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An Analysis of the Incorporation of Lightning into the Nowcasting of Enhanced Frozen Precipitation

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ABSTRACT

The major goal of this research is to investigate the potential of using cloud-to-ground (CG) lightning data in the nowcasting of winter storms. Incorporation in this context means comparing lightning data with other data sets just like a forecaster would do on an interactive workstation at an NWS Forecast Office, at the Storm Prediction Center (SPC), at an AF Weather Regional Hub such as the one at Sembach Airbase in Germany, or at some other location. The first three objectives focus on the relationship of lightning data to satellite imagery, radar data, and model output parameters (respectively) in nowcasting (within 500 km and 6 hours) of heavy frozen precipitation. Hypotheses regarding these first three objectives are: (1) Lightning will occur in areas of satellite detected clouds where vertical motions perceived by satellite-derived radiation can be visualized; (2) lightning can detect areas of high upward vertical motion related to large radar reflectivity returns in winter storms, and lightning should exist slightly upstream of the radar echoes; and (3) model output would help locate features such as moisture flow, the advection of warm theta-e air, areas where elevated or slantwise convection may develop, etc. The final objective involves the compilation of all the results of the case study analyses and a determination of if and when CG lightning data can be used in conjunction with other data sources to nowcast enhanced frozen precipitation.

Major findings of this research are: (1) Lightning activity (as defined by 10x10 km bins) often occurs on the most intense gradient of cloud top temperature fields, 100-200 km equatorward of the coldest cloud area; (2) Bursts/progression of lightning activity identify oncoming heavy snow and ice more efficiently and faster (i.e., with 1-2 hours more lead time) than NEXRAD data; (3) Lightning activity (observed via the progression of lightning packets within a high qE tongue) (a) improves the identification of the enhanced moisture flux into winter storms, and (b) enhances the forecaster interpretation of model-derived strong vertical motion fields (more than 7 μbars/sec) within 500 km and 6 hours upstream of heavy snow and ice; (4) Lightning activity not only identifies the strength and location of strong low-level moisture flow (as defined by a tongue of enhanced low-level θ_E and southerly winds exceeding 35-40 kt) into a winter storm, but also depicts strong lifting along tight low-level θ_E gradients where lifting may be in doubt; and (5) Lightning provides a more valuable nowcasting tool for winter type precipitation as one proceeds from the East Coast to the Western Plains.

Key Words: Lightning, Enhanced Frozen Precipitation, Snowbands, Nowcasting

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INTRODUCTION

Convective activity (i.e., lightning, high winds, heavy precipitation, etc.) impacts DoD (Department of Defense), government, and civilian operations on a daily basis. These operational impacts include threats to personnel safety, computer system malfunctions, destruction of expensive communications equipment, and damage to aircraft or spacecraft. Winter storms greatly impact human functions in any setting whether it be urban, rural, or in the sky.

The primary purpose of this research is to investigate if and how lightning data can enhance the prediction of heavy snow and ice, over a short time scale that will be defined later. Lightning data provides the forecaster with a means to define the spatial extent of convection. Lightning does occur in winter storms, even near the area of frozen precipitation (Pfost and Burse, 1996; Roohr and Vonder Haar, 1996; Holle and Watson, 1996). Unfortunately little research has been accomplished in the field of winter lightning, especially with regard to how lightning activity relates to current meteorological conditions.

In the mid 1980s the U.S. Government set out to modernize the National Weather Service. The three major observational components of the modernization effort include the next generation Geostationary Operational Environmental Satellite (GOES-Next) program, the Next Generation Weather Radar (NEXRAD) or Weather Surveillance Radar 1988 Doppler (WSR-88D), and the Automated Surface Observing System (ASOS). In one of its recommendations the NWS Modernization Committee states, "Modernization must continue beyond the implementation of systems now being procured. Provision should be made to incorporate data from additional new technology, such as wind profilers and a lightning detection network..." (NOAA, 1991, p. 15). Access to lightning data has been and will continue to be a problem. Lightning data are the only major weather data set not owned by the government; many NWS and military forecasters have realized the importance of lightning data and are frustrated that not more can be done to obtain, process and display lightning data on a real-time basis. Forecasters have used radar and satellite data, along with NWP guidance, to nowcast severe winter weather (LaDue, 1996; Rasch and Scarlett, 1996; Nouhan and Barker, 1996). Nowcasting refers to the forecasting of a weather occurrence within the next 6 hours and 500 km; these spatial and temporal values define most winter weather systems that span a multi-state region. Nowcasting in winter storm situations can be difficult as satellite imagery can give a false impression of consistent intensity across a certain region. Also, radar scans can overshoot the shallow precipitation echoes of snow producing cells. Finally, model products only depict mesoscale features on a 6 hour incremental basis (and this guidance may not be accurate). The relationship of lightning to features of a winter storm as observed by satellite, radar, and rawinsondes, as well as predicted by models, is supported physically by various mechanisms. The main links between lightning and other data are lift, instability and moisture. These three components are important to the generation of lightning activity as well as to the intensity of frozen precipitation in a winter storm.

