winds into Murphy (480 m elevation) off the higher terrain upwind (i.e., Great Smoky Mountains with ridge tops between 1.5 and 1.8 km; Fig. 8). These downsloping winds likely resulted in additional warming through adiabatic compression as the air entered the lower terrain. Comparative trajectories for Raleigh-Durham (Fig. 8) revealed cooler air blowing from the northeast with relatively little large-scale vertical motion (i.e., negligible warming through adiabatic compression).

Vertical Mixing and Dry-Down

One of the distinguishing features of the August 2007 heat wave was the variability in humidity throughout the month. This is revealed by the time series of surface dew point temperatures at Raleigh-Durham, which indicates a daily maximum in the morning (typically between 6:00 and 9:00 a.m. LST) and a daily minimum in the afternoon (typically between 3:00 and 6:00 p.m. LST) (Fig. 9). The magnitude of the drop in dew point temperature can be tied to the depth of vertical mixing in the boundary layer and the presence or absence of relatively drier air aloft. Days with deep convective mixing and drier air aloft show the greatest drops in the dew point temperature. In order to diagnose the occurrence of this scenario, the vertical mixing depth over the Piedmont was estimated using the 00 UTC (7:00 p.m. LST) radiosonde observations at Greensboro. As in Kunkel et al. (1996), the vertical mixing depth was identified as the surface-based layer of nearly constant virtual potential temperature. The top of the mixing layer was identified as the level at which the virtual potential temperature begins to increase significantly with height.

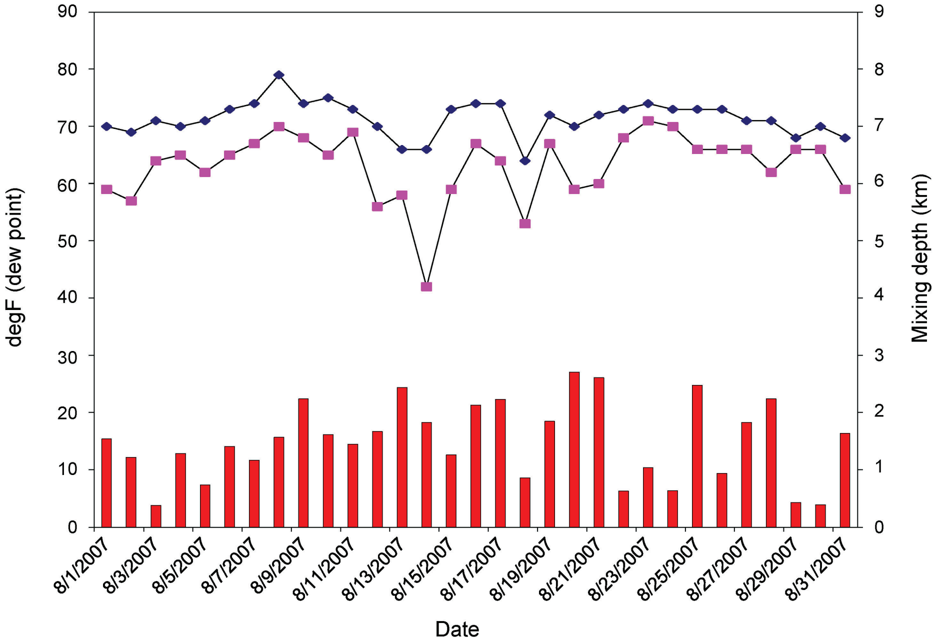

Fig. 9. Daily morning maximum (top line) and daily afternoon minimum (bottom line) dew point temperatures at Raleigh-Durham and maximum daytime mixing layer depths (bars) estimated from radiosonde data at Greensboro.

