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The 10 January 2011 Southeast Ice Storm: Evaluating Ageostrophic Contributions to Boundary Layer Thermal Balance, Surface Winds and Temperature Advection to Anticipate Cold Air Damming Evolution and Predict Precipitation Type

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ABSTRACT

During the morning of 10 January 2011 an ice storm affected most of the National Weather Service (NWS) Charleston, South Carolina (SC) forecast area. This event featured a cold air damming (CAD) regime marked by a strong surface high pressure and a dry, cold air mass with boundary layer wet bulb temperatures at or below 0°C. Freezing rain developed as warm, moist air was forced above this environment. Advection of cold, dry air sustained boundary layer evaporational cooling and outweighed warming processes produced by the moderate to heavy freezing rain, which supported a period of rapid ice accretion on exposed surfaces at all but the far southern locales of the NWS Charleston, SC forecast area. Numerical model forecasts of this CAD event and associated rapid ice accretion proved accurate across most inland counties of the NWS Charleston, SC forecast area. Across coastal and southern counties of the NWS Charleston, SC forecast area, model guidance prior to the onset of precipitation depicted erosion of the periphery of the CAD regime by a combination of processes including inland penetration of the coastal front, changing any freezing precipitation initially supported by evaporational cooling to warm rain before major travel impacts occurred. Indeed, this scenario conforms to climatology and was assigned a high probability of occurrence by objective guidance and operational forecasters. However, during the morning of 10 January 2011 cold air expanded slightly farther south and east than expected during the period of heaviest precipitation. This unusual expansion of the CAD regime into coastal areas was facilitated by a chain of events that began with the ageostrophic maintenance of cold, dry air and dominance of the inland CAD regime. Mean sea level pressure rises within this inland cold dome and concurrent mean sea level pressure falls associated with the coastal front enhanced the isallobaric component of the ageostrophic wind, which eventually dominated the surface flow. The resulting offshore surface wind advected cold, dry, stable boundary layer air into population centers near the coast and, in turn, disrupted the normal onshore progression of the coastal front and associated warmer marine layer. A post-mortem, concurrent examination of isallobaric winds and the evolution of the surface wet bulb temperature offered important clues to CAD expansion and associated precipitation type changes along the coast during the morning of 10 January 2011. Additionally, this post-mortem adds to prior research by showing that routine evaluation by forecasters of specific meteorological fields and diagnostics may lead to more effective assessment of the mesoscale aspect of CAD evolution. Forecasters can apply this diagnosis to more accurate near-term precipitation type forecasts during CAD events in the coastal southeast U.S.

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1. Introduction

During the morning hours of 10 January 2011, a significant ice storm impacted a large portion of the National Weather Service (NWS) Charleston, South Carolina (SC) forecast area (Figs. 1-2). This event featured a cold air damming (CAD) regime. CAD or "wedge" events are not uncommon during the winter months across southeast Georgia (GA) and southeast SC (Bailey et al. 2003). CAD can contribute to freezing and frozen precipitation events across this region. However, freezing precipitation events remain rare across the NWS Charleston SC forecast area (Gay and Davis 1993; Fig. 3) because this region frequently lies at the southern periphery of the CAD affected area, where low-level cold air is often eroded by myriad processes that warm the boundary layer. Lackmann (2002) summarized boundary layer warming processes active during moderate to heavy freezing rain events. Further, Bell and Bosart (1988) addressed the role of boundary layer destabilization in promoting mixing and vertical momentum transfer that erode the periphery of the CAD regime and contribute to the formation and inland penetration of the coastal front. The roles of the coastal front and the coastal low in CAD erosion were summarized by both Stanton (2003) and Green (2006). As described by Riordan (1989) and Raman et al. (1998) in further detail, the coastal front frequently pushes inland across this region and greatly alters the low-level thermal environment. During the vast majority of cool season precipitation events across southeast SC and southeast GA, these warming processes dominate and either maintain surface temperatures above 0°C, supporting liquid precipitation, or readily support temperature recovery above 0°C, rapidly changing any frozen or freezing precipitation to liquid form. Normally, this climatologically favored temperature trend greatly limits the duration and impact of any freezing/frozen precipitation that might occur due to evaporational (and sublimational) cooling at the onset of a CAD precipitation event.

However, in rare instances, the replenishment of cold, dry air and continuous evaporational cooling within the boundary layer can offset warming processes, resulting in a persistent CAD regime defined by sub-freezing surface temperatures and associated freezing and/or frozen precipitation events across this region. Specifically, this paper addresses aspects of the unique event from 10 January 2011, when the combination of persistent sub-freezing surface temperatures, sustained warm advection above the boundary layer and elevated deep, moist convection produced heavy liquid precipitation rates and rapid ice accretion, especially between 1000 UTC and 1500 UTC, across a large swath of the NWS Charleston, SC forecast area.

Diagnosing the magnitude of warm advection above the boundary layer, the potential for elevated convection and associated high precipitation rates were key components of an effective forecast but remain outside the scope of this paper. Of paramount interest, properly anticipating the evolution of the CAD regime, specifically boundary layer wet-bulb temperature magnitude, distribution and trends, was indispensable to a successful precipitation-type forecast for 10 January 2011. Numerical guidance accurately depicted the persistence of the CAD regime with surface temperatures at or below 0°C and associated significant freezing rain across inland counties of the NWS Charleston, SC forecast area. Operational forecasters effectively interpreted and utilized numerical and administrative guidance (Fig. 4) to issue Winter Storm Watches, Warnings and Advisories for many counties on 9 January (Fig. 5) well prior to the onset of freezing rain at about 0900 UTC 10 January. However, boundary layer cold air and associated significant freezing rain shifted slightly farther south and east than depicted by pre-event numerical guidance and anticipated by operational forecasters. This mesoscale deviation pushed the ice storm into population centers near the coast and compelled an expansion of Warnings and Advisories into these population centers during the morning hours of 10 January (Fig. 6). For operational forecasters critical attention shifted to near-term CAD evolution and associated boundary layer spatial and temporal thermal trends along with precipitation type. A concurrent examination of observed and model depictions of low-level thermal and ageostrophic wind fields offered important clues to the evolution of the CAD regime that modulated the intensity, expanse and impact of the 10 January 2011 ice storm.

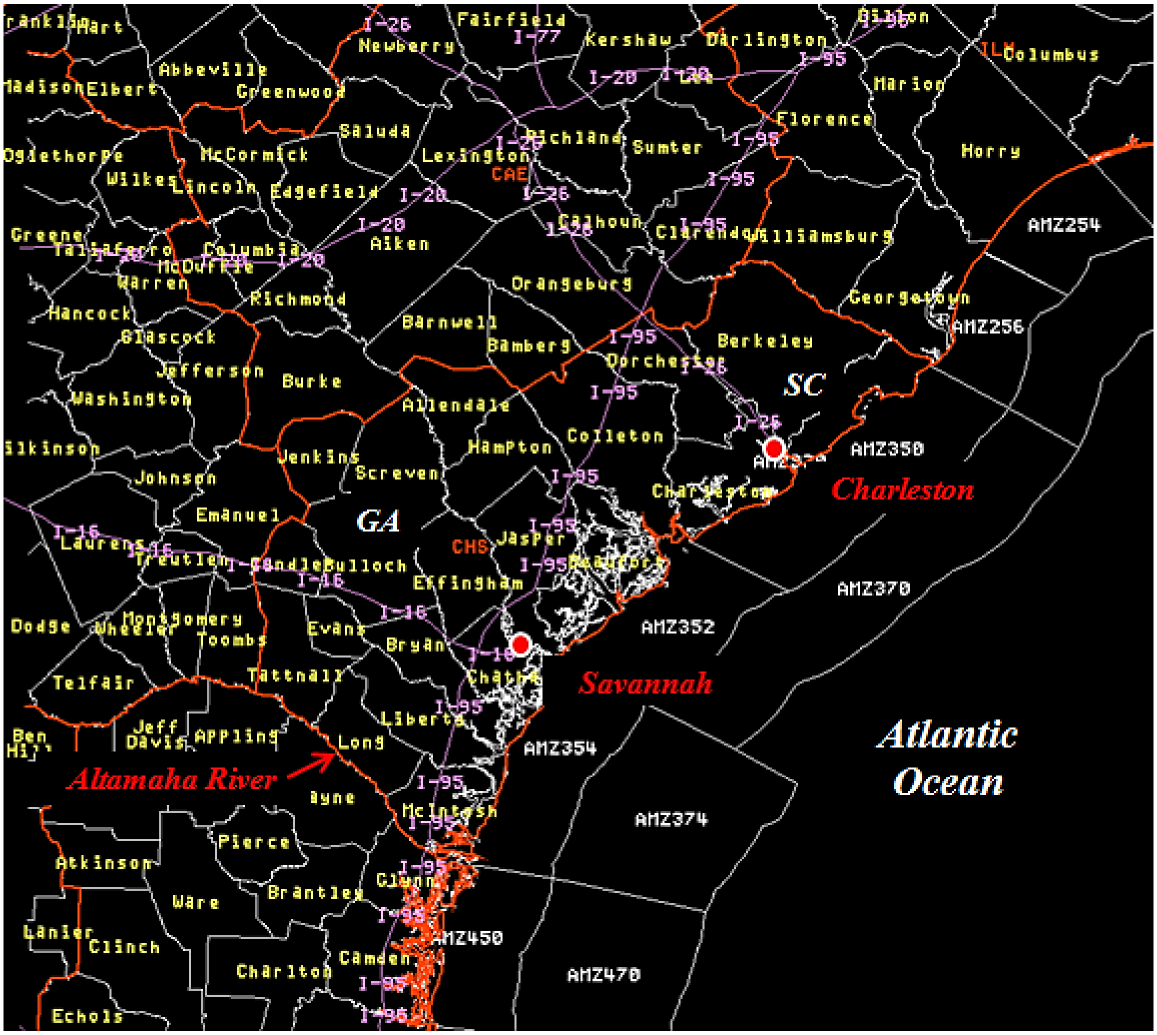

Figure 1. Detail of the NWS Charleston, SC forecast area (County Warning Areas are delineated in red), including county boundaries and names and the locations of the population centers of Charleston and Savannah. The southern terminus of the CWA is marked by the Altamaha River.