Objectives

The objectives of this work center around one main theme, that is to investigate the potential for lightning data to enhance the forecasting of heavy snow and ice over the short term (up to 6 hours and less than 500 km). This investigation has to involve the comparison of lightning data (CG) to the observational data sets and model output that forecasters will eventually see on the fully capable AWIPS platform. In this regard it has to take into account the physical attributes that link lightning activity with weather features observed by other platforms. The work was divided up into four main sections, treating storms that affect the Western Plains, the Central and Northern Plains, the Midwest and South, and the Northeast, respectively. The categorization itself is needed not only because of the differences in synoptic and mesoscale features that combine in the development and intensification of the storms. The categorization also helps forecasters understand which areas of the country can benefit the most from the incorporation of lightning data into winter storm nowcasting. Each of the objectives will be treated in these sections to place into perspective the potential of the hypothesized relationships between lightning and other weather parameters in nowcasting enhanced frozen precipitation in each region. Discussion of how well the correlation of lightning data to other data sources did in nowcasting bands of frozen precipitation (as observed with the case studies) will take place. Finally, conclusions will be made as to if and when lightning data should be used in severe winter weather.

The first objective focuses on the relationship of lightning data to satellite imagery in nowcasting heavy frozen precipitation. The hypothesis is that lightning will occur in areas of satellite detected clouds where vertical motions (i.e., strong updrafts) are present (as inferred from the convective signatures observed with various satellite channels). Lightning enhances the ability of a forecaster using satellite imagery to nowcast heavy snow/ice downstream since it depicts regions of deeper, more vigorous vertical motion. Sometimes strong updrafts can be detected from satellite imagery by a cauliflower-shaped cloud top among a field of smooth stratiform cloud cover. Strong vertical motions can also be inferred from sharp edges in jet streaks and the interaction of jet streaks as depicted by visible imagery. However, since visible imagery is not available for up to 15 hours per day during the winter, lightning data can prove to be valuable as a substitute. When interpreting longwave imagery (i.e., IR), attention should focus on the coldest cloud tops where convection may exist. The IR imagery will likely depict not only where the largest upward vertical motions exist (since the coldest cloud tops often represent the highest clouds) but also the surrounding field of upper level blowoff from the storm (composed of many ice crystals). Lightning should better depict the ongoing and downstream banding of snow and ice, since lightning will indicate the linear or cellular nature of strong updrafts. When using 3.9 micron imagery, the main feature to focus on is the microphysical nature of the cloud tops. The imagery should be able to detect where higher vertical motions are based on the amount of water in the upper reaches of the storm; it should also determine dissipation based on widespread glaciation of the upper level clouds. Lightning is hypothesized to exist under clouds with high levels of liquid water in the upper portions. Research into the comparison of 3.9-micron imagery to CG lightning activity has not been attempted previously by any researchers.

The second objective centers around the relationship between radar data and CG lightning, and involves a close examination of the role of each in forecasting frozen precipitation. Doppler radar obviously provides a valuable tool for the forecaster. This is due to the fact that a time series analysis of a band or cell of heavy snow or ice (as depicted by high reflectivity fields of between 30 and 50 dBZ) can help in diagnosing which locations will be affected downstream, as well as when and to what degree they will be affected. Radar reflectivity patterns can also be monitored on an hourly basis to detect moisture flow into storm systems. The high reflectivity values often are indicative of large aggregates and ice pellets which have grown by microphysical interactions during their relatively long suspensions (as well as other mechanisms) in strong updrafts inside clouds. The large updraft speeds and instability associated with high reflectivity returns are also important to the generation of lightning activity. An individual radar can only infer vertical motion not measure it; lightning gives the forecaster a better idea of regions of enhanced vertical motions (i.e., updrafts) within sectors of the storm. The hypothesis is that lightning can detect areas of large updraft speeds related to large radar reflectivity returns in winter storms. Lightning can also help detect areas of widespread lifting caused by overrunning or frontogenesis. The lightning (CG and IC) should exist slightly upstream of the radar echoes due to the influence of the horizontal wind field on the precipitation.