During the August 2007 heat wave, the depth of the 00 UTC mixing layer at Greensboro was greater than 1 km on 23 of 31 days (74%) and greater than 2 km on 8 of 31 days (Fig. 9). In contrast, mixing depths across a large portion of the Midwest during the July 1995 heat wave were generally less than 1 km (Kunkel et al., 1996). These shallow mixing depths helped to trap low-level moisture and prevent a reduction in the surface dew point temperature; this was a distinguishing feature of that 1995 heat wave. Kunkel et al. (1996) attributed the shallow mixing depths over the Midwest to strong synoptic-scale subsidence beneath the core of an upper-level ridge. During the August 2007 heat wave, the core of the upper-level ridge was located across the Lower Mississippi River Valley (Fig. 5), where synoptic-scale subsidence was maximized. This resulted in shallower mixing depths across parts of Tennessee, Arkansas, and Mississippi compared to those observed across central North Carolina. Weaker synoptic-scale subsidence and strong solar insolation over North Carolina most likely yielded deeper mixing depths, which helped to draw down drier air from above the boundary layer.

The impact of vertical mixing and dry-down on surface humidity is also revealed through an examination of hourly heat index values (which provide a measure of the combined influence of temperature and humidity on thermal stress). During the August 2007 heat wave, the hourly heat index at Raleigh-Durham typically reached a daily maximum at 2:00 p.m. LST. Conversely, the maximum in daily air temperature typically occurred two hours later at 4:00 p.m. LST (Fig. 10). By aiding in

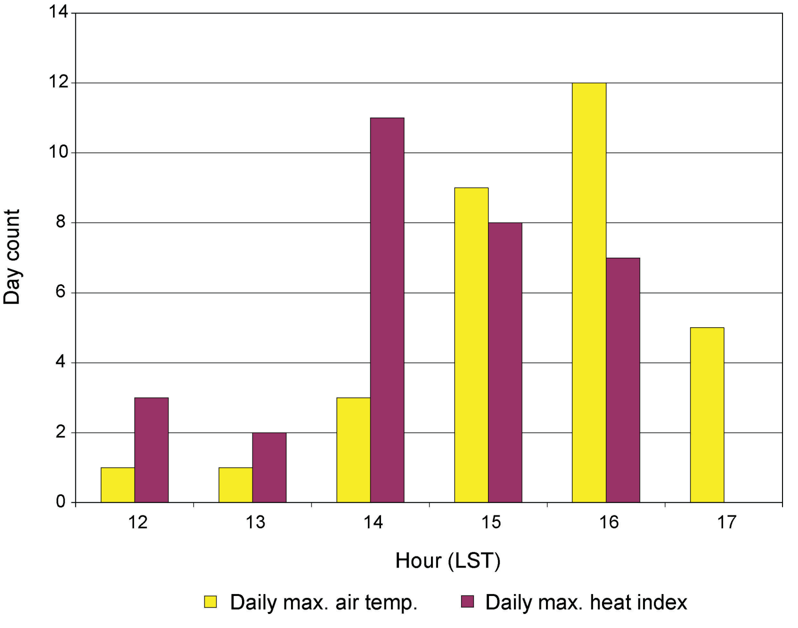

Fig. 10. Frequency of days in August 2007 in which the daily heat index and daily maximum air temperature at Raleigh-Durham occurred each hour between 12:00 p.m. LST and 5:00 p.m. LST.

the reduction of the afternoon dew point temperature, daytime vertical mixing and dry-down in the Piedmont acted to shorten the duration of excessively high index values.

Lee-Side Thermal Troughing

The temperature pattern along the North Carolina coast during August 2007 was markedly different than in the Piedmont or the mountains. In particular, stations nearest the coastline (i.e., Elizabeth City, Cape Hatteras, New Bern, Wilmington, Morehead City) observed far fewer days with extreme daily maximum temperatures (Figs. 3 and 4). However, daily minimum temperatures were unusually high in these areas during most of the month. Analysis of 72-hour back-trajectories provides a useful clue as to why the temperature pattern was different along the coast. On most days, the low-level flow over the mountains and Piedmont displayed a strong westerly or northwesterly component. These continental trajectories advected drier and warmer air into the Piedmont, while winds with a southerly component of motion were frequently found along the coast (Fig. 11). The cooler, moister trajectories along the coast, combined with a sea-breeze circulation, likely moderated daytime temperatures while preventing significant cooling at night.

