Synoptic-Scale Airflow and Moisture Transport Associated with Freezing Rain Events in Central North Carolina

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ABSTRACT

Freezing rain is one of the most hazardous and costly types of weather phenomena. The central Piedmont of North Carolina is a preferred region for freezing rain due to interactions between the atmosphere and the local topography as well as its proximity to nearby moisture sources. While previous studies have described the synoptic climatology of freezing rain in central North Carolina, much uncertainty remains as to the evolution and characteristics of the large-scale airflow and patterns of moisture transport associated with freezing rain. Atmospheric soundings and backward trajectory analysis using the NOAA HYSPLIT model were used to calculate various thermodynamic fields for air parcels connected with a sample of freezing rain events in the central Piedmont of North Carolina. This study reveals for the first time empirical evidence that sensible and latent heat fluxes off the Atlantic Ocean play an important role in the airflow characteristics and moisture budgets associated with freezing rain production over central North Carolina. This may have important implications in the forecasting of freezing rain, especially if Atlantic sea-surface temperatures continue to increase under current climate change scenarios.

Keywords: freezing rain; trajectory analysis; marine boundary layer; potential temperature

INTRODUCTION

Freezing rain (FZ) is one of the most hazardous and costly types of weather phenomena. Numerous studies have documented its devastating impact on property, power utilities, communication networks, transportation, ecosystems, and human life (e.g., Bendel and Patton, 1981; Kocin, 1997; Bernstein and Brown, 1997; Irland, 2000; Changnon, 2003; Cortinas *et al.*, 2004). The Southeast United States, particularly east of the Appalachian Mountains, is a preferred region for FZ because of its proximity to nearby moisture sources (e.g., Atlantic Ocean, Gulf of Mexico), the positioning of the mountains that allow for cold, dry air to "dam" alongside and east of the escarpment in the low-levels, and the track of wave cyclones and frontal boundaries that advect relatively warm, moist air over the surface-based cold air. If conditions are right, the interaction between these features can lead to a vertical thermodynamic profile conducive to FZ at the earth's surface: an elevated warm (>0°C) and moist layer situated atop a shallow layer of relatively dry, subfreezing air (referred to as "warm" and "cold" layers, respectively; Fig. 1).

Previous climatological studies of FZ in the Southeast (e.g., Bernstein, 2000; Rauber *et al.*, 2001; Robbins and Cortinas, 2002) suggest that the most common synoptic configuration involves a surface cyclone or quasi-stationary arctic front located to the southwest of the region with warm

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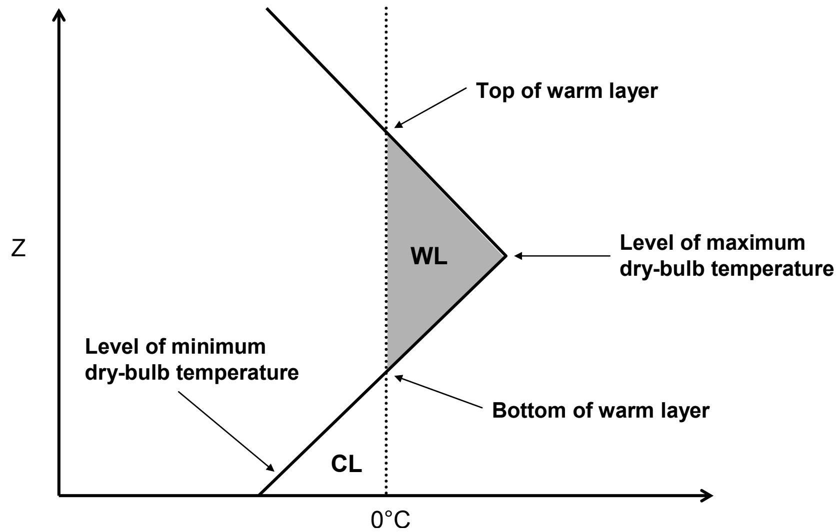

Figure 1. Schematic showing the thermodynamic profile of FZ: an elevated warm layer (WL) situated atop a surface-based cold layer (CL). The dotted vertical line represents the 0°C isotherm and the thick line represents the environmental lapse rate. Backward trajectories are computed from the four levels identified in the schematic.

air advection and isentropic lift occurring over a west-to-east oriented warm front. Thus, it is hypothesized that the predominant trajectory of the warm air advection and moisture should originate over the Gulf of Mexico (Hunter *et al.*, 2001). On the other hand, the influence of air trajectories originating over the Atlantic Ocean is likely not as straightforward. Lackmann and Stanton (2004) show that secondary cyclogenesis near the Carolina coast creates an easterly fetch off the Atlantic in the low-levels, which effectively warms and erodes the surface-based cold layer. In this case, any Atlantic influence would likely be below the level of warm air advection and would result in a transition to liquid precipitation. Conversely, da Silva *et al.* (2006) used a regional atmospheric model to show that anomalously warm Atlantic sea-surface temperatures lead to increased warming and deepening of the warm layer during FZ events in central North Carolina and Virginia. Their study suggests that the added heat and moisture from an anomalously warm (4°C above normal) subtropical Atlantic Ocean can lead to as much as 10% more FZ in the region. An earlier study by Gyakum and Roebber (2001) had shown that air parcels connected with the 1998 ice storm over southeast Canada spent considerably more time in the Atlantic marine boundary layer than other less severe ice storms. These results stand in contrast to a study by Lackmann *et al.* (2002) who contended that the thermodynamics of the surface-based cold layer (i.e., diabatic cooling from evaporation, adiabatic cooling due to orographic flow, persistent low-level cold air advection) are more strongly tied to prolonged and heavy FZ. Taken together, these studies illustrate a lack of consensus regarding the evolution and characteristics of the airflow and moisture transport associated with FZ and the role they play in dictating the type and intensity of precipitation as the event unfolds.