The third objective is to compare forecast model output to lightning data, concentrating on those parameters which enhance the chances for CG lightning in winter storms. Heavy frozen precipitation often occurs over smaller spatial and temporal scales than can be resolved by operational models. The higher spatial temporal resolution of lightning data may help to refine model forecasts. Specifically, it may be possible to use lightning data with model output help locate features such as moisture flow, the advection of warm theta-e air, and areas where elevated or slantwise convection may develop.

The final objective involves the compilation of all the results of the case study analyses to determine if and when CG lightning data can be used in conjunction with other data sources to nowcast enhanced frozen precipitation. The case studies are used to find answers to the first three objectives. Hypothesized physical connections concerning parameters that help to define both lightning activity and heavy snow and ice will be examined for nowcasting potential. The ultimate goal is to provide forecasters with products and techniques which can help in a "borderline" (i.e., high potential for a forecast bust) winter weather event in which lightning and enhanced frozen precipitation occur.

OVERVIEW OF DATA AND ANALYSIS PROCEDURES

Scanning of Large Data Set.

Data from satellite, radar, lightning, surface, upper air, and forecast models were collected for 110 cases from 1987 to 1998. For all of these cases the various types of data were visualized in some manner, and the location and timing of bands of enhanced frozen precipitation were correlated to areas of lightning activity (usually found in the deformation zone or within the warm conveyor belt of the storm system). The heavy bands of ice and snow for each storm were identified from Storm Reports, climatological reports from the National Climatic Data Center (NCDC), and newspaper accounts.

In 27% of the cases there existed no CG lightning activity within 500 km and 6 hours of enhanced frozen precipitation. Of the remaining cases, there were only 9 in which CG lightning occurred near or within the cold sector of the storm and enhanced snow and ice did not develop immediately downstream. This research will not determine those regions in which lightning is of little use in forecasting winter storms. It will not examine how total lightning (i.e., intracloud and cloud-to-ground lightning flashes, as opposed to the sole use of cloud-to-ground lightning in this research) can be used, or determine situations in which the use of cloud-to-ground lightning data will cause false alarms. These initiatives must await future research.

Procedure for Selection of Cases.

For more detailed analysis, storms were chosen from the 110 total cases in the data set on the basis of two primary criteria. The first criterion was the availability of lightning, satellite, surface and radar data, as well as model fields. In order to make the study consistent and current concentration was focused on data sources associated with the NWS modernization effort (GOES satellite, WSR-88D radar, and Eta model fields). The other criterion was that each case have some amount of CG lightning activity upstream (within 6 hours and 500 km) of well-defined bands of heavy snow or ice.

Principal Limiting Factors Associated with Storm Selection.

Cases in which the use of lightning data would cause false alarms (lightning within nowcasting range of potential heavy snow/ice, but no actual frozen precipitation band developing downstream of the lightning activity) could not be adequately analyzed. This is due to the fact that all 110 storms in the data set had enhanced frozen precipitation, whether or not lightning existed within nowcasting range of the bands. The only false alarms occurred in 9 cases (mostly in the Southeast and Central Plains) in which lightning activity was within the nowcasting range of the cold sector of the storm system (in a different region and time than the snow or ice band that was used for the case). Only widespread lighter amounts of snow or ice occurred within 500 km and 6 hours of this lightning activity. The data set did not include cases in which only moderate or light snow occurred in the analysis domain. It would be necessary to determine how many such cases occurred to analyze false alarms adequately. This issue was not practical for the present project, but needs to be addressed in future research.

Also, those cases in which heavy snow or ice occurs with no lightning within nowcasting range are not considered. The two most notable were the February 18-19, 1989 storm that left a 18–20-in. band of snow across southern Virginia, and the January 5-6, 1988 storm that left an area from the Ozarks to the Smokies with up to 14" of snow. Of the 6 lake effect storms studied, only one contained lightning activity immediately upstream of the heavy snow, and that one produced only 3 CG flashes overall. Thus, lake-effect winter storms probably are not good subjects for the forecasting techniques developed by this project.