The contrast in the low-level flow between the Piedmont and the coast results from a feature known as a thermal trough (referred to locally as a "Piedmont trough;" Koch and Ray, 1997). This feature is typically identified in the surface pressure field

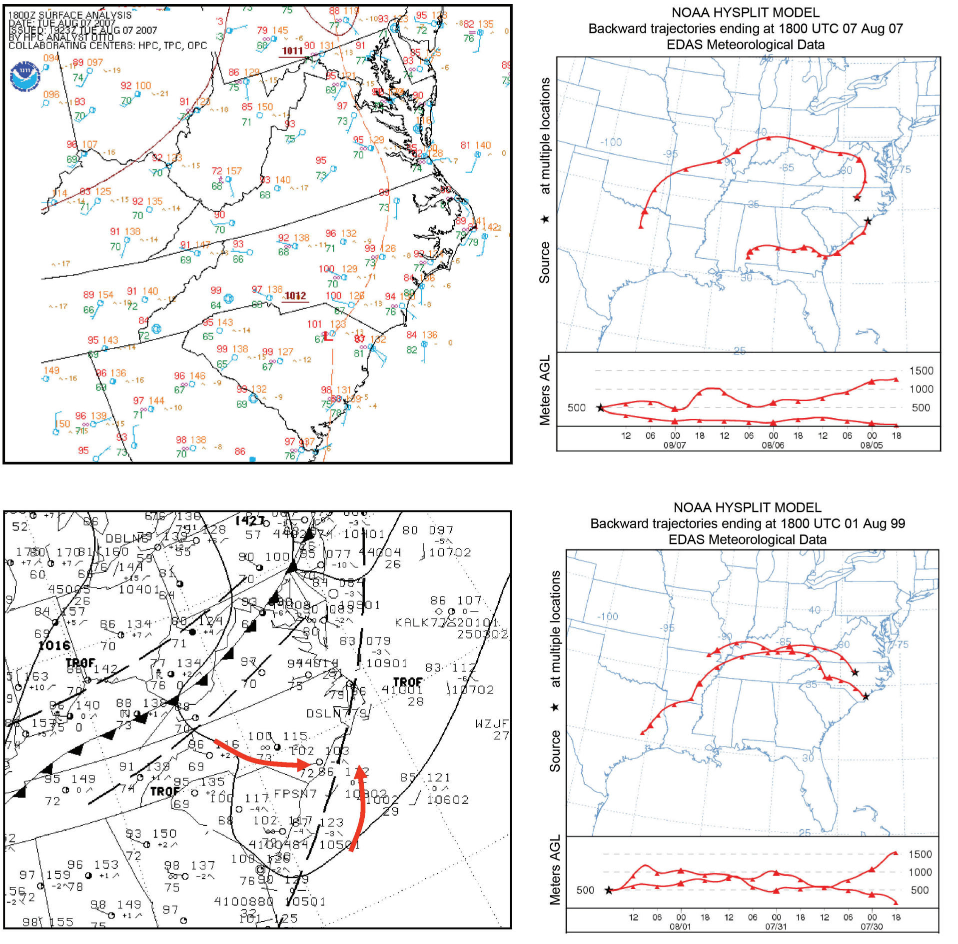

Fig. 11. Surface analyses showing the location of a thermal trough (dashed line) through eastern North Carolina (left panels) and the corresponding 72-hour back-trajectories terminating in the boundary layer (500 m AGL) at Wilmington and Raleigh-Durham (right panel) on 18 UTC 7 August 2007 (top panel) and 1 August 1999 (bottom panel). Wilmington recorded its second highest all-time maximum temperature on 1 August 1999 (39°C). Arrows in bottom left panel represent the mean low-level flow about the trough axis.

as a mesoscale trough and has been shown to develop due to adiabatic compression of air descending the lee side of the Appalachian Mountains (Weisman, 1990). The presence of low-level southerly flow to the east of the trough and westerly flow to the west of the trough is the result of geostrophic adjustment processes and conservation of potential vorticity as air crosses the mountains (Weisman, 1990). Thermal troughing across central and eastern North Carolina can also occur due to the differential heating of clay soils in the Piedmont and sandy soils in the Sandhills and coastal plain (Koch and Ray, 1997; Raman et al., 2005; Boyles et al., 2007). Low-level convergence along the axis of the trough often leads to clouds and precipitation on the east side of the axis, which can further moderate daytime temperatures along the coast.