The purpose of this study is to identify and characterize the predominant synoptic-scale (1-3 days) airflow and moisture transport associated with FZ events in central North Carolina. Backward trajectory analysis and atmospheric soundings were used to calculate various thermodynamic fields for air parcels connected with FZ. The utility of trajectory analysis in identifying the three-dimensional airflow and moisture transport of midlatitude weather systems has been examined by Shultz (2001), Fink and Knippertz (2003), Ulbrich *et al.* (2003), Brimelow and Reuter (2005), and Perry *et al.* (2007), among others. Specifically, in this paper we determine the vertical and horizontal components of the synoptic-scale airflow and moisture transport, the source regions of the moisture, and the contribution of adiabatic and diabatic processes to the vertical thermal profile during FZ events in central North Carolina.

DATA AND METHODS

Hourly surface weather observations from the first-order National Weather Service station at Greensboro, NC (GSO; 36.08°N, 79.95°W) were used to identify FZ events during the period 1975 to 2003. The reason for selection of GSO was three-fold: 1) previous climatologies of FZ identify a regional maximum over the central Piedmont of North Carolina and extreme southern Virginia (Bennett, 1959; Bernstein, 2000; Robbins and Cortinas, 2002; Changnon and Karl, 2003); 2) hourly observations of FZ at GSO over the period of record have been quality-controlled or have otherwise been deemed reliable (see Ramsay, 1997 and Changnon, 2003 for details); and 3) twice-daily radiosonde soundings over GSO allow for identification of warm and cold layers and their characteristics.

Initially, winter weather events were identified from the hourly surface weather observations if measurable precipitation was recorded with at least one observation of a frozen or freezing precipitation type (i.e., snow, sleet, freezing rain, freezing drizzle). An event was terminated if there was more than a 24-hr lapse in these conditions (after Gay and Davis, 1993). This method allows for airflow and moisture trajectories to be determined over the lifecycle of a given event, thus providing a connection to the prevailing synoptic and planetary circulation (to be examined in a forthcoming study). Freezing rain events were identified and segregated from the initial database of winter weather events under the following set of conditions: 1) If the total FZ was 0.10-0.24 in (0.25-0.61 cm) and accounted for at least 75% of the total event precipitation and duration; 2) if the total FZ was 0.25-0.49 in (0.64-1.24 cm) and accounted for at least 50% of the total event precipitation and duration; or 3) if the total FZ was at least 0.50 in (1.27 cm) then no dominance thresholds were applied. These conditions indicate that FZ events may include other precipitation types (Cortinas *et al.,* 2004). Observations of freezing drizzle were treated independently of observations of FZ and thus were not used to determine the storm-total FZ or FZ duration. FZ events identified in this study (n = 66) accounted for approximately one-third of all winter weather events at GSO during the study period.

The thermodynamic structure of FZ events was determined using twice-daily (00 and 12 UTC) radiosonde data and soundings from GSO (WBAN 13723). Data were obtained from the University of Wyoming North American radiosonde archive[2]. To accurately portray the thermodynamic characteristics of FZ events, FZ must have been recorded in the surface weather observations at the time the sounding was launched (either 23 or 11 UTC). Only 17 (8) out of the initial 66 events recorded FZ at one (more than one) sounding time, leaving a total of 25 FZ events and 35 individual FZ soundings for analysis. In cases where FZ was recorded at more than one sounding time during an event, only the first 00 UTC sounding was used for trajectory analysis.

Backward (i.e., antecedent) airstream trajectory analysis was performed for parcels in the warm and cold layers over GSO using the National Oceanic and Atmospheric Administration's Hybrid Single-Particle Lagrangian Ingregrated Trajectory (HYSPLIT) model[3]. The reader is directed to Draxler and Hess (1998) and Brimelow and Reuter (2005) for details on the HYSPLIT model. Seventy-two hour (72-hr) backward trajectories were calculated at the 23 and 11 UTC FZ times for parcels at four elevations: 1) top of the warm layer, 2) level of maximum dry-bulb temperature, 3) bottom of the warm layer, and 4) level of minimum dry-bulb temperature (i.e., cold layer) (see Fig. 1). National Center for Environmental Protection-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (2.5° resolution) were used to compute trajectories due to their availability over the study period. Results from Perry *et al.* (2007; their Fig. 5) and from a preliminary analysis of a sample of events in this study (not shown) show that horizontal trajectories computed using the reanalysis data compare favorably with trajectories computed using higher-resolution datasets (i.e., 191 km FNL and 80 km EDAS). Five meteorological fields were plotted at 1-hr intervals along each trajectory: elevation, pressure, dry-bulb temperature, potential temperature, and mixing ratio.

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[2] Available online at http://weather.uwyo.edu/upperair/sounding.html

[3] Available online at http://www.arl.noaa.gov/ready/hysplit4.html

To better understand the airflow characteristics and patterns of moisture transport connected with FZ events (and their changes over the lifecycle of each event), each 1-hr segment of each 72-hr airstream and moisture trajectory was plotted atop a regional classification grid (Fig. 2). This grid demarcates the primary water bodies (Atlantic Ocean and Gulf of Mexico) as well as the sub-continental (West/Northwest and North/Northeast) and sub-oceanic (Subtropical Atlantic and Northeast Atlantic) boundaries that have been shown or suggested to play a role in the occurrence and/or intensity of FZ in the Southeast region. Trajectories originating or residing over the Pacific Ocean were also noted.