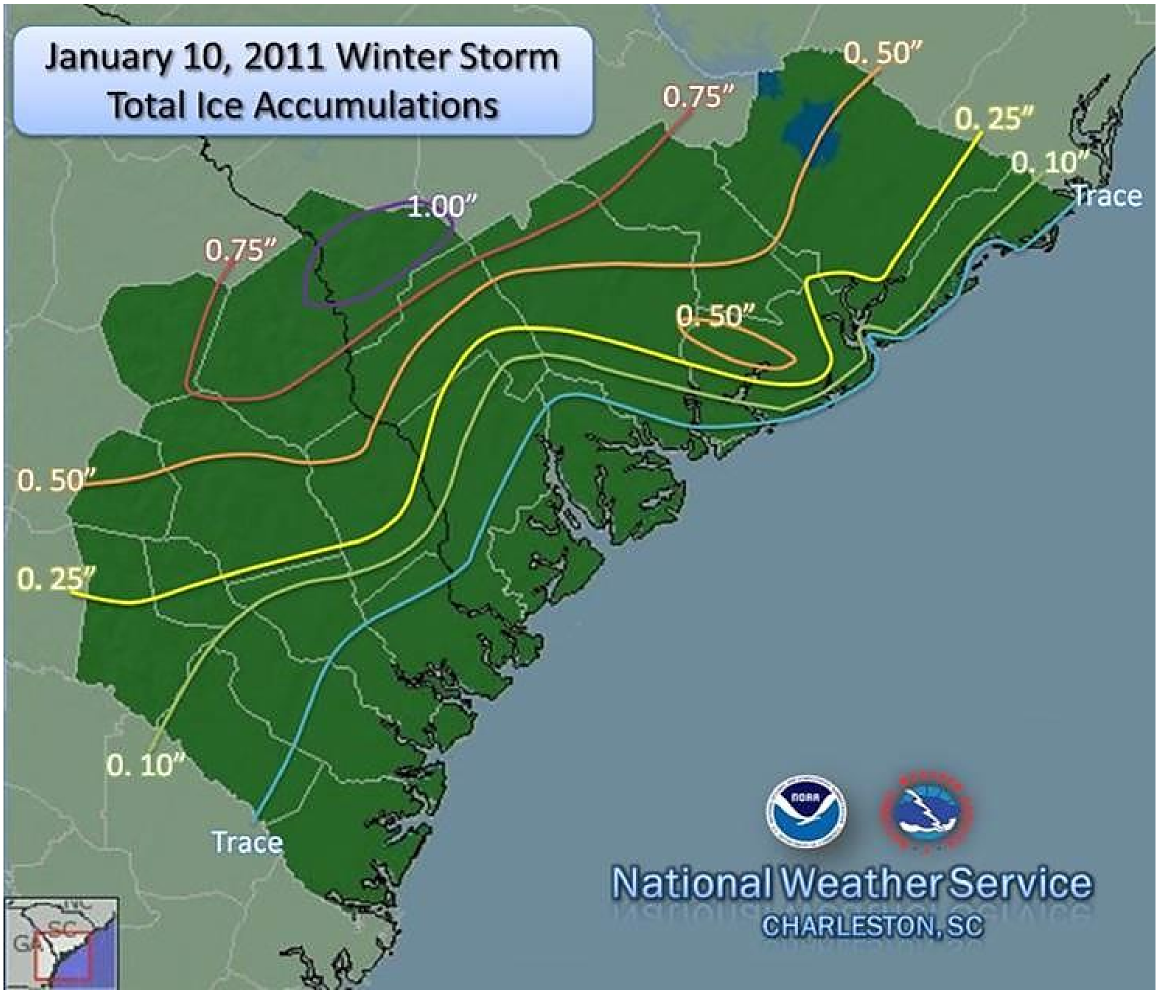

Figure 2. Ice accretion totals across the NWS Charleston, SC forecast area during the 10 January 2011 ice storm (Compiled and composed by Steven Taylor, NWS Charleston, SC Meteorologist).

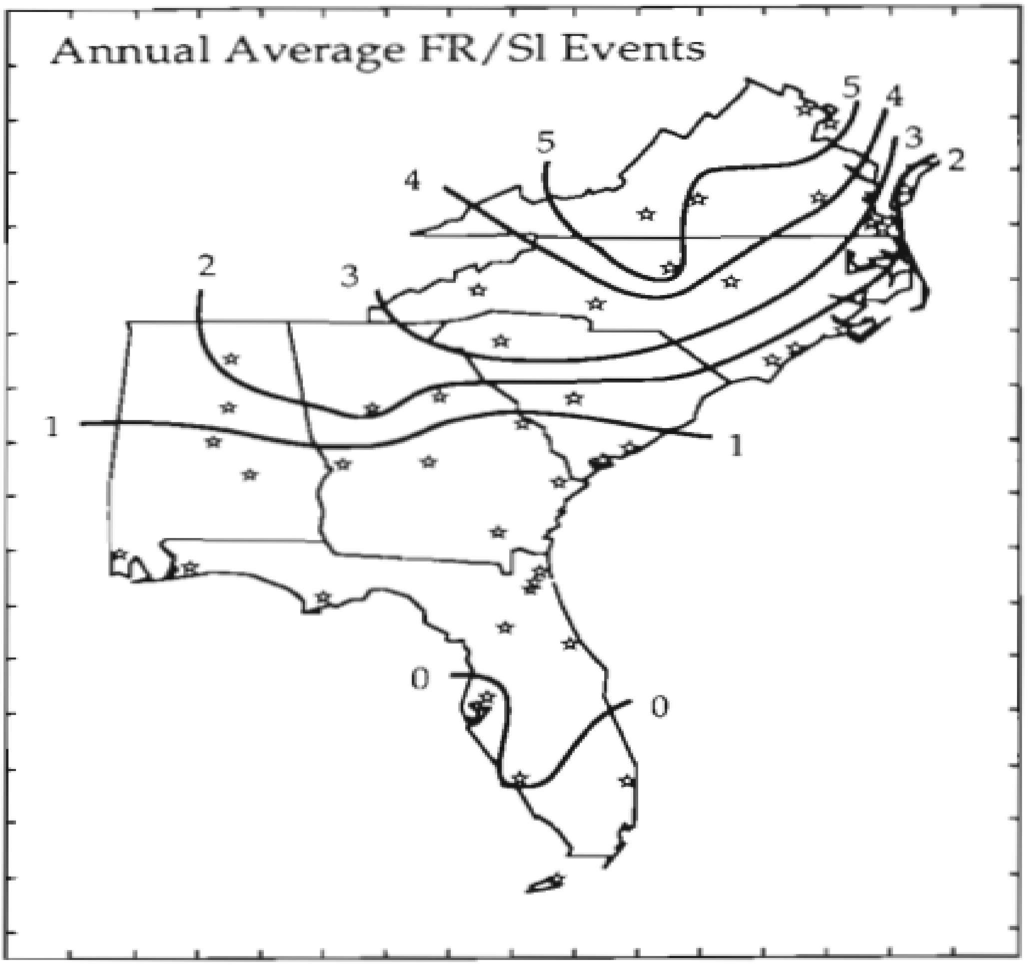

Figure 3. Southeast U.S. freezing rain and sleet climatology. Annual average number of freezing rain and sleet events is contoured. Freezing rain and sleet events only occur an average of less than once each year across the NWS Charleston, SC forecast area. (Gay and Davis 1993)

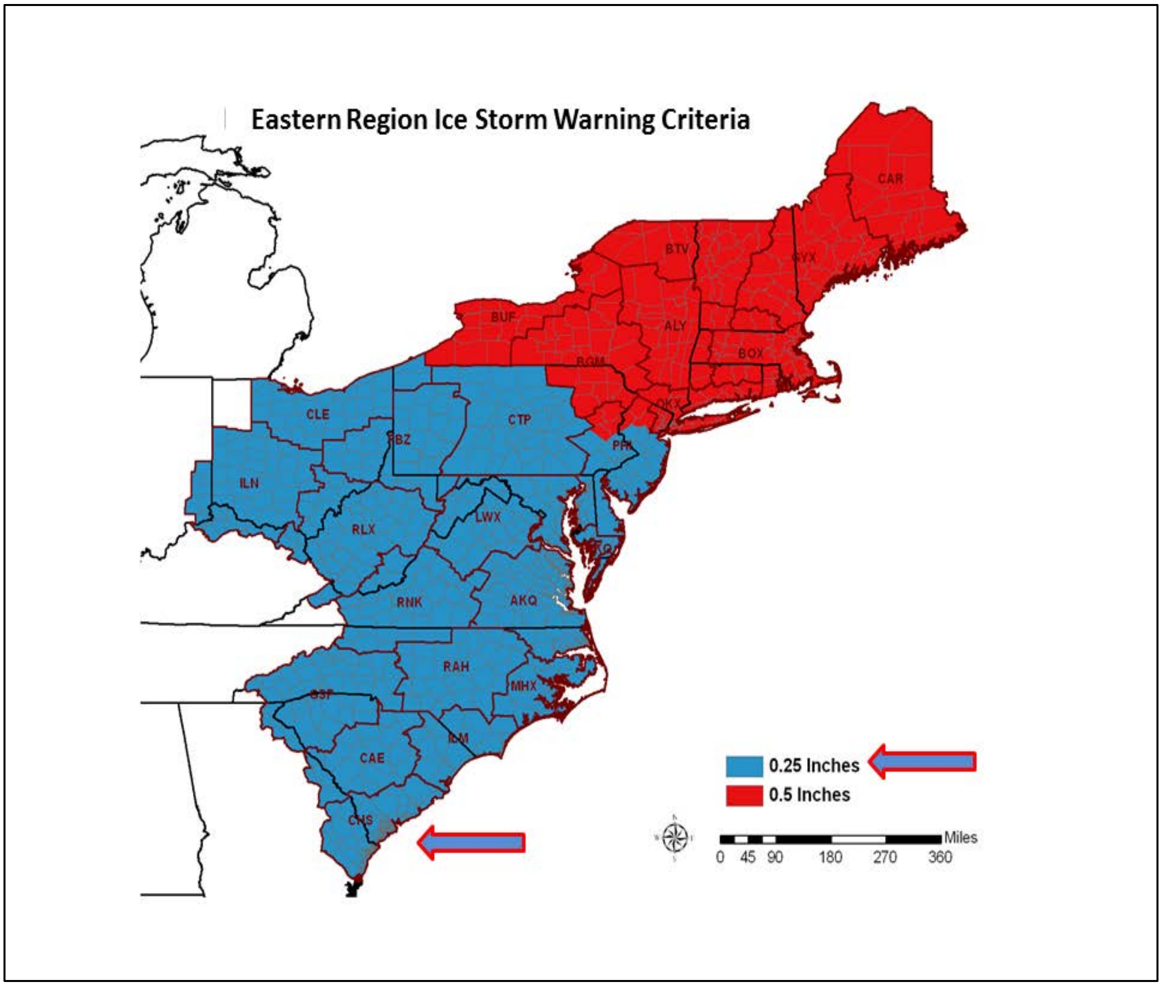

Figure 4. Ice Storm Warning Criteria for National Weather Service Eastern Region. The figure highlights the NWS Charleston, SC forecast area. Across southeast SC and southeast GA, expected ice accretion of ¼” or greater prompts Winter Storm Watches followed by Winter Storm or Ice Storm Warnings.