We hypothesize that exceptionally hot days along the North Carolina coast are associated with a thermal trough anchored off the immediate coastline under strong low-level westerly flow. An examination of the hottest days in Wilmington (>37° C) from 1979 to 2006 revealed an eastward-displaced trough axis on 21 of 31 days (68%). An example is shown in Fig. 11 (bottom panel). A corollary to this is that the hottest days also lack the moderating influence of the onshore sea-breeze circulation, resulting in warmer, drier continental air being advected into the coastal plain. Indeed, on days in August 2007 with an onshore wind of at least 2.2 ms^{-1} at Wilmington between 12:00 and 6:00 p.m. LST (i.e., a sea breeze), the average temperature was between 0.6 and 1.6° C (1–3° F) cooler compared to days without a sea breeze. These sea-breeze days occurred frequently at Wilmington during the month (22 of 31 days in August 2007) due to weak southwesterly (i.e., along-shore) synoptic-scale flow and a strong land-water thermal gradient resulting from ample sunshine and strong solar insolation.

Local and Upstream Surface Moisture Character

Past research has shown that surface energy and moisture budgets can have a significant impact on heat wave type (i.e., dry or humid) and intensity. Kunkel et al. (1996) and Livezey and Tinkler (1996) showed that local evapotranspiration from wet soils contributed to the record-breaking dew point temperatures experienced across much of the Midwest during the infamous 1995 heat wave, while a pronounced urban heat island effect likely exacerbated the excessive daytime and overnight temperatures observed in downtown Chicago, IL. Chen and Konrad (2006) found that 30-day cumulative antecedent precipitation distinguished the driest summer days from the most humid summer days, suggesting that local evapotranspiration is a significant contributor to summertime humidity in central North Carolina.

There is evidence that both local and upwind surface conditions were contributing factors in the August 2007 wave across North Carolina. First, the August heat wave occurred during one of the worst droughts on record across the Southeast U.S. Maxwell and Soulé (2009) showed that the pattern of dryness across the region began earlier in the year in parts of the Deep South and Tennessee River Valley, though moderate drought conditions (according to the Palmer Drought Severity Index) had persisted across much of the region during the previous year. As the 2007 summer season began, the Crop Moisture Index, an estimation of potential evapotranspiration and overall vegetation stress, was in the abnormally dry to excessively dry categories across the region (not shown). By the end of July, nearly all of North Carolina was in the abnormally dry category, with a small area of excessively dry conditions observed through the Sandhills region (not shown). Recall that extreme daily maximum temperatures during the first heat event were initially observed in the Sandhills region (Fig. 3). The excessively dry, sandy soils are likely to have restricted the amount of evapotranspiration, resulting in a greater sensible heat flux and subsequent increase in surface temperature. By the middle of August, nearly the entire Southeast and lower Mississippi River Valley were in the excessively dry