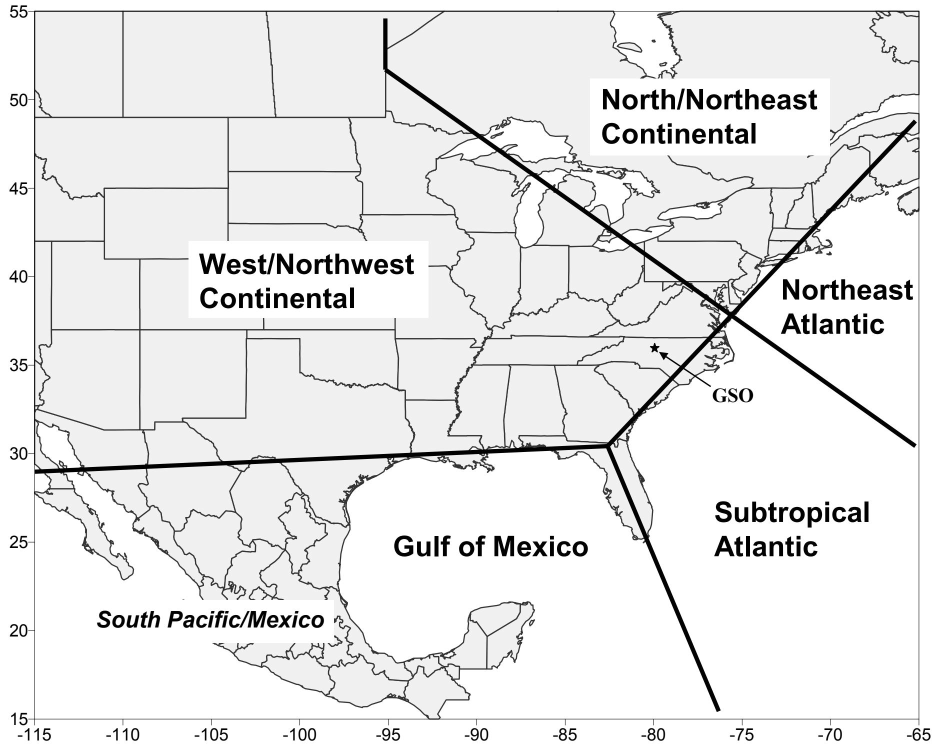

Figure 2. Trajectory classification grid and location of Greensboro, NC (GSO).

RESULTS

Sounding statistics

To gain a general perspective on the thermodynamic characteristics of FZ events at GSO, various sounding statistics were calculated. Consistent with previous climatological studies (e.g., Bernstein, 2000; Robbins and Cortinas, 2004), elevated warm layers were generally deep (69% between 1200 and 2700 m) and warm (71% between 4 and 11°C), while surface-based cold layers were rather shallow (94% between 200 and 900 m) and cold (51% between -6 and 0°C) (Fig. 3a,b). Some of the warm layers were relatively shallow compared to climatology (31% between 300 and 1000 m). In these cases, FZ was likely mixed with sleet and/or freezing drizzle (Bernstein, 2000).

Objective forecast guidance in central North Carolina has relied on partial thicknesses between standard pressure levels (i.e., 850-700 hPa and 1000-850 hPa) to determine the presence and magnitude of warm and cold layers, respectively (Keeter and Lee, 2001). For the FZ soundings used in this study, the top of the warm layer was between 850 and 675 hPa, the level of maximum temperature was between 925 and 800 hPa, the bottom of the warm layer was between 950 and 850 hPa, and the level of minimum temperature was between 975 and 900 hPa (Fig. 3c). In over half of the soundings, the top of the warm layer occurred at 700 hPa, while in over two-thirds of the soundings the maximum temperature in the warm layer occurred between 850 and 825 mb. Nevertheless, the range of values demonstrate that there is much variability in the specific heights of the melting and freezing layers during FZ events and that reliance on partial thicknesses may bias a precipitation-type forecast (Cuviello, 2007).

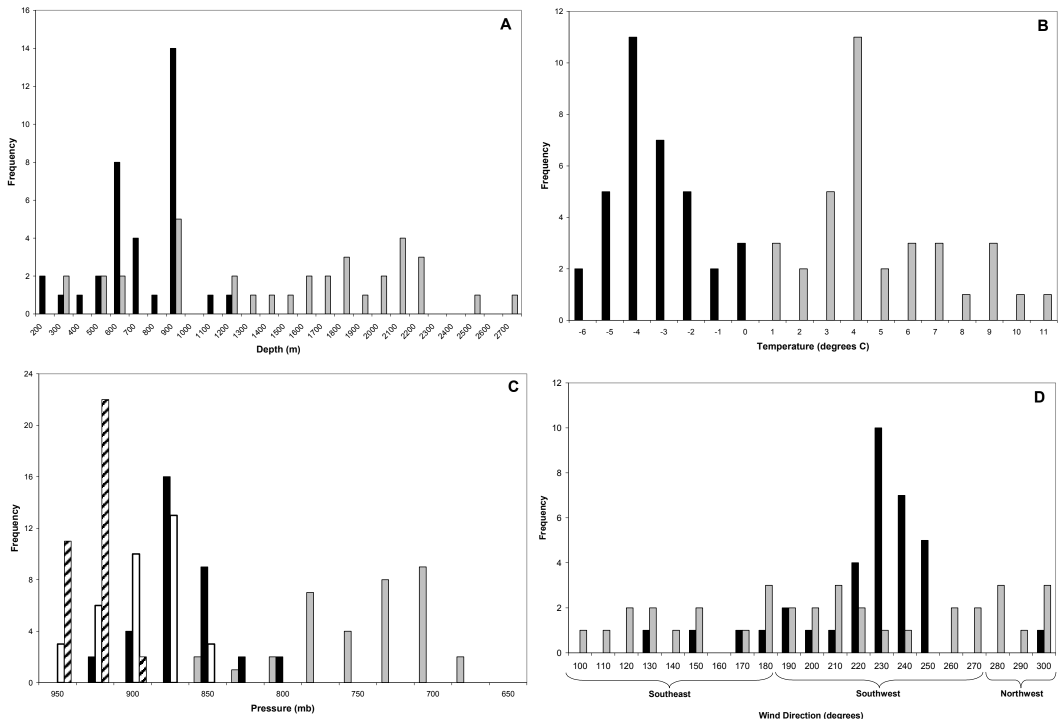

Figure 3. Summary of sounding statistics for 35 individual FZ soundings at GSO from 1975 to 2003: frequency distribution of (A) cold layer (black bars) and warm layer (gray bars) depths; (B) minimum dry-bulb temperature (black bars) and maximum dry-bulb temperature (gray bars); (C) pressure level at the top of the warm layer (gray bars), at the maximum dry-bulb temperature (black bars), at the bottom of the warm layer (white bars), and at the minimum dry-bulb temperature (hatched bars); (D) wind direction at 700 hPa (black bars) and 850 hPa (gray bars).