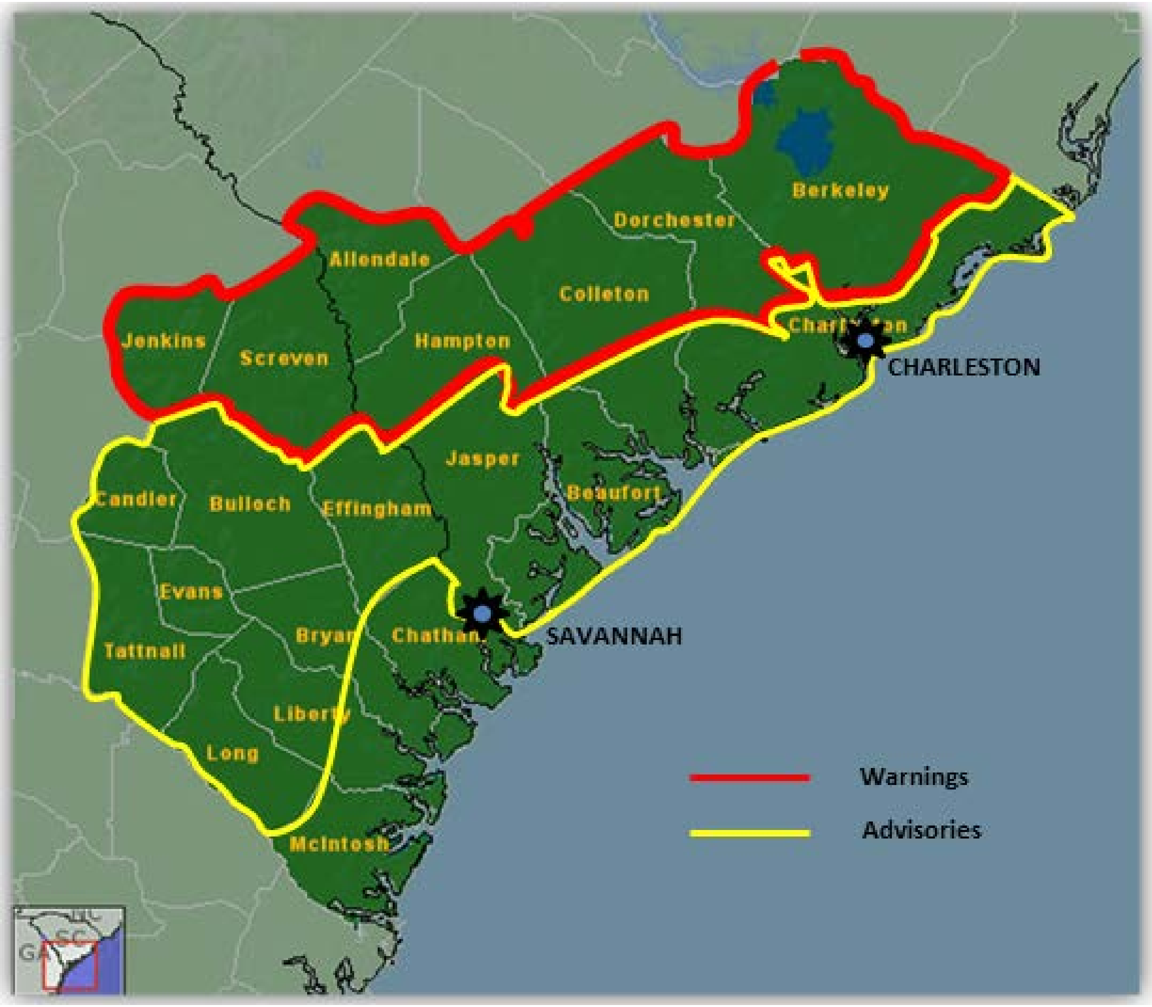

Figure 5. Summary of the initial Winter Storm Warnings and Winter Weather Advisories issued 9 January 2011 (prior to the onset of precipitation), for the NWS Charleston, SC forecast area, valid 10 January 2011.

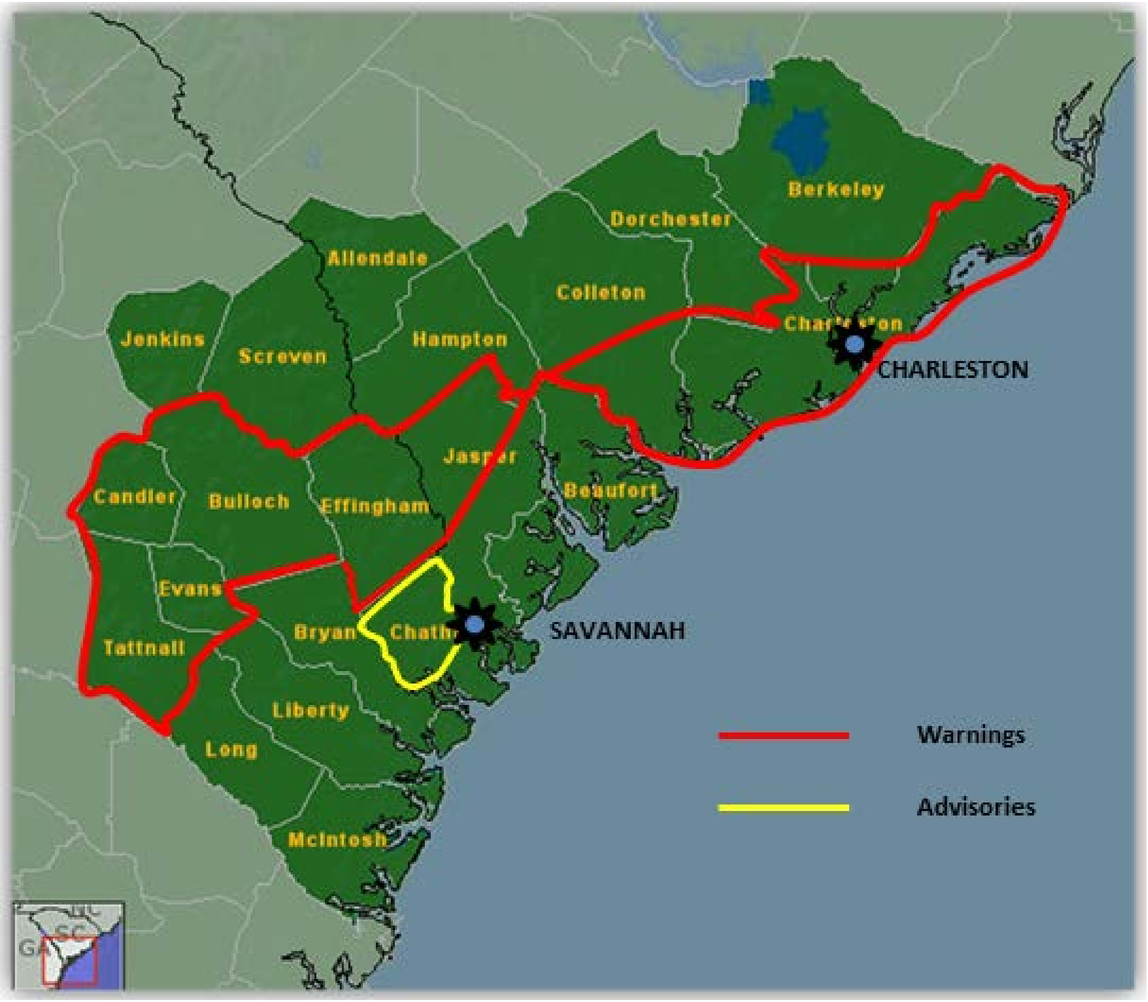

Figure 6. Expansion of NWS Charleston, SC Winter Storm Warnings and Winter Weather Advisories during the morning of 10 January 2011.

2. Data and Methodology

Kinematic and thermodynamic parameters were examined and compared using the 0000 UTC and 0600 UTC 10 January 2011 operational runs of the North American Mesoscale Model, displayed at 20 km resolution (NAM20), as well as the 1000 UTC 10 January Rapid Update Cycle Model, displayed at 40 km resolution (RUC40). Specifically, NAM and RUC forecasts of surface wet bulb temperatures, 1000 hPa ageostrophic winds, surface pressure gradients and isallobaric winds and surface wet bulb temperatures were examined and compared with 1200 UTC 10 January surface observations. Also, base reflectivity radar data was obtained from the National Climatic Data Center. Finally, NWS employees, law enforcement, SKYWARN® spotters, local media and the public provided ice accumulation reports, which were compiled and disseminated by the NWS Charleston, SC staff.

3. Results

a) Event Overview

By 2100 UTC 9 January, arctic high pressure had pushed a cold front south of Florida, and a cold, very dry air mass had overspread the southeast U.S. including southeast South Carolina and southeast Georgia (Fig. 7). This dry onset (CDRY) CAD regime in the mid-Atlantic and southeastern states was defined in the classification scheme developed by Bailey et al. (2003). By 1200 UTC 10 January, the surface analysis depicted a surface low over the northern Gulf of Mexico and a CAD/wedge regime in place east of the Appalachian Mountains (Fig. 8) Meanwhile, by 1200 UTC 10 January low- to mid-level moisture transport supported by an intense low-level jet, isentropic ascent and elevated destabilization produced an expanding shield of convective precipitation, which overspread southeast Georgia and southeast South Carolina (Fig. 9).

Precipitation that began as a mix of snow, sleet and freezing rain changed to all freezing rain everywhere except far southern portions of the Charleston, SC forecast area, specifically south of Interstate 16 and close to the coast in southeast GA. The persistent sub-freezing temperatures supporting freezing rain offered unambiguous evidence that the boundary layer thermal balance favored the replenishment of dry, cold air and maintenance of evaporational cooling over the thermodynamic and diabatic warming processes. Further, the CAD regime and associated cold boundary layer air spread south and east during the morning of 10 January, supporting freezing rain across population centers near the coast, including the Charleston, SC and Savannah, GA areas. The most significant rainfall rates occurred during a 3 to 5 hour period between 1000 UTC and 1500 UTC, sufficient to produce ice accretion amounts around one-quarter inch (Fig. 2) and significant travel disruptions across a wide swath of southeast counties of GA and SC. Well inland, localized ice accumulations around one inch damaged trees and power lines.

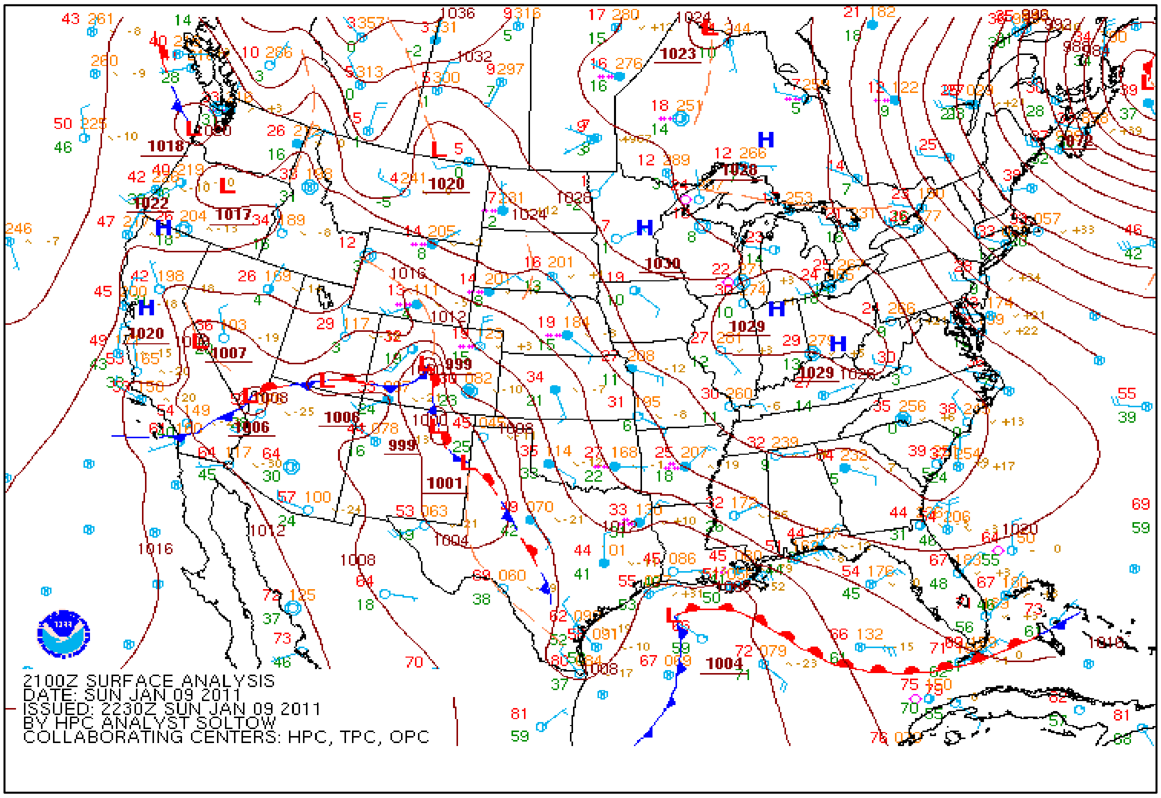

Figure 7. Surface analysis valid 2100 UTC 9 January 2011 (NWS Weather Prediction Center archive).