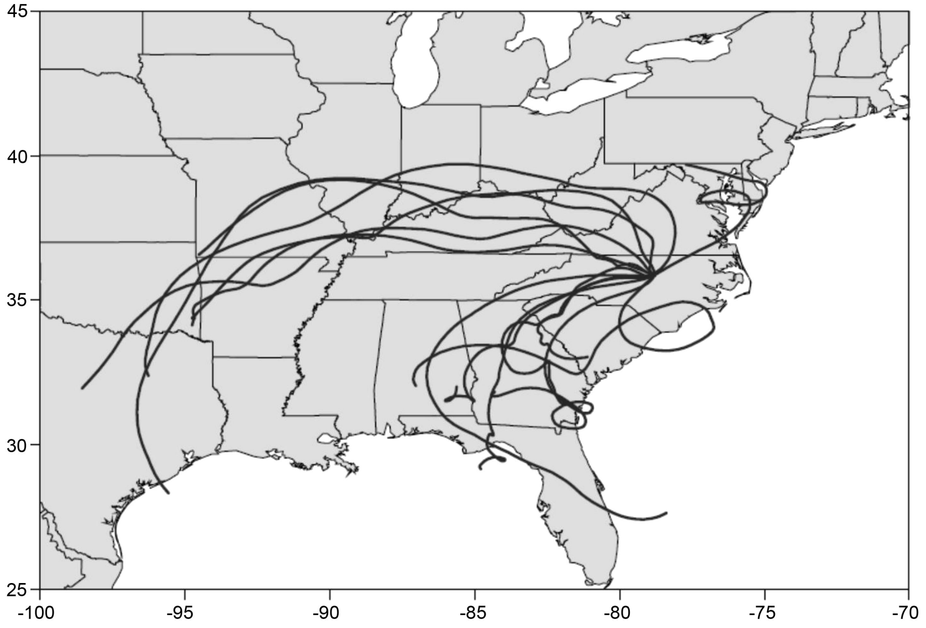

Fig. 12. Horizontal component of 72-hour back-trajectories terminating in the boundary layer (500 m AGL) at Raleigh-Durham on the 14 warmest days from August 2007.

to severely dry categories, while central North Carolina, northeast Alabama, and western Tennessee were in the extremely dry category (not shown).

We hypothesize that the exceptionally dry surface conditions upwind of the low-level air trajectories resulted in a higher sensible heat flux and contributed to additional warming of air parcels advected into North Carolina. A plot of 72-hour back-trajectories terminating in the boundary layer at Raleigh-Durham for a sample of the hottest days in August 2007 (> 36° C) revealed a combination of predominantly west-northwesterly and southerly trajectories that traversed ground with exceptionally dry soils (Fig. 12). Many of the southerly trajectories likely carried moisture from either the Gulf of Mexico or the Atlantic Ocean, as these trajectories occurred in association with many of the more humid days observed in the Piedmont. Therefore, low-level moisture advection may have been at least partially responsible for the increase in humidity observed during some of the heat events across the Piedmont region. Further evidence for moisture advection (as opposed to local evapotranspiration) as a key process stems from the extreme lack of rainfall across a large portion of North Carolina in July and August (Fig. 13).

Dry upwind surface conditions may have also been responsible for extreme temperatures in other parts of North Carolina. For example, on 23 August, Murphy tied its all-time record high temperature of 37.2° C (99° F). The boundary layer trajectory on this day revealed a slow anticyclonic turn across the lower Mississippi River and Tennessee River Valleys (Fig. 14) that was capped beneath the strong upper-level ridge (Fig. 5E). Although adiabatic warming downstream of the ridge likely