With regard to wind direction, 43% of FZ soundings indicated southwesterly winds at 850 hPa, while 34% indicated southeasterly winds at that level (Fig. 3d). Southwesterly winds were more common at 700 hPa (86% of FZ soundings). These results suggest that in a number of FZ events, the warmest air in the warm layer is strongly influenced by sensible and latent heat fluxes over the Atlantic Ocean (i.e., southeast trajectories), while fluxes over the Gulf of Mexico (i.e., southwest trajectories) are maximized for parcels closer to the top of the warm layer. These hypotheses are investigated in more detail below.

Air parcel trajectories

The results of the trajectory classification are presented in Table 1, while the air parcel trajectory plots at each elevation (see Fig. 1) are presented in Figure 4. Over 50% of trajectory segments at the top of the warm layer occurred over the Gulf of Mexico (Fig. 4a). The origin of the 72-hr trajectory for these parcels was generally over the Gulf of Mexico and some trajectories likely traversed the Mexican continent or the southeast Pacific Ocean. Examination of the horizontal and vertical airstream plots revealed that most of these parcels descended anticyclonically over the Gulf of Mexico, likely contacting the marine boundary layer (MBL) (below 2 km, see Gyakum and Roebber, 2001) before ascending over central North Carolina. In more than two-thirds of the FZ events, this ascent was associated with the warm conveyor belt of a surface cyclone (not shown). In the remaining cases, ascent was associated with isentropic lift over an arctic or stationary frontal boundary.

Air parcel trajectories associated with the level of maximum warm layer temperature typically originated over the continent to the west-northwest of GSO (Fig. 4b). These parcels descended anticyclonically from the middle to lower troposphere over the Northeast coast and contacted the Atlantic MBL before recurving and ascending over central North Carolina. Interestingly, the frequencies of trajectory segments at this level were very similar over the continent and subtropical Atlantic Ocean (37.3% and 39.3%, respectively; Table 1). This suggests that air parcels at this level decelerate upon contact with the Atlantic MBL, entraining significant moisture and warming sensibly (examined in more detail later) before entering central North Carolina. Similar trajectories were noted at the bottom of the warm layer with shorter residence times in the MBL and more modest ascent over central North Carolina (Fig. 4c). Air parcel trajectories at the level of minimum temperature (i.e., cold layer) originated further north into Canada (Fig. 4d) and spent considerably less time in the Atlantic MBL (only 18% of trajectory segments; Table 1).

Table 1. Trajectory classification statistics: total frequency of 6-hr trajectory segments (freq); percentage of all trajectory segments at each elevation (per); mean number of hours (out of 72) spent in each trajectory region (avg).

	Top of WL			Max DB Temp			Bottom of WL			Min DB Temp		
Class	Freq	Per	Avg	Freq	Per	Avg	Freq	Per	Avg	Freq	Per	Avg
W-NW Cont	60	20.0	14.4	112	37.3	26.9	143	47.7	34.3	151	50.3	36.2
N-NE Cont	11	3.7	2.6	32	10.7	7.7	36	12.0	8.6	65	21.7	15.6
NE Atlantic	4	1.3	0.9	18	6.0	4.3	20	6.7	4.8	31	10.3	7.4
SE Atlantic	67	22.3	16.2	118	39.3	28.3	100	33.3	24.1	53	17.7	12.7
Gulf	158	52.7	37.9	20	6.7	4.8	1	0.3	0.2	0	0.0	0.0

Moisture transport

The results above suggest that the subtropical Atlantic Ocean contributes a significant amount of the moisture available at the level of maximum temperature during FZ events in central North Carolina, while the Gulf of Mexico contributes much of the moisture at the top of the warm layer. A more detailed examination of the moisture trajectories associated with FZ events is presented. In this paper, only those trajectories associated with the warm layer are discussed.

Air parcels in the elevated warm layer exhibited increases in moisture content over the 72-hr trajectory period (Fig. 5). The increase in moisture was most pronounced at the level of maximum temperature and at the bottom of the warm layer, particularly over the last 36-hr of the trajectory as the parcel descended into the Atlantic MBL. The increase in moisture was less pronounced at the top of the warm layer where air parcels were typically located just at or above the MBL (2 km) and were already moist after spending time over the eastern Pacific Ocean and Gulf of Mexico. Although air parcels that descend over the continent typically warm and dry adiabatically, some subtle increases in moisture transport over the continent were noticeable. These increases may be connected to moisture source regions extending beyond 72-hr, trajectories extending over the Great Lakes, or residual moisture from an incipient precipitation event (i.e., moisture "recycling").