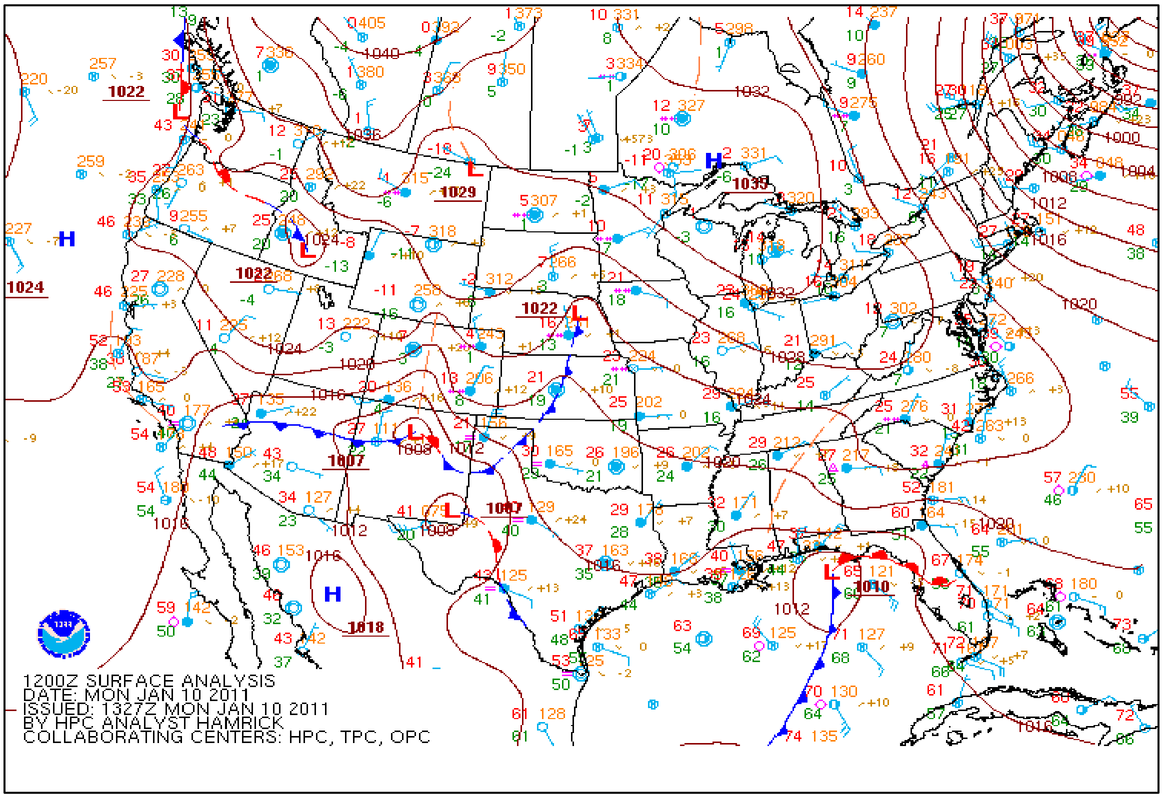

Figure 8. Surface analysis valid 1200 UTC 10 January 2011 (NWS Weather Prediction Center archive).

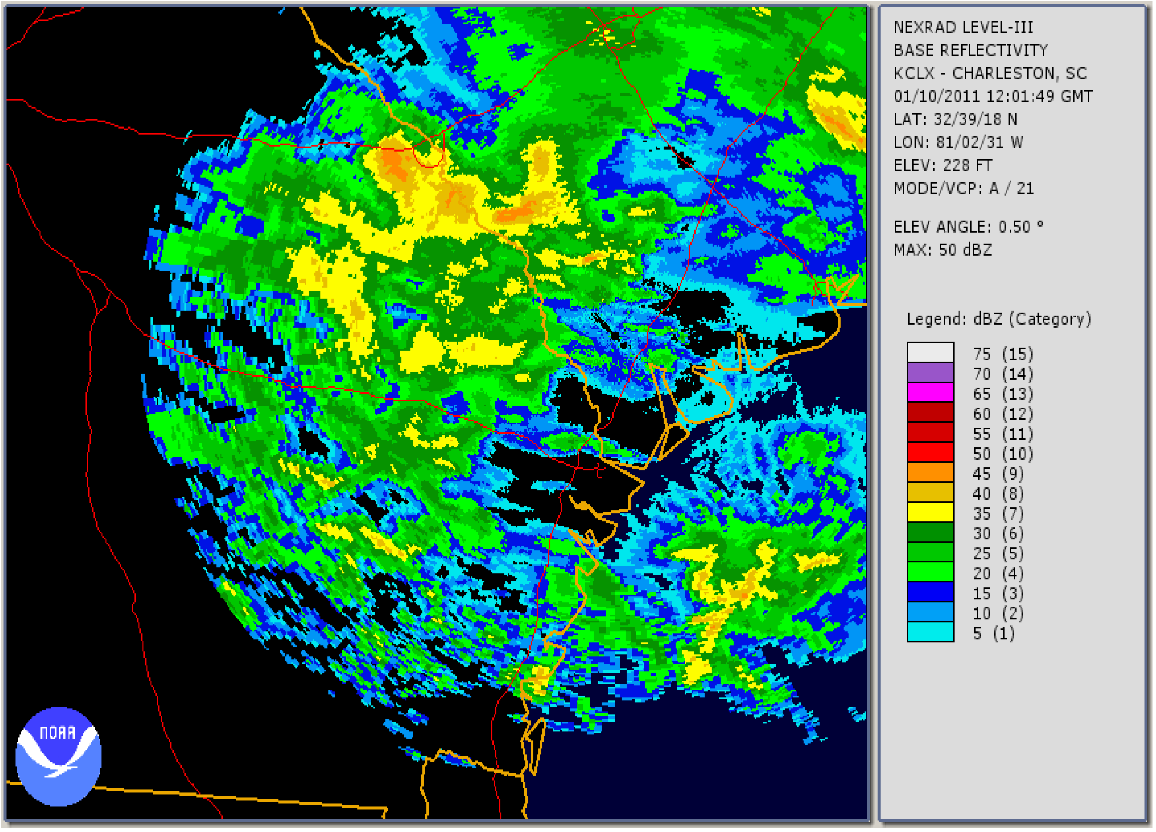

Figure 9. KCLX (Charleston SC) WSR-88D 0.5 degree base reflectivity, valid 1201 UTC 10 January 2011 (National Climatic Data Center archive).

b) Forecaster Challenges

In all cases, guidance valid for the morning of 10 January depicted strong warm advection aloft, and model soundings at inland locations portrayed classic warm air advection (WAA) signatures with elevated layers well above 0°C and sufficiently deep to completely melt snowflakes accompanied by sufficiently cold surface temperatures to produce freezing rain (Fig. 10). Indeed, operational guidance continued to forecast sufficient liquid equivalent precipitation amounts to support significant ice accretion across inland counties. The earlier guidance had prompted the issuance of initial Warnings and Advisories on 9 January (Fig. 5). Across a swath of territory, which included coastal southeast GA and southeast SC as well as inland southeast GA counties between Interstate 16 and the Altamaha River (Fig. 1), operational guidance consistently forecasted mainly liquid precipitation or a brief period of freezing/frozen at the event onset during the early morning of 10 January, with limited travel impacts as the CAD regime eroded and surface temperatures rose above 0°C. Thus, forecasters initially issued either Winter Weather Advisories or no winter weather headlines for this area. Importantly, this swath of territory includes more than 50 percent of the total population of the NWS Charleston, SC forecast area and encompasses the Charleston, SC and Savannah, GA metropolitan areas. From a climatology standpoint, this scenario conformed to the "normal" conceptual model applied by NWS Charleston, SC forecasters. The 0600 UTC NAM20 forecast of surface winds, valid at 1200 UTC (Fig. 11), depicted the coastal front over coastal counties north of the Savannah River entrance, as illustrated by an onshore component of flow across coastal counties and marked by axis of confluence as described by Raman et al. (1998). The 1000 UTC RUC40 forecast of surface winds, valid at 1200 UTC (Fig. 12), displaced the coastal front farther south and east as compared with the 0600 UTC NAM20, implying that cold air would approach coastal population centers. As will be discussed, even subtle differences between model and observed wind direction would alter the relative positions of the inland cold dome and coastal front and would translate into critical surface temperature differences that governed precipitation type, particularly close to the coast.

As the precipitation event commenced during the early morning of 10 January, the near-term forecasters faced a challenging scenario. How would the CAD regime evolve? Would Warnings/Advisories already in effect for inland counties suffice, or would significant freezing rain expand into population centers, where either Advisories or no headlines existed, during the morning rush hour?

Before proceeding to a discussion about useful operational parameters and applications for this scenario, this paper will present a brief review of CAD precipitation thermodynamics, ageostrophic processes and erosion.

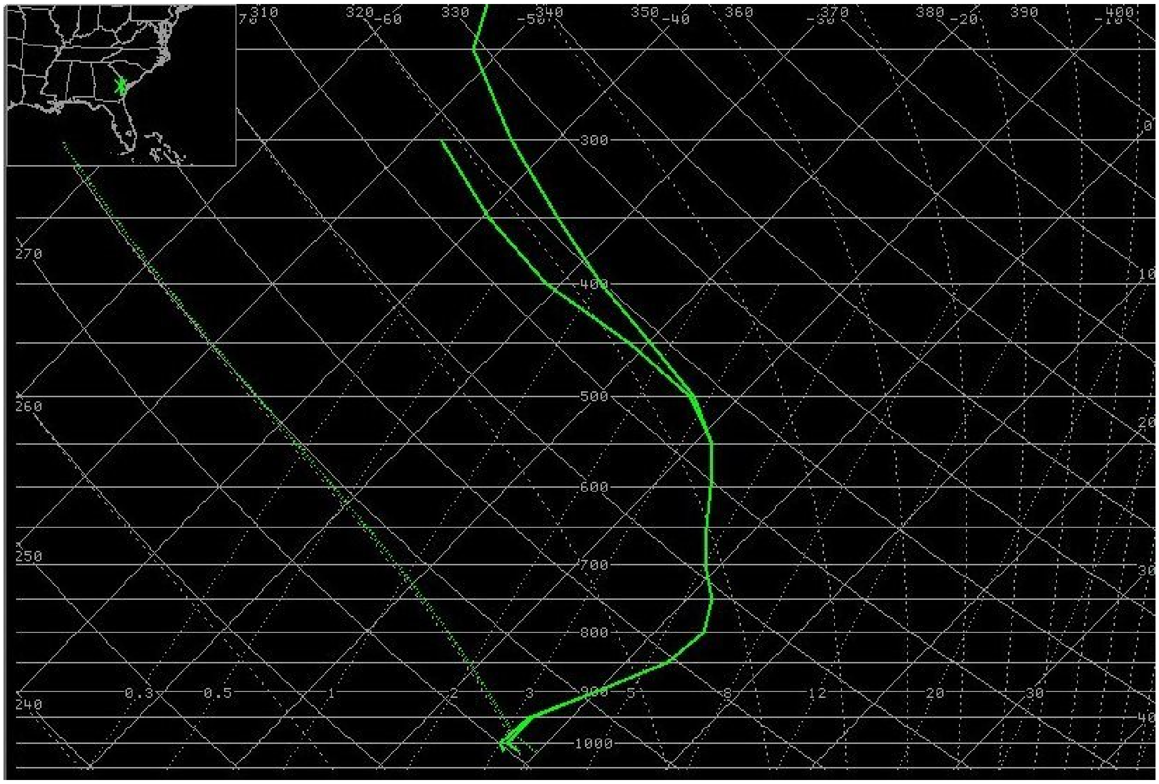

Figure 10. The 1000 UTC 10 January 2011 RUC40 forecast sounding, valid 1200 UTC at KTBR (Statesboro, GA).