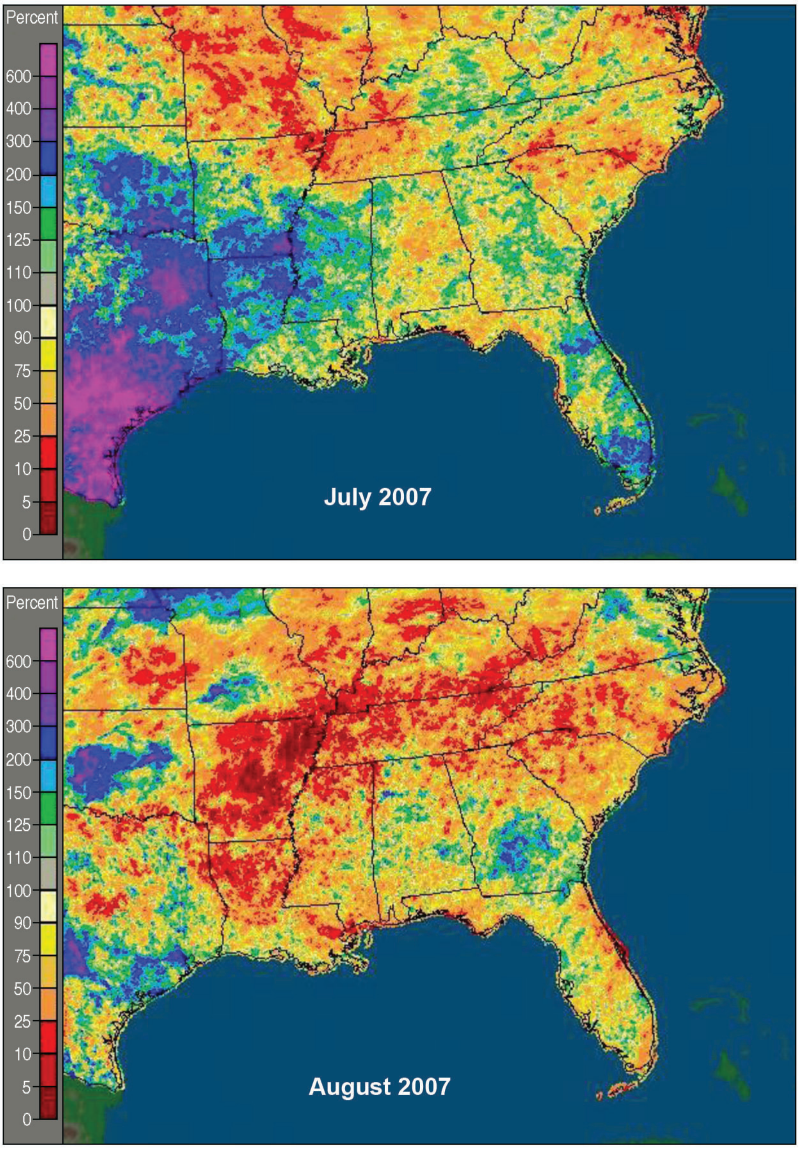

Fig. 13. Percent of normal radar-derived estimates of monthly rainfall over the Southeast U.S. in July (top) and August (bottom) 2007. Images were obtained online from http://water.weather.gov/precip.

contributed to the record warmth at Murphy, the low-level flow had shifted from northerly to southerly over the last 12 hours of the trajectory and therefore was not subject to downslope warming (see Fig. 8). Instead, it is likely that the record-tying warmth at Murphy was due largely to exceptionally dry soils upwind of the attendant low-level trajectories, resulting in a higher sensible heat flux and additional warming of the air being advected into southwest North Carolina.

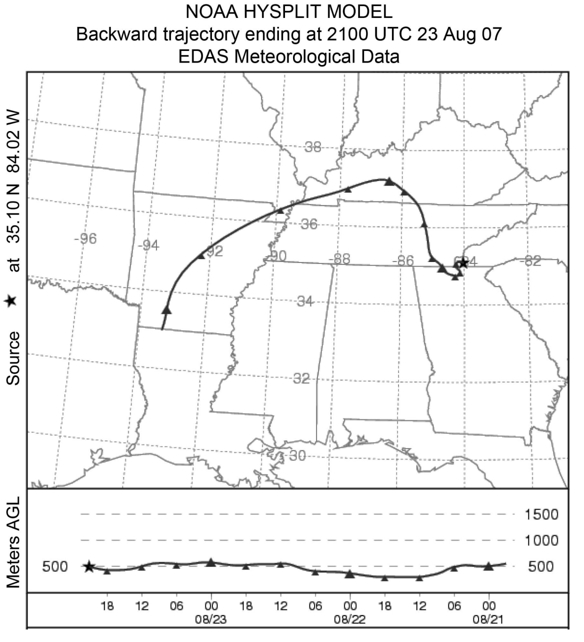

Fig. 14. Horizontal and vertical components of the 72-hour back-trajectory terminating in the boundary layer (500 m AGL) at Murphy, NC on 23 August.

DISCUSSION AND CONCLUSIONS

The month of August 2007 was exceptionally warm and dry across the Southeast U.S. In North Carolina, the impacts of the hot and dry weather throughout the month had a significant effect on agriculture, energy, water supplies, and human health. Though state-wide average monthly temperatures indicate that the August 2007 heat wave was a regional-scale event (Fig. 1A), our research revealed significant spatial and temporal variability in the character of heat and humidity across North Carolina. Specifically, locations in the Piedmont and Sandhills experienced the greatest number of days with exceptionally high maximum temperatures, while coastal locations observed more exceptionally high minimum temperatures than maximum temperatures. Daily minimum temperatures were not unusually warm in the mountains, particularly in the valleys. A similar analysis of conditions across other states in the Southeast affected by the heat wave would likely reveal important variability as well, adding greater specificity and detail to the regional-scale characterization of hot weather shown in Figure 1A.