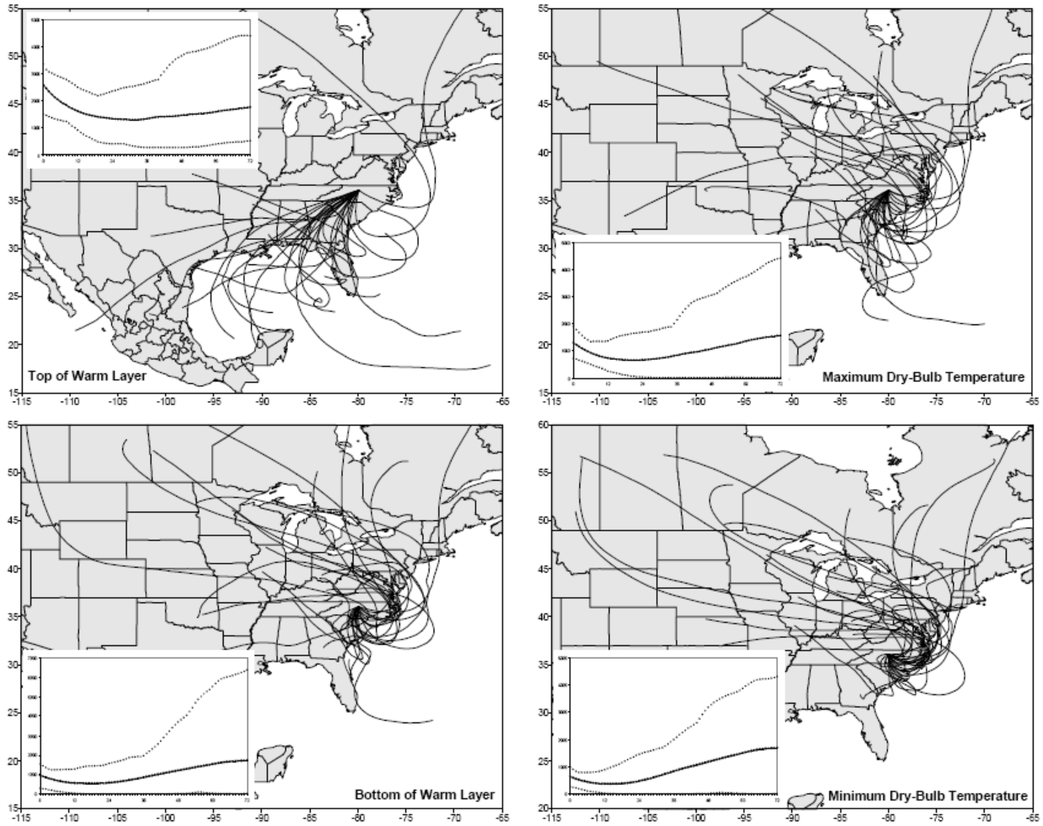

Figure 4. Horizontal and vertical airstream trajectory plots for all 25 FZ events at each elevation in Fig.1 beginning 72-hr prior to the FZ time at GSO. The vertical axis on the inset plots is height above ground level (m) (solid line is the mean height, dotted lines are minimum and maximum values at each trajectory) and the horizontal axis is the backward trajectory (i.e., hours prior to the FZ time).

Following identification of the primary source regions of the moisture in the warm layer (beginning 3 days prior to the FZ time at GSO), the relative contributions of each region to the total moisture at each elevation are presented. Figure 6 illustrates the relationship between the mean increase in moisture and the percent moisture contribution from each trajectory region (see Fig. 2). At the top of the warm layer, trajectories over the Gulf of Mexico contributed both minimally (20%) and maximally (≥100%) to the total available moisture, although the magnitude of the moisture flux was generally small (<4 g $kg^{-1}*10^2$/hr) (Fig. 6a). It is important to note that contributions ≥100% likely reflect the short temporal scale (3 days) over which air parcel trajectories were calculated (i.e., most of the moisture originated from more remote sources) or indicate that moisture was removed from the air closer to the FZ time through precipitation processes or mixing with drier air (Brimelow and Reuter, 2005). The greatest increases in moisture at the top of the warm layer were found over the continent and Atlantic Ocean. At the level of maximum temperature, trajectories over the subtropical Atlantic Ocean contributed the greatest amount of total available moisture (>50%) and exhibited the highest moisture fluxes (>6 g $kg^{-1}*10^2$/hr) (Fig. 6b). Moisture contributions and transport from the continent were smaller at this level compared to those at the top of the warm layer. A similar pattern was noted at the bottom of the warm layer with the exception of recurving, anticyclonic trajectories from the subtropical Atlantic Ocean into central North Carolina (Fig. 6c). These trajectories contributed an average of 40% of the total available moisture and were connected with some of the highest moisture fluxes at the bottom of the warm layer (>8 g $kg^{-1}*10^2$/hr). Decreases in moisture contribution and moisture transport were greatest over the continent at all three warm layer elevations (not shown).

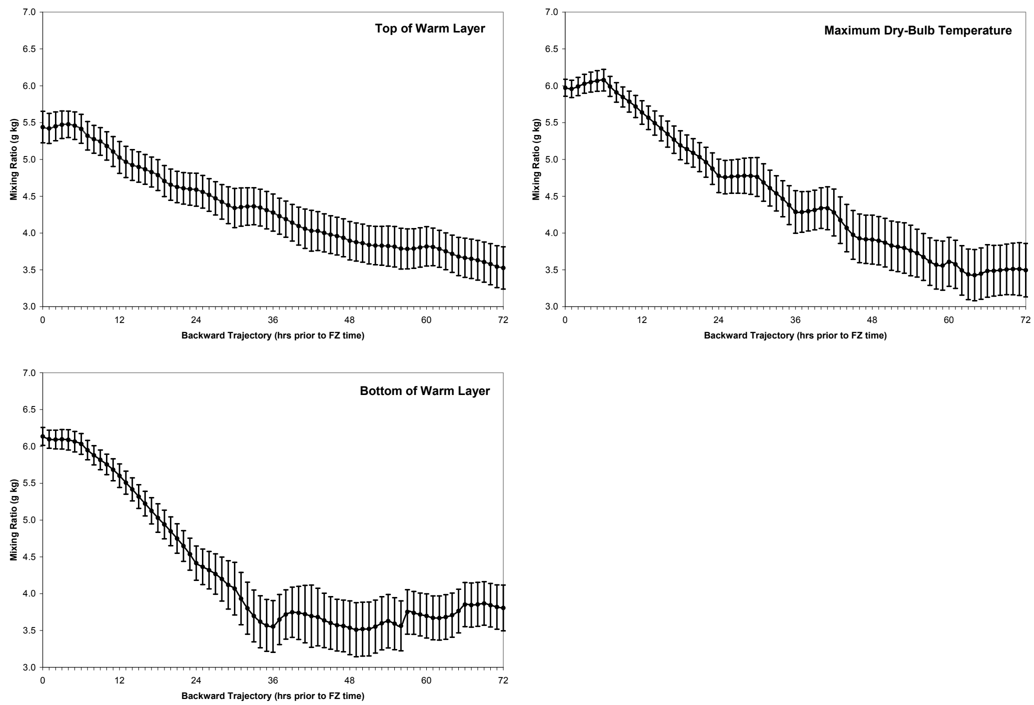

Figure 5. Mean 1-hr moisture trajectory plots for all 25 FZ events at the top of the warm layer, at the level of maximum temperature, and at the bottom of the warm layer beginning 72 hr prior to the FZ time at GSO. Bars show the standard error (+/–).