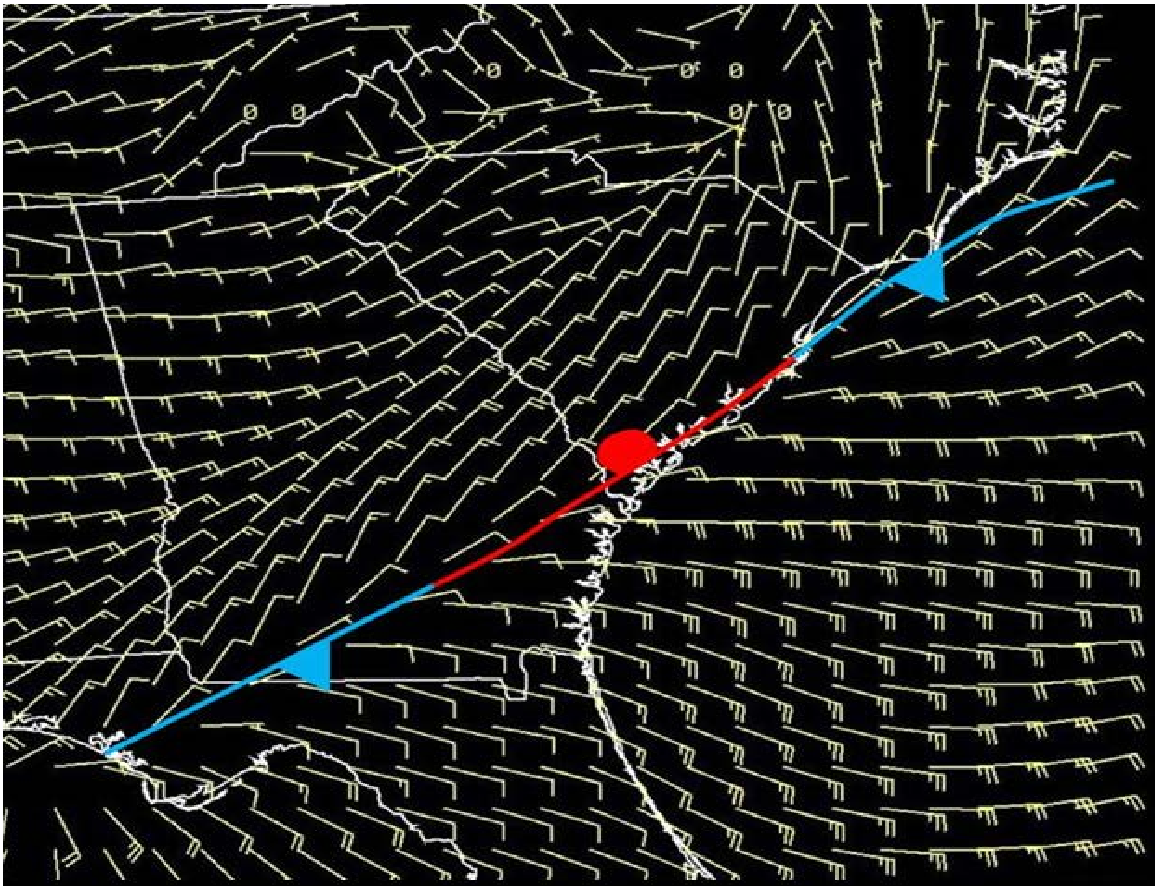

Figure 11. The 0600 UTC 10 January 2011 NAM20 forecast of surface winds valid 1200 UTC. The approximate forecast position of the coastal front has been added.

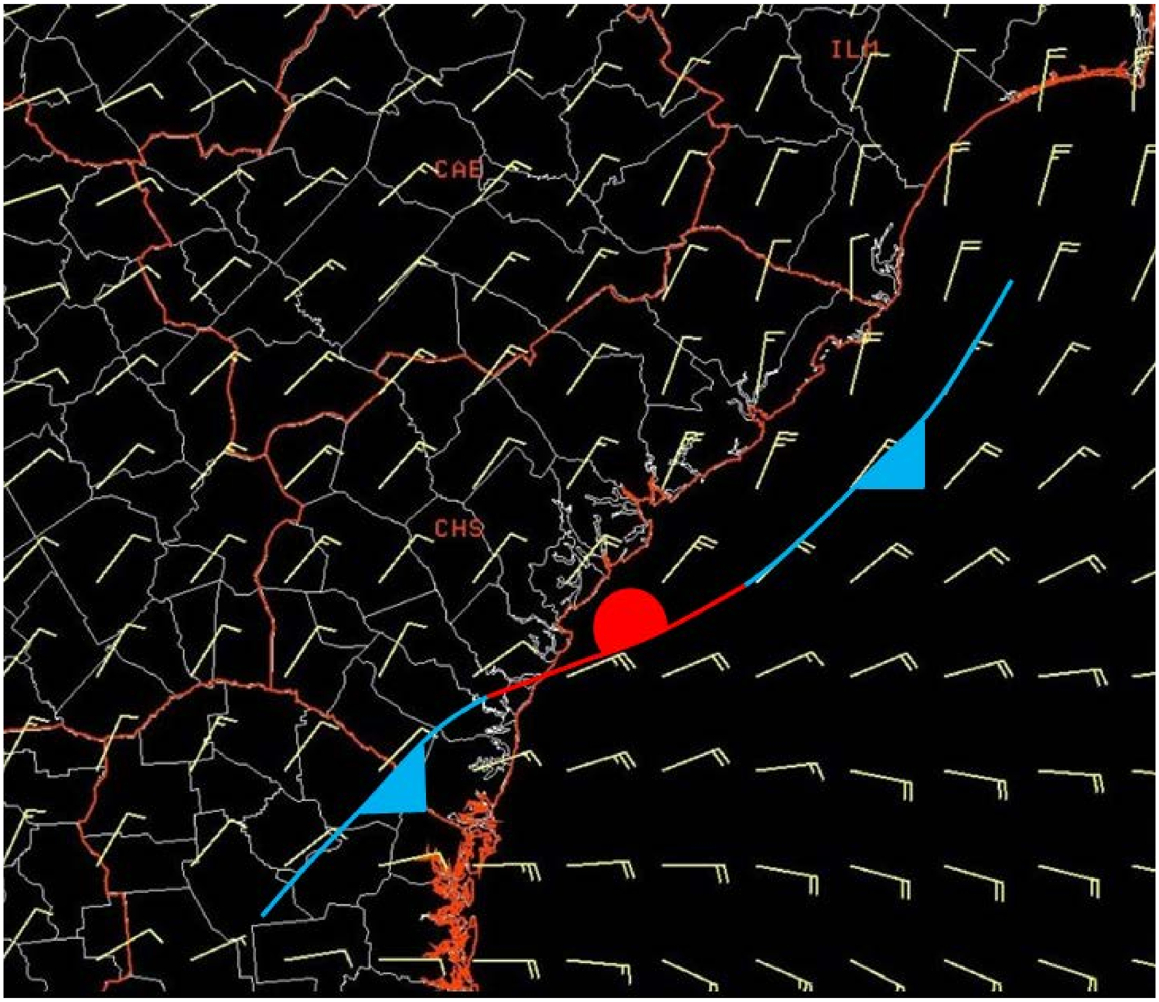

Figure 12. The 1000 UTC 10 January 2011 RUC40 forecast of surface winds valid 1200 UTC. The approximate forecast position of the coastal front has been added.

c) Precipitation Thermodynamics

Lackmann (2002) illustrated how moderate to heavy freezing rain can warm the boundary layer. Absent the advection of cold, dry boundary layer air into the precipitation area, latent heat of fusion, sensible heat transfer by falling raindrops and radiative heat transfer by clouds warmer than 0°C (Fig. 13) can raise the boundary layer temperature around 2°C. At temperatures close to 0°C, this subtle temperature increase can translate to a change from freezing rain to rain. Only a fresh supply of cold, dry boundary layer air can offset these warming processes. Surface wet bulb temperatures can offer compelling evidence of this process: where wet bulb temperatures remain at or below 0°C despite moderate/heavy liquid precipitation, the boundary layer thermal balance favors evaporational cooling as the CAD environment resupplies cold, dry air.

Prior to and during the 10 January ice storm, forecasters utilized the Advanced Weather Interactive Processing System (AWIPS) to assess observations and model forecasts of boundary layer thermal trends, specifically, surface wet bulb temperature tendencies. Early on, this evaluation established that the replenishment of low-level, dry, cold air would continue inland of the coast and far southern locales, prolonging evaporational cooling. As expected, this cooling offset previously discussed warming processes, maintained the CAD regime and associated surface temperatures at or below 0°C and supported a major ice storm across interior sections of southeast SC and southeast GA. Indeed, in large measure, model forecasts of surface wet-bulb temperatures formed the basis for winter weather Watches, Warnings and Advisories that were initially issued for these areas prior to the onset of precipitation. To expand this application of thermodynamic principles to near-term forecast adjustments, a brief discussion of ageostrophic processes is useful.