Our research suggests that the variability in heat and humidity across the Piedmont was tied at least partially to variations in the upwind sensible heat fluxes and the depth of boundary layer mixing. In addition, adiabatic warming associated with westerly downsloping winds off of the southern Appalachian Mountains contributed to the greater frequency of exceptionally high daily maximum temperatures in central North Carolina, particularly in the western Piedmont. This supports results from a climatological study of summertime heat and humidity in the Piedmont (Chen and Konrad, 2006). Analysis of low-level back-trajectories indicated that air arriving into central North Carolina had traversed extremely dry ground. The reduction in soil moisture severely limited evapotranspiration and the potential for latent cooling of the boundary layer air. The more humid conditions observed intermittently during the month may be tied to moisture advection from the Gulf of Mexico rather than to evapotranspiration over land, as southerly flow was present on most humid days and exceptionally dry surface conditions prevailed.

The lack of exceptionally high surface humidity in the Piedmont during the August 2007 heat wave may have also been tied to vertical mixing of drier air aloft into the boundary layer. Large 500 mb geopotential height and 850 mb temperature anomalies over North Carolina would normally support a reduction in mixing depths due to the increase in low-level stability resulting from strong synoptic-scale sinking motions. In the case of the August 2007 heat wave, the strongest sinking motions were found across the Lower Mississippi River Valley, while weak mid-level instability was present across North Carolina. It is likely that the exceptionally dry soils and greater sensible heat flux may have decreased the low and mid-level stability sufficiently to promote deeper mixing depths. This hypothesis is supported by results from a modeling experiment conducted by Kunkel et al. (1996) on the July 1995 Midwest heat wave. In their simulation, when the land surface condition was changed from abundant soil moisture to bare (dry) soil, the resulting boundary layer was deeper, warmer, and drier. In the present study, the presence of deep mixing layers coincided with mid-afternoon decreases in the heat index across the Piedmont region. Though air temperatures continued to rise through much of the afternoon, the highest heat indices often occurred early in the afternoon around 2:00 p.m. LST. Accurate forecasts of mixing layer depths are, therefore, of tremendous value to those working outdoors or planning outdoor activities during hot summer days.

Recent model simulations of summer season temperatures over Europe suggest a strong link between soil moisture deficits and more frequent and persistent heat waves (Fischer et al., 2007; Lorenz et al., 2010). When soil moisture content is low, most of the incoming solar energy is converted to sensible heat, which directly warms the surface. A thermodynamically driven positive feedback loop may then ensue whereby continued warming leads to continued drying of soils, which then feeds back to continued warming. A dynamically driven feedback loop can also develop whereby increased drying of soils leads to increased lower-tropospheric warming, which leads to greater upper-level ridging and persistence of a dry synoptic pattern. A modeling study of the 2003 European heat wave revealed that the strength of this feedback between soil moisture and upper-level ridging may explain up to 10 m of the 500 mb geopotential height field (Fischer et al., 2007). Climate model simulations project an increase in the 500 mb geopotential height field under various warming scenarios as well as larger geopotential height anomalies during future heat waves in places such as Chicago and Paris (Meehl and Tebaldi, 2004). These findings raise the question as to whether the heat wave observed across North Carolina in August 2007, particularly later in the month, and the associated 500 mb geopotential height anomalies would have occurred if the soil moisture content had been higher. We leave this question for future research.

The pattern of heat and humidity along the North Carolina coast appears to be contingent upon the occurrence and positioning of the thermal trough, as well as the presence and strength of the sea-breeze circulation. During the August 2007 heat wave, a thermal trough was present most days over central or eastern North Carolina, resulting in southerly and southeasterly trajectories over the coastal plain. These trajectories advected relatively cooler marine air into the coastal plain, resulting in a modification of afternoon temperatures. During the heat wave, the sea-breeze circulation reduced the temperatures at Wilmington by as much as 1.6° C (3° F). Additional research is needed to determine the effect of the sea-breeze circulation on coastal heat waves. One hypothesis is that continued warming of the subtropical Atlantic Ocean, as projected in numerous global climate models (Meehl et al., 2007), would result in a long-term increase in the warmth and moistness of the sea breeze, thereby increasing the frequency of hot, humid days along the coast.

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