A summary of the total moisture contribution for each trajectory region is presented in Figure 7. Nearly half of the available moisture at the top of the warm layer was connected to air parcel trajectories over the Gulf of Mexico. By comparison, the Gulf of Mexico contributed only 7% of the available moisture at the level of maximum temperature. The majority of the available moisture at this level was contributed by the subtropical Atlantic Ocean. Over the cooler waters of the Northeast Atlantic Ocean, this value dropped to below 10%. At the bottom of the warm layer, anticyclonically curving trajectories extending inland off the Atlantic Ocean (i.e., Atlantic Recurve in Fig. 7) contributed over 25% of the available moisture. The continent provided an appreciable contribution to the total available moisture, particularly at the top of the warm layer and at the level of maximum temperature (14% and 12%, respectively).

Contribution of adiabatic and diabatic processes

Results from the trajectory analysis above show that air parcels arriving in the elevated warm layer (>0°C) often originate in the middle troposphere where the environmental temperature is well below freezing. In some cases, air parcels may warm by as much as 40°C over the 72-hr trajectory period. To determine the relative contribution of adiabatic and diabatic processes to sensible warming of air parcels, the potential temperature (θ) was calculated for each trajectory segment. Only those elevations associated with the warm layer are examined in this paper. Potential temperature is a conservative property in the absence of diabatic processes. When the air becomes saturated (i.e., condensation is occurring), the adiabatic assumption is negated and the air parcel will no longer move along the original θ surface (Anderson, 1984). The change in θ over time (i.e., θ excess) reflects the movement of an air parcel along different θ surfaces resulting from diabatic processes (e.g., solar and terrestrial radiation, latent heating, convective mixing).

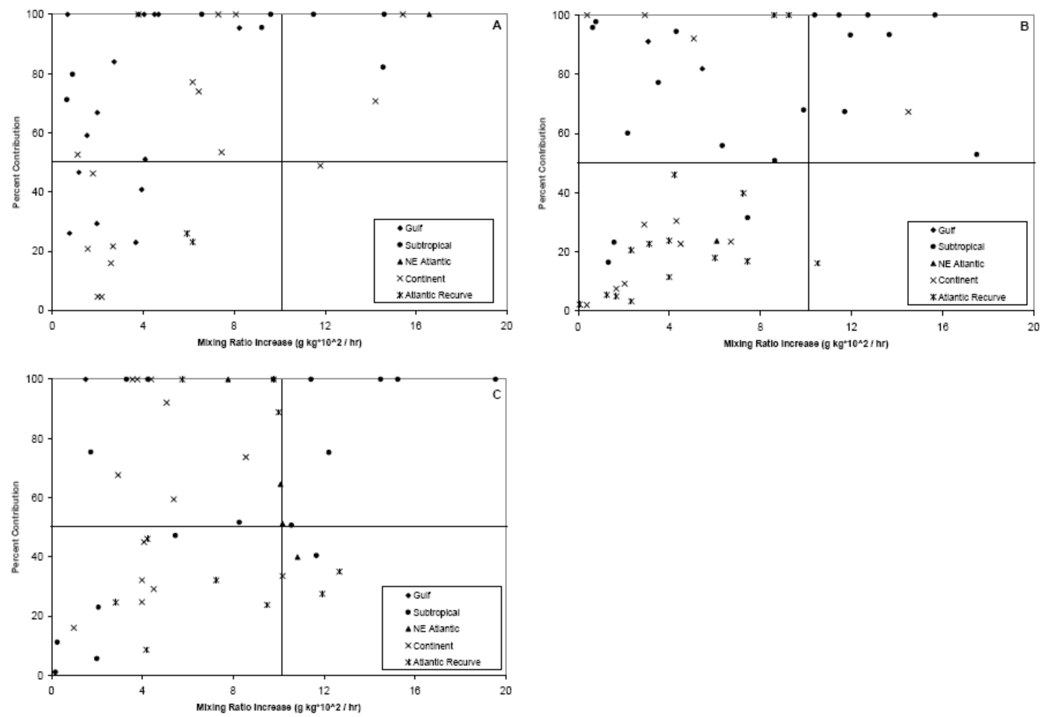

Figure 6. Scatter plot showing the relationship between the mean 1-hr increase in mixing ratio and the percent moisture contribution in each trajectory classification region for individual FZ events at (A) the top of the warm layer, (B) the layer of maximum temperature, and (C) the bottom of the warm layer. The Continental region includes both the west-northwest and north-northeast regions in Figure 2.

The connection between ocean-air fluxes and sensible warming of air parcels is illustrated through a small case study. The FZ event of 27 February 1982 was one of the heaviest FZ events identified in the FZ climatology at GSO [0.95 in (2.4 cm)]. The 72-hr air parcel connected with the level of maximum temperature originated over central Canada at an altitude of over 4 km (Fig. 8). The parcel took a trajectory just north of the Great Lakes and descended into the Atlantic MBL just near the Delmarva Peninsula. The parcel spent approximately 36-hr in the Atlantic MBL before ascending into the warm conveyor belt of a surface cyclone (not shown). As the parcel descended over the continent, it warmed adiabatically (no change in θ) from -42°C to -18°C (Fig. 9). Following descent of the parcel into the subtropical Atlantic MBL, θ increased from 273 K to 292 K (θ excess = 19 K) while the parcel's ambient temperature increased from -15°C to 2°C despite the reduction in the rate of vertical descent. An increase in the latent heat flux over the subtropical Atlantic Ocean likely contributed significantly to this additional warming, as moisture values increased dramatically in the MBL.

DISCUSSION AND CONCLUSIONS

The central Piedmont region of North Carolina is a preferred region for FZ due to various atmospheric and topographic variables and experiences significant financial and human losses because of these events. Since temperature and moisture are critical components in the forecasting of precipitation type and intensity, this study utilized backward air parcel trajectory analysis and atmospheric soundings to reveal the character of the synoptic-scale airflow and moisture transport associated with FZ events in the region.

While the analysis of sounding parameters generally confirmed the results of previous climatological studies, it is worth noting that there was significant variability in the range of warm layer depths and maximum temperatures. This is likely related to hourly variations in the intensity and overall duration of precipitation during the events, as the rate and duration of precipitation has a marked effect on the thermal structure of the atmosphere due to the phase changes of water and conversion of latent energy (i.e., melting, freezing, sublimation, evaporation). Research is currently underway to determine the relationship between FZ intensity and the character of the airflow and moisture transport patterns identified in this study.