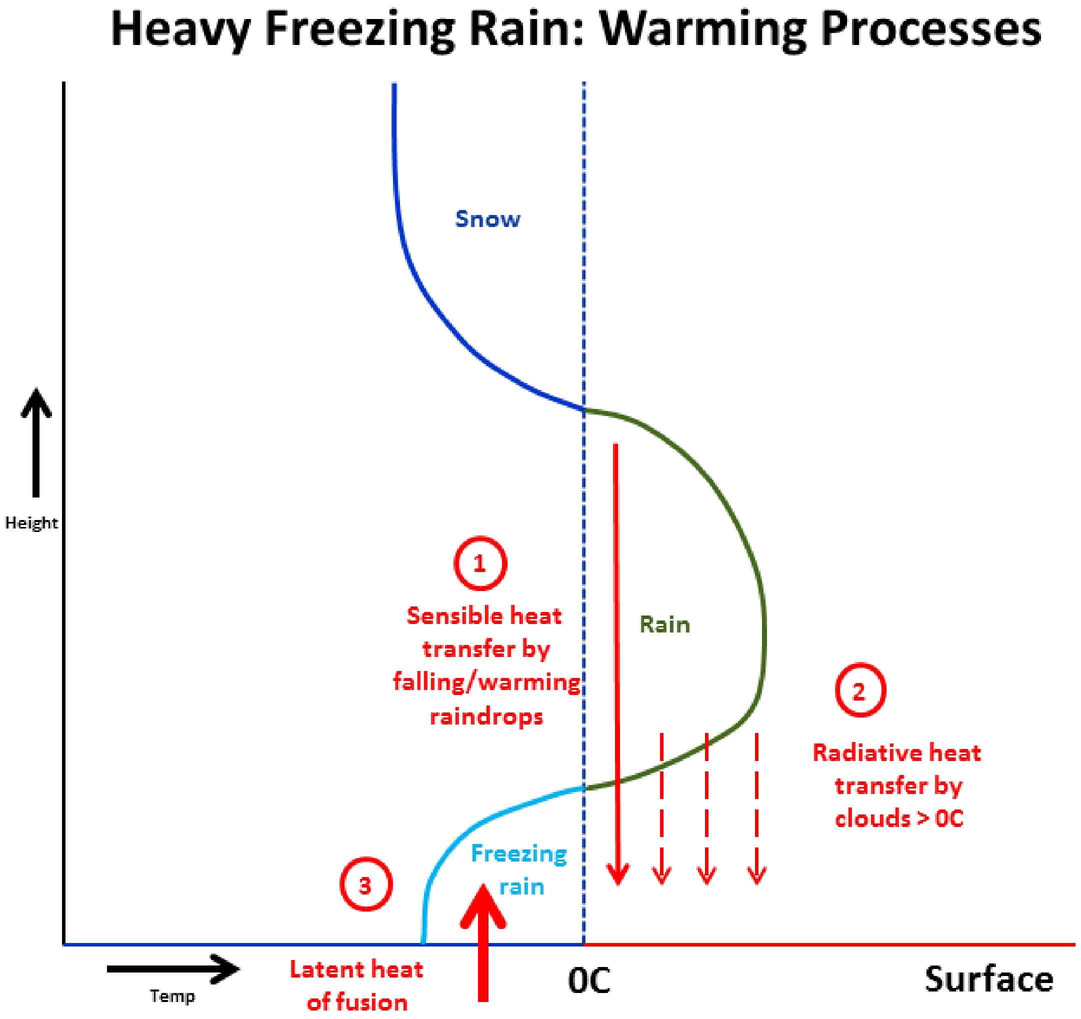

Figure 13. Schematic of boundary layer warming processes during moderate/heavy freezing rain (Adapted from Lackmann 2002). To maintain significant ice accumulation, cold, dry boundary layer air must be replenished to maintain evaporational cooling and offset these warming processes.

d) Ageostrophic Winds in CAD Regimes

Forbes et al. (1987) quantified the ascendancy of the ageostrophic component of the total wind within the boundary layer during a CAD event and discussed the critical impact of boundary layer temperature advection by the ageostrophic wind within a CAD regime. Specifically, the authors demonstrated how the isallobaric component of the ageostrophic wind (and friction) can dominate the boundary layer flow. An assessment of the isallobaric contribution of the surface wind can further enhance forecaster understanding and anticipation of boundary layer thermal advection. This is especially important near the coast where the surface wind direction modulates the relative position and influence of cold continental air and warmer maritime air. NWS forecasters can view the ageostrophic winds and can approximate the isallobaric component of the surface winds utilizing parameters available through AWIPS.

e) CAD Erosion

In addition to the warming influence of moderate to heavy freezing rain, numerous additional processes can combine to erode the CAD. Across coastal sections of GA and SC, these processes are climatologically favored and are thus considered reasonable when depicted by model guidance. Bell and Bosart (1988) described how weakening boundary layer stability promotes vertical mixing of south/southeast momentum aloft into the boundary layer along the periphery of the cold dome, which is typically located near the coast. Further, these authors demonstrated that this mixing promotes surface pressure falls at the edge of the cold dome, enhancing the isallobaric wind component of the ageostrophic wind. Together the destabilization, mixing and mean sea level pressure falls promote onshore flow of warmer marine air and frequently contribute to CAD erosion. Stanton (2003) further elaborated how this shear-induced mixing (along with lower-tropospheric divergence within the cold dome) contributes to development and inland progress of the coastal front. Operational Meteorologists at coastal offices devote considerable time to diagnosing the strength and position of the coastal front during CAD and winter precipitation events, as this boundary frequently delineates precipitation types. Indeed, as the entire NWS Charleston, SC forecast area resides within 100 statute miles of the Atlantic Ocean, much of the CAD precipitation type problem centers on the position of the coastal front. Riordan (1989) and Raman et al. (1998) described the properties of coastal fronts and investigated the roles of mass confluence and diabatic processes in frontogenesis and inland progress of these boundaries. The 0600 UTC 10 January NAM20 surface wind forecast (Fig. 11) depicted the expected position of the coastal front at 1200 UTC. The 1000 UTC 10 January RUC40 surface wind forecast (Fig. 12) depicted the coastal front farther south. Considering the typical coastal CAD erosion processes discussed, these numerical forecasts of the coastal front offered further rationale for the precipitation-type forecast and for associated Watches, Warnings and Advisories issued prior to the onset of precipitation. However, even small errors in this reasonable, climatologically favored coastal front forecast could translate to major temperature and precipitation-type discrepancies.

f) Operational Applications

During the morning of 10 January, NWS Charleston, SC near-term forecasters were tasked with refining Warnings, Advisories and ice accretion forecasts as necessary. Evaluating the parameters and applying principles discussed within the previous two sections offered important clues regarding CAD evolution. Specifically, it will be explained how a concurrent evaluation of surface wet bulb temperatures and low-level ageostrophic winds, including the isallobaric component of ageostrophic winds, can highlight discrepancies in model forecasts versus observed parameters and can inform near-term forecast changes.

During the early morning of 10 January, forecasters evaluated forecasts of surface wet bulb temperatures and 1000 hPa ageostrophic winds. Examples include the 0600 UTC NAM20 and the 1000 UTC RUC40, both valid 1200 UTC 10 January (Figs. 14-15). As described by Armstrong et al. (2007), the surface wet bulb temperature (Tw) offers optimal operational utility because this thermal metric efficiently accounts for the impact of evaporational cooling; as such, Tw is an effective tool for estimating where freezing rain will occur. Both models depicted 1200 UTC 10 January surface Tw of 0°C or colder entrenched across much of the NWS Charleston, SC forecast area, away from the immediate coast and removed from far southern counties of the region. Further, the 1000 UTC RUC40 (Fig. 15) pushed critical Tw values slightly farther south and east as compared with the 0600 UTC NAM20 forecast (Fig. 14). When combined with model forecasts of the coastal front position (Figs. 11-12), this forecasted trend toward an expansion of cold air toward the coast offered a basis for precipitation type updates. However, even given the expansion of cold air depicted by the 1000 UTC RUC40, an objective analysis of the observed surface Tw at 1200 UTC (Fig. 16) revealed a gap between forecast and observed Tw values, especially within coastal counties. Significantly, this gap encompassed population centers along the coast and behind the coastal front. Forecasters had to try and reconcile this disparity to implement accurate forecast adjustments.

The 0600 UTC 10 January NAM20 (Fig. 14) and the 1000 UTC 10 January RUC40 (Fig. 15), both valid 1200 UTC, depicted a 35 to 45 kt northwesterly ageostrophic component of the total 1000 hPa wind that persisted through the 10 January morning period of heaviest precipitation. The direction and magnitude of the ageostrophic wind offered compelling evidence that the advection of low-level cold, dry air (Tw 0°C or colder) and resulting CAD maintenance and freezing precipitation was strongly modulated by the ageostrophic wind, a scenario consistent with results presented by Forbes et al. (1987). For operational forecasters, this combination of kinematic and thermal variables offered confirmation that freezing rain would impact northern and western counties of the NWS Charleston, SC forecast area and justified ongoing Warnings and Advisories in effect for this area. However, effective forecast adjustments hinged on a more detailed examination of ageostrophic parameters and the associated influence on the thermal environment and CAD evolution.

Within the NWS Charleston, SC forecast area, an accurate precipitation type forecast is highly dependent on an accurate surface wind direction forecast, because the wind direction determines the coverage and magnitude of relatively warm marine air. Forbes et al. (1987) discussed the contribution of the isallobaric component of the ageostrophic wind to the surface wind within a CAD environment. An examination of isallobaric parameters valid 1200 UTC 10 January and the associated isallobaric component of the ageostrophic wind offered important clues regarding expected surface wind direction. This wind direction forecast, in turn, provided a basis for reconciling the gap between forecast and observed Tw values near the coast (Figs. 14-16). The 0600 UTC 10 January NAM20 forecast of 3 hourly mean sea level pressure trends (Fig. 17) valid 1200 UTC depicted a couplet of surface mean sea level pressure rises focused within the core of the cold dome north/northwest of the NWS Charleston SC forecast area and mean sea level pressure falls associated with the coastal front at the periphery of the wedge centered south of the region. This pressure trend configuration directed an isallobaric component of the surface winds toward the south with a marked offshore component along the coast especially north of the Savannah River entrance, a result that verified reasonably well as shown in the 1200 UTC surface observation plot (Fig. 16).

A more complete view of the isallobaric component of the ageostrophic winds can be gained by examining the 0000 UTC 10 January NAM20 forecast of the 1200 UTC surface pressure gradient magnitude (ubar km^{-1}) (Fig. 18). The surface pressure gradient orientation clearly supported a strong isallobaric, offshore acceleration of the surface wind. As described by Forbes et al. (1987), this isallobaric component of the ageostrophic winds likely contributed greatly to the observed, marked cross isobar surface wind from the north (Fig. 16). Due to orientation of the SC and GA coastlines, a northerly wind is directed offshore across much of the NWS Charleston, SC coastal forecast area. This dominant offshore, isallobaric wind component pushed cold, dry air already entrenched and replenished across inland areas toward the coast. The progress of the cold air exceeded the expectations of forecasters when Warnings and Advisories were initially issued on 9 January and exceeded 0600 and 1000 UTC 10 January model Tw forecasts. The gap between forecast and observed Tw (Figs. 14-16) encompassed only 15-35 statute miles, but this relatively minor spatial adjustment eliminated the moderating influence of marine air at many coastal locations. As a result, significant freezing rain fell within the population center in and around Charleston, SC closing many bridges and essentially grinding motor vehicle travel to a halt during the morning commute. Freezing rain also fell across the population center in and around Savannah, GA.

Because of the proximity of the Atlantic Ocean, minor fluctuations in wind direction and associated temperatures can translate to significant changes in precipitation types and associated impacts over relatively small distances within CAD regimes. In the case of 10 January, the replenishment of cold, dry boundary layer air and the associated persistence of freezing rain during the period of heaviest precipitation shifted only about 15 to 35 statute miles south and east of areas originally anticipated by forecasters. However, considering that this relatively narrow corridor included population centers encompassing close to one million citizens during the morning rush, the impact of relatively minor spatial deviations from model guidance and importance of timely forecast adjustments becomes clear. Operational models did not explicitly depict the full expansion of low-level cold, dry air and associated significant freezing rain into areas close to the coast. Forecaster assessment of Tw forecasts and of the ageostrophic contribution to the replenishment and spread of cold, dry air sufficient to promote continued evaporational cooling and maintenance of surface wet bulb temperatures at or below 0C formed the basis for a successful initial forecast of significant freezing rain across inland counties of southeast SC and southeast GA. During the morning of 10 January, forecaster recognition of the gap between observed and forecast Tw (Figs. 14-16), combined with an assessment of the isallobaric contribution to the offshore surface wind component (Figs. 16-18) and the associated expansion of the CAD regime offered a rationale for bridging the Tw gap. This, in turn, provided a basis for critical, effective near-term precipitation type adjustments and expansion of warnings and advisories.