The use of data sources from the NWS modernization era (post 1991) precluded the use of many cases before 1991 (at least in the context of this research); the only case used in the project for years preceding 1991 was from March 1990. Many of the cases obtained before 1991 had some satellite, radar, and surface data associated with them; however, it was sometimes difficult to determine frozen precipitation bands with the digitized radar data from WSR-57 and WSR-74 units and with the data from GOES-7. CG lightning data were obtained for all cases before 1991.

Cases Selected

Twenty-six of the 110 cases met the criteria mentioned above and had enough data to address the objectives. To help give forecasters an idea of how effective the use of lightning can be in nowcasting enhanced frozen precipitation over certain regions of the U.S., the cases were divided up into those occurring in the Western Plains (6), those occurring in the Northern/Central Plains (6), those occurring in the Southern Plains/Southeast (6), and those occurring in the Northeast (8).

NEXRAD (Next Generation Radar) provided radar reflectivity data for all 26 cases, in the form of Level II data, Archive IV, and composite 8-km imagery obtained from NASA-Huntsville AL. The Level II data were visualized with WATADS, and the Archive IV output were displayed in a playback mode on the Denver NEXRAD PUP (Principal User Processor) terminal. Satellite data came from the CSU archive and consisted of visible, IR, and/or 3.9 μm data from GOES-7 (Geostationary Operational Environmental Satellite), GOES-8, GOES-9 and Meteosat (for 1994 storms). The GOES data were sectorized and formatted for viewing the complex cloud patterns of convective winter storms. Lightning data were obtained in ASCII format from NASA-Huntsville and Global Atmospherics Inc. in Tuscon AZ. The data were visualized using a display program on CSU's aging VAX/VMS system, and gridded in 10-km bins to observe intensity/frequency of strikes as well as growth and dissipation. Surface and upper air data came from both the CSU archive and the NSSL (National Severe Storms Laboratory) archive; they were both visualized with GEMPAK (General Meteorological Package). The Storm Prediction Center provided the Eta model output in a PC-GRIDDS display format. There were some MM5 (Penn State University/National Center of Atmospheric Research Mesoscale Model version 5) output obtained for the 1997-1998 storms.

Process Used to Analyze Data

All data were analyzed on an hourly basis within nowcasting range (within 500 km and 6 hours) of the occurrence/location of the enhanced frozen precipitation band. Model output (with forecast intervals of 6 hours) were analyzed within mesoscale range of the potential bands (generally within 12 hours and 1000 km).

The first part of the process involved the examination of model-derived parameters near the area of potential convection and enhanced frozen precipitation. The second part involved the examination of satellite imagery, radar reflectivity, and lightning data on a regional scale within nowcasting range of potential bands of heavy frozen precipitation. The final part of the analysis involved the examination of satellite imagery, radar reflectivity, and lightning on a local scale, very close in time and space to the developing bands.

While performing the analysis and comparing model output, radar data, and satellite data to lightning activity, information on model derived vertical velocity at 700 mb, the gradient of θ_E at the 850 mb surface, satellite derived cloud top temperature, radar reflectivity, etc. were catalogued near the lightning activity within nowcasting range of the frozen precipitation band(s). These statistics were compared on a case to case basis and then on a regional basis to facilitate the development of the forecaster methodologies, and ascertain which areas of the country that lightning data could help a forecaster in the nowcasting of frozen precipitation bands.

SAMPLE CASE ANALYSIS

The case that involved heavy snow over the mid-Atlantic coast during the period of 1-3 Feb 1996 was used to portray the analysis of lightning in the nowcasting of enhanced frozen precipitation bands. This storm was the third in a series of large storm systems that belted the East Coast in the 1995-1996 winter.

Summary of Storm.

The early February storm of 1996 was one of many big extra tropical cyclones to hit the mid-Atlantic coast in the winter of 1995-1996. The storm lay a path of very heavy snow from eastern Tennessee to the Del Marva Peninsula (Figure 1). As had been the case for most of the winter a large, longwave 500 mb trough sat over the mid-section of the country. At 02/12Z a very strong jet streak (with maximum 300 mb winds of 160-170 kt) was over the northeast, placing the mid-Atlantic seaboard and Ohio River Valley in danger of enhanced upward vertical motion. A broad 700 mb trough existed over the south-central United States but there was no definable low. At 850 mb a closed low developed along a zone of strong frontogenesis that existed from eastern Texas to central Virginia.