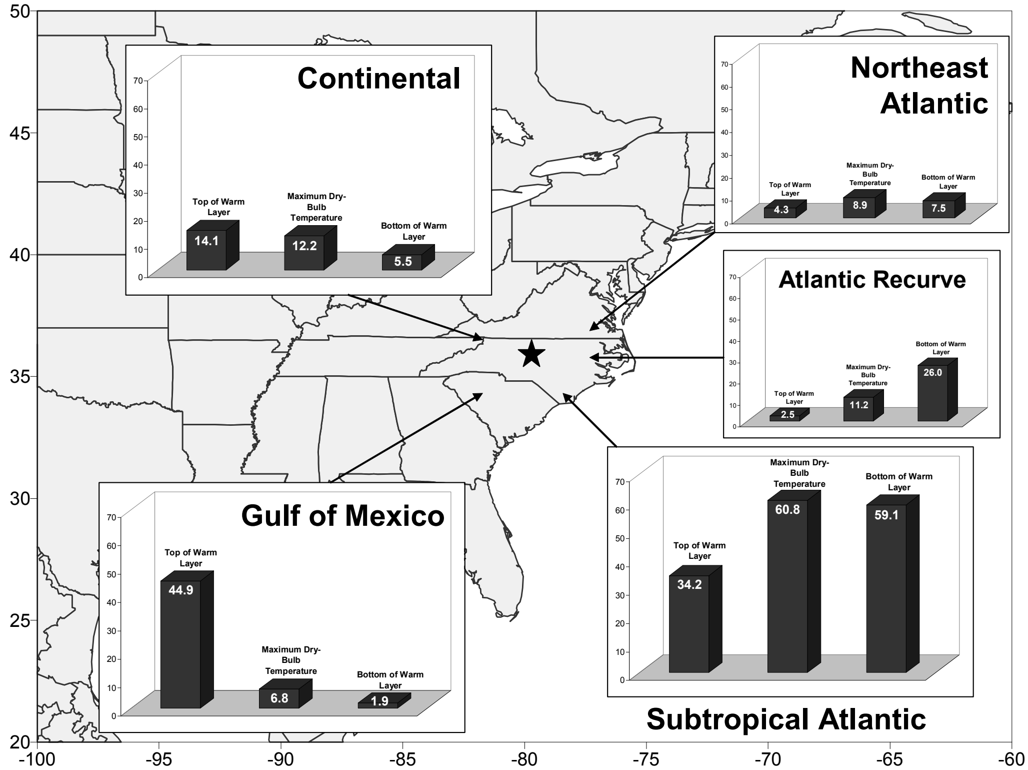

Figure 7. Summary of the percent contribution of each classification region to the total moisture received at each elevation over GSO.

The anticyclonic curvature exhibited in the air parcel trajectory plots (except at the top of the warm layer) bears some resemblance to the anticyclonically curved component of the cold conveyor belt model described by Carlson (1980) and reexamined by Shultz (2001) using a mesoscale model. Easterly flow in the low-levels associated with a cold conveyor belt-like feature has been noted during winter storms in the Carolinas, but primarily in the context of cold layer erosion (Lackmann and Stanton, 2004). The trajectory plots presented in this study suggest that air parcels arriving via the Atlantic Ocean may be connected with either cold layer erosion or warm layer maintenance. Examining air parcel trajectories at different stages of each FZ event may help clarify the character of the cold conveyor belt, particularly under varying synoptic settings.

This study investigated airflow and moisture transport over a synoptic scale (i.e., temporal resolution of 3 days and spatial resolution of 2.5°). It is clear, however, from the curvature of the airstreams and their points of origin that extrapolation of trajectories beyond 72-hr would likely reveal more remote sources of moisture. At the top of the warm layer, anticyclonically curving trajectories over the Gulf of Mexico beginning 72-hr prior to the FZ time at GSO likely encountered the Atlantic MBL as much as 240-hr (10 days) prior to the FZ time. Such a trajectory may align spatially with the synoptic-scale trajectories taken by parcels at the other three levels examined in this study (see Figs. 1 and 4). A cursory examination of the 500-hPa geopotential height field at each FZ time suggested that in most cases these parcels descended along the leading branch of a departing shortwave ridge, recurving anticyclonically along the ascending branch of an approaching shortwave trough. For air parcels at the top of the warm layer, this trajectory may instead be embedded within a more persistent, long wave feature (e.g., circumpolar vortex). In other cases, trajectories at the top of the warm layer curved cyclonically over the Gulf of Mexico, suggesting that these parcels may have entrained moisture from the Pacific Ocean beyond 72-hr prior to the FZ time.

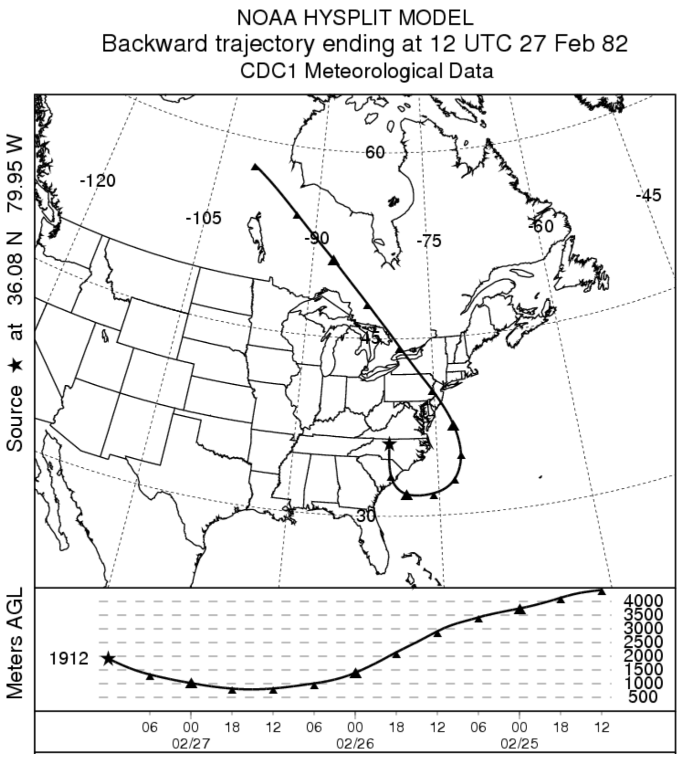

Figure 8. Horizontal and vertical airstream trajectory (72-hr) for the air parcel arriving at the level of maximum dry-bulb temperature over GSO (12 UTC 27 February 1982).