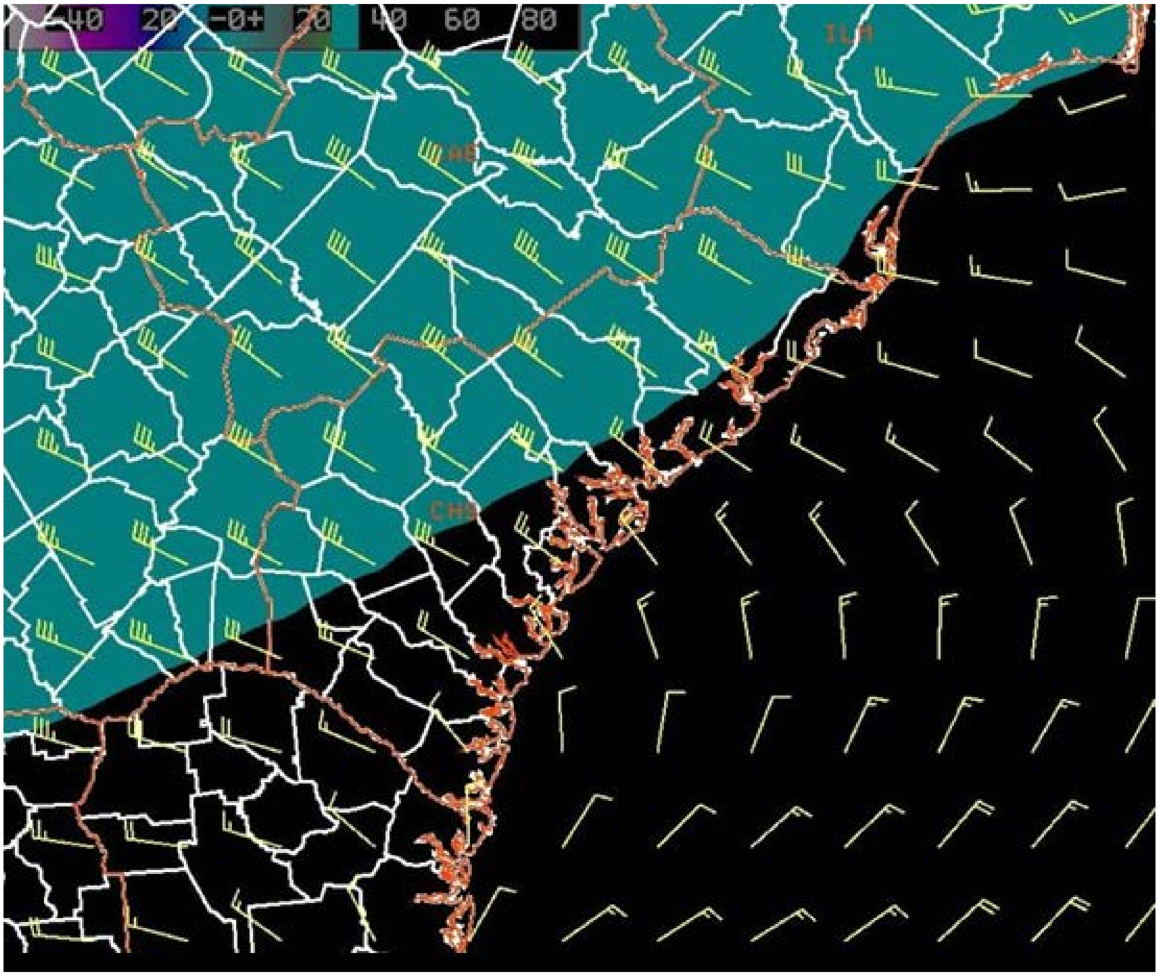

Figure 14. The 0600 UTC 10 January 2011 NAM20 depiction of surface wet bulb temperatures (0°C or colder shaded) and 1000 hPa ageostrophic winds (wind barbs) valid 1200 UTC.

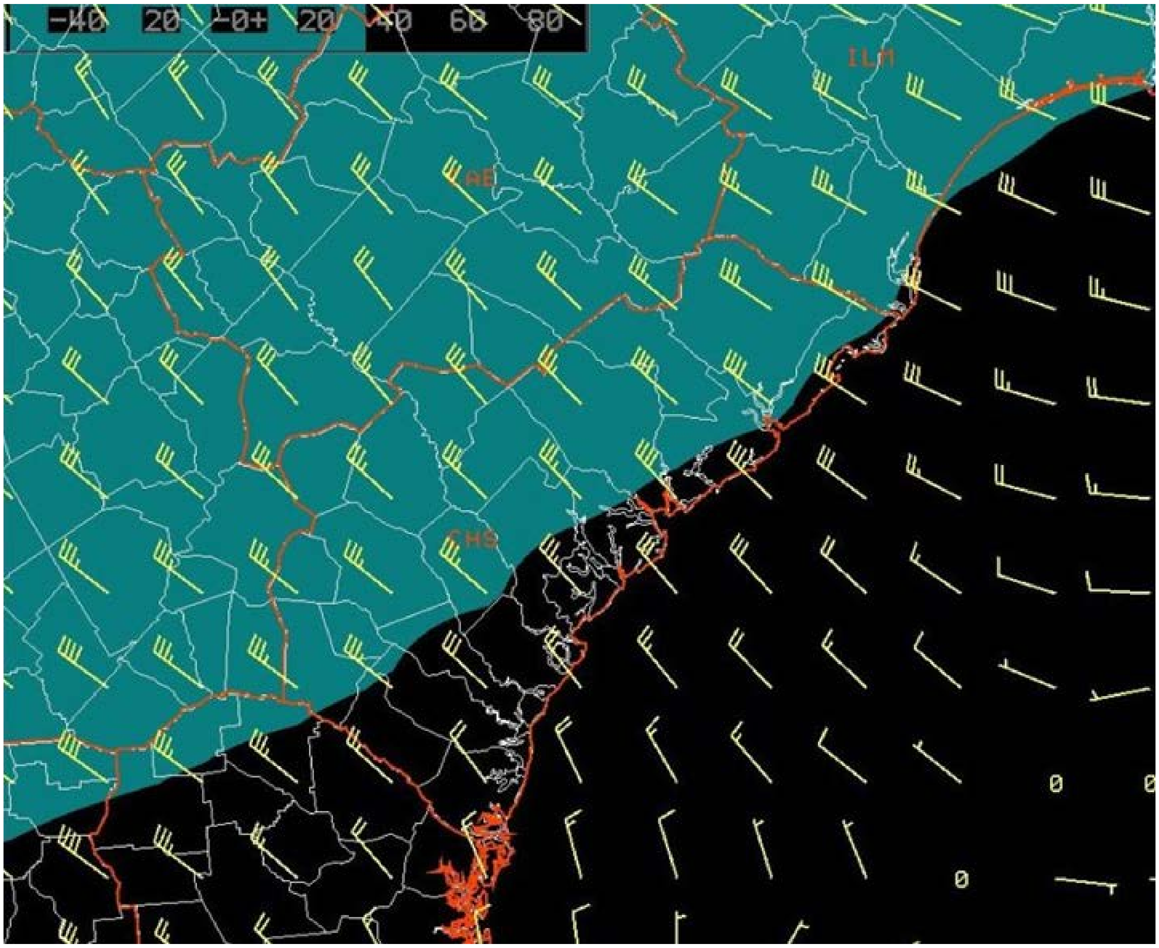

Figure 15. The 1000 UTC 10 January 2011 RUC40 forecast of surface wet bulb temperatures (0°C or colder shaded) and 1000 hPa ageostrophic winds (wind barbs) valid 1200 UTC.

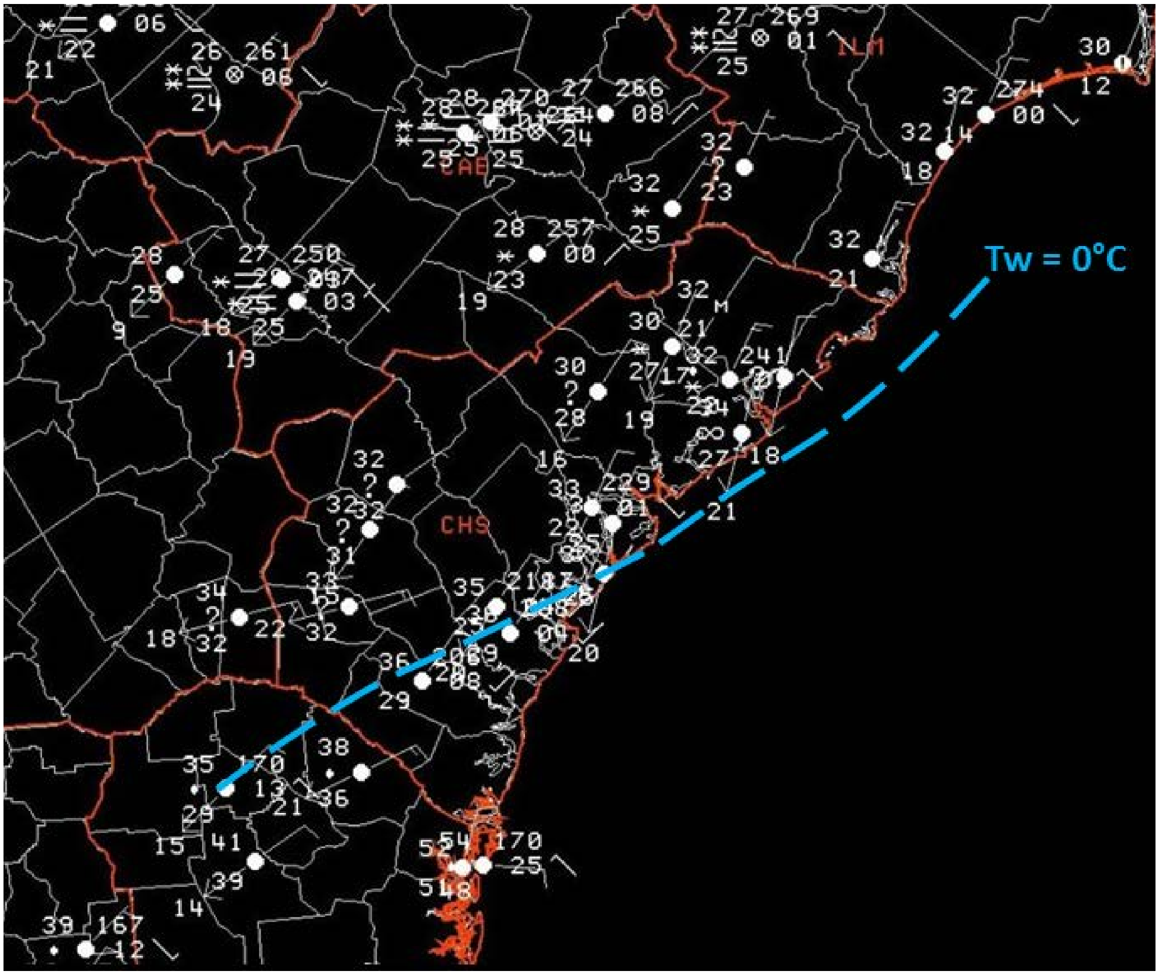

Figure 16. The 1200 UTC 10 January 2011 surface observations and surface wet bulb (Tw) 0°C analysis.