A more detailed multi-scale analysis of FZ should include examination of mesoscale features and processes that influence moisture transport and precipitation intensity. An earlier study by Hunter *et al.* (2001) suggested that ice crystals from upstream convective clouds could be advected northward over a west-to-east oriented surface front and "seed" low-level clouds above the downwind subfreezing air mass. The tops of these convective clouds were generally found to be between 700 and 600 hPa, which we identified as the level where southwesterly winds predominate over central North Carolina during FZ events. Moreover, the predominant trajectory of air parcels at the top of the warm layer (near cloud-top between 725 and 700 hPa) was from the southwest over the Gulf of Mexico. These results add further support to the hypothesis that ice crystals from the tops of convective clouds may be advected downwind into a region of frozen or freezing precipitation. Additionally, a more detailed analysis of the thermodynamic characteristics of air parcels may benefit from higher resolution datasets (e.g., 40 km EDAS) which have been shown to more accurately represent the vertical component of the three-dimensional trajectories at subsynoptic scales (B. Perry, personal communication).

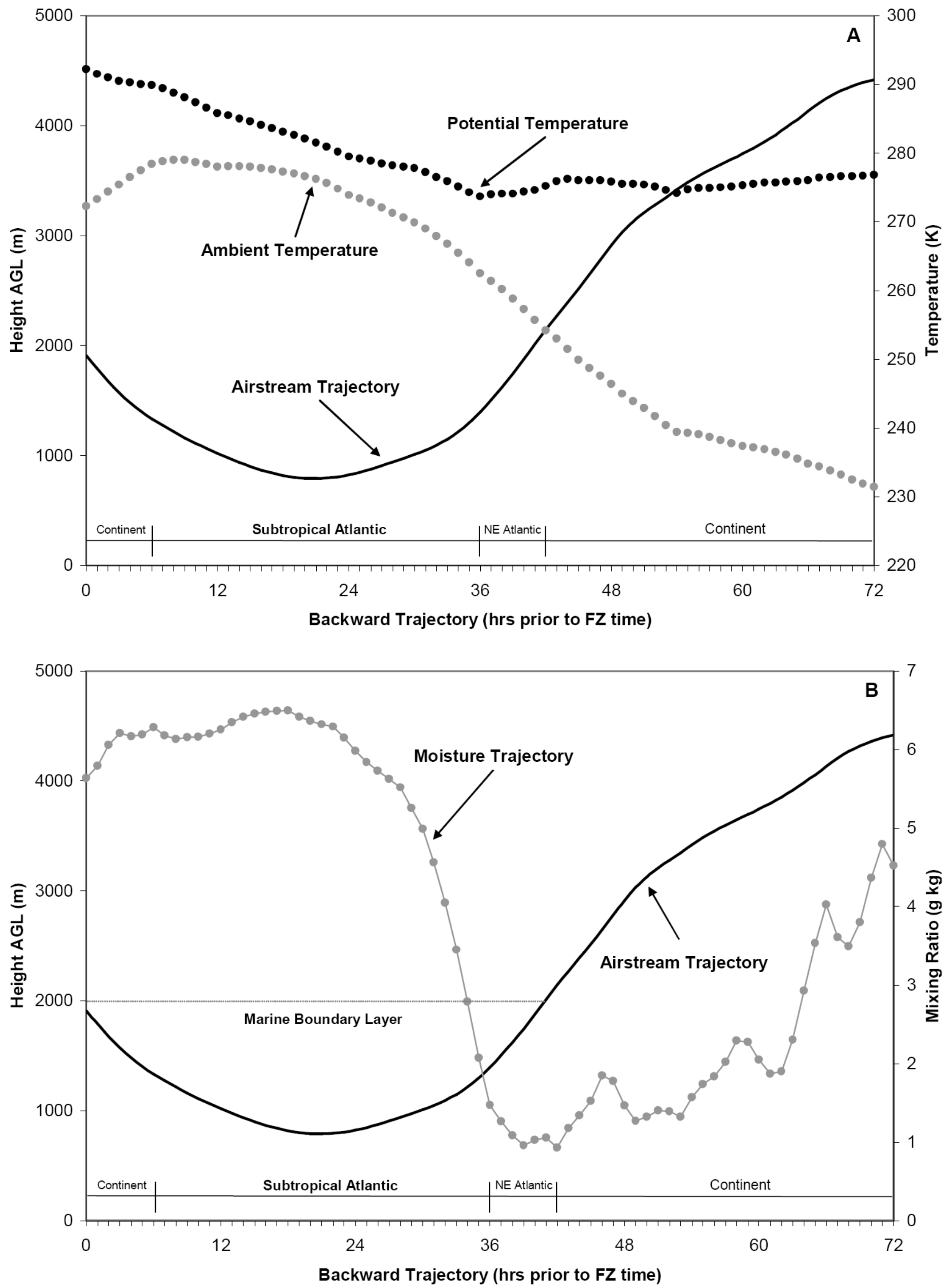

Figure 9. Diagnoses of the air parcel in Figure 10 each 1-hr for (A) height AGL (m), potential temperature (K) and ambient air temperature (K), and (B) height AGL (m) and mixing ratio (g kg^{-1}). Land-water boundaries are demarcated on the abscissa in both (A) and (B). The height of the marine boundary layer (2 km) is demarcated in (B).

In summary, observations made in this study indicate that sensible and latent heat fluxes off the Atlantic Ocean contribute significantly to the moisture and warmth in the elevated warm layer over central North Carolina. This may have important implications in the forecasting of freezing rain in the region if Atlantic sea-surface temperatures continue to increase under current climate change scenarios. The influence of trajectories over the Gulf of Mexico may also result in a more efficient "seeder-feeder" process over the region of freezing precipitation.

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