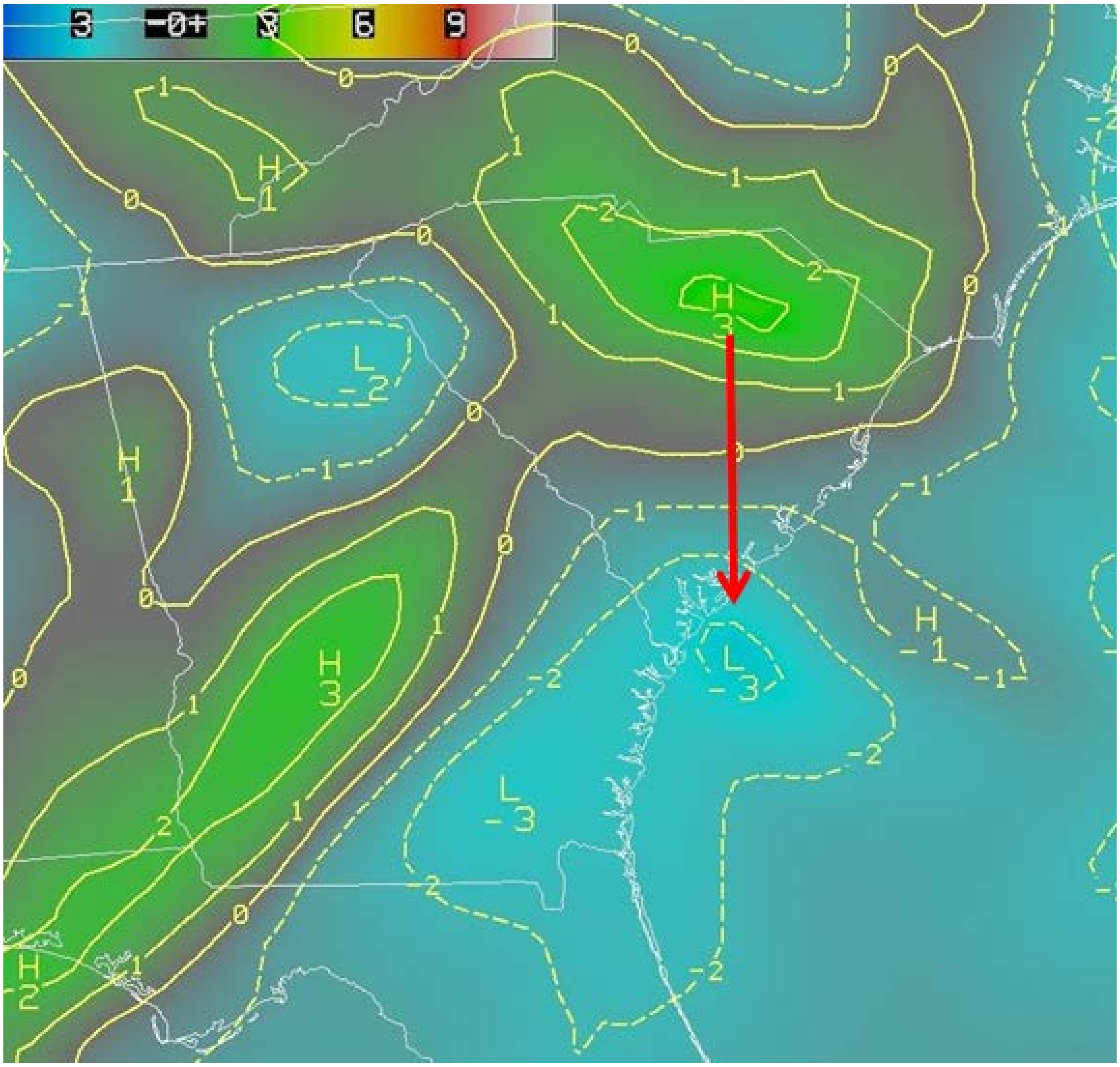

Figure 17. The 0600 UTC 10 January 2011 NAM20 forecast of 3 hour surface mean sea level pressure (hPa) changes valid 1200 UTC. The generalized isallobaric component of surface flow is represented by the red arrow.

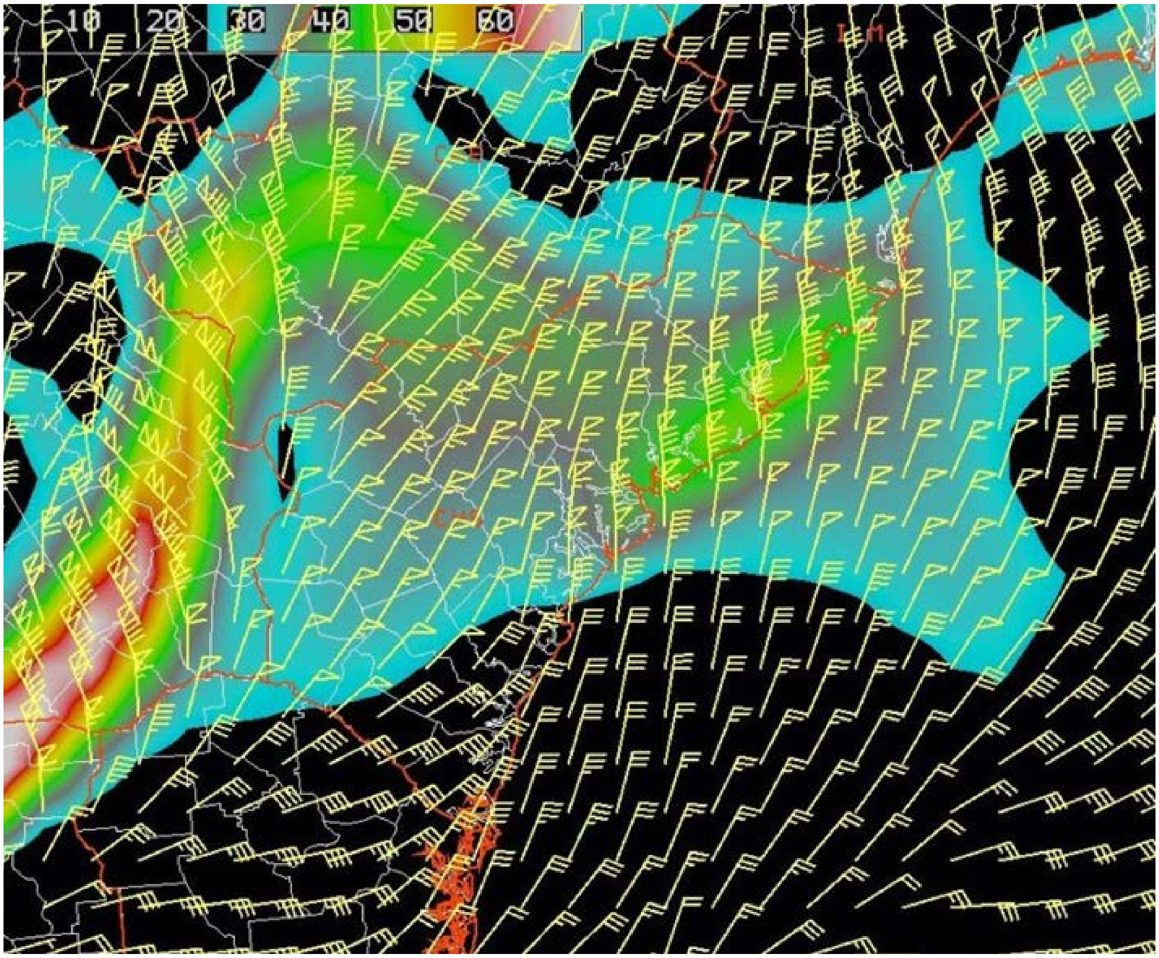

Figure 18. The 0000 UTC 10 January 2011 NAM40 forecast of the surface pressure gradient magnitude valid 1200 UTC (ubar km^{-1}).

4. Conclusions

Winter weather events are rare across the NWS Charleston, SC forecast area, especially across coastal portions of the region where air mass modification provided by the adjacent Atlantic Ocean usually warms the boundary layer. However, when such events occur, cold air damming (CAD), a common phenomenon east of the Appalachian Mountains, is usually associated with these infrequent episodes of freezing and frozen precipitation. Since the region is typically located at the periphery of CAD regimes, myriad processes, including inland penetration of the coastal front and thermodynamic and diabatic warming, normally erode the dome of low-level cold air, raising temperatures and diminishing or eliminating the coverage and impact of non-liquid precipitation. To maintain non-liquid precipitation types in this environment, the replenishment of low-level cold, dry air (Tw 0°C or colder) by ageostrophic adjustments within CAD regimes is required to maintain evaporational cooling to offset these warming processes. Once the thermal balance has tipped in favor of evaporational cooling within the cold dome, ageostrophic processes can further modulate CAD evolution, sometimes prompting an expansion of the wedge regime.

On 10 January 2011, a relatively brief but intense freezing rain event occurred across most of the NWS Charleston, SC forecast area. This ice storm, which disrupted transportation and caused extensive damage to trees and power lines, occurred because elevated convection produced heavy rainfall rates, which fell into a CAD regime that did not erode but rather remained entrenched due to the ageostrophic replenishment of low-level cold, dry air. This replenishment maintained sufficient evaporational cooling to offset warming processes inherent within moderate to heavy freezing rain. Prior to the event, numerical guidance accurately portrayed the entrenchment of the cold dome and the resulting ice storm across inland sections of southeast SC and southeast GA. As the event progressed, the isallobaric component of the ageostrophic wind offset normal CAD erosion processes on the periphery of the cold dome and contributed to a southward and eastward expansion of the CAD regime. This expansion resulted in freezing rain for population centers near the coast, magnifying the impact of the event. This mesoscale trend, which was not explicitly depicted by numerical guidance prior to the onset of precipitation, compelled significant near- term forecast adjustments that impacted a large segment of the population within the NWS Charleston, SC forecast area.

Concurrent analyses of observed and forecast surface wet-bulb temperatures and low-level ageostrophic winds established the presence and maintenance of the inland CAD regime. A subsequent recognition of a gap between forecast and observed Tw values across population centers near the coast offered clues to make forecast adjustments. An assessment of overall low-level ageostrophic winds, surface mean sea level pressure trends and gradients and the resulting isallobaric component of the ageostrophic wind supported the offshore component of surface winds observed at 1200 UTC 10 January. Ageostrophic winds offered compelling indications that the CAD regime would not erode during the period of heaviest precipitation. This offered a basis for bridging the gap between observed and forecast Tw by expanding the mention of freezing rain into population centers near the coast.

Forecasters frequently assess the thermal environment and employ partial thickness schemes and thermal and moisture profiles provided by model soundings to determine precipitation type within CAD regimes. Combining these techniques with an analysis of low level thermal and ageostrophic fields and trends may offer deeper insight regarding the evolution of CAD regimes and associated precipitation types. Additional research into model Tw biases in coastal CAD environments could enhance this insight.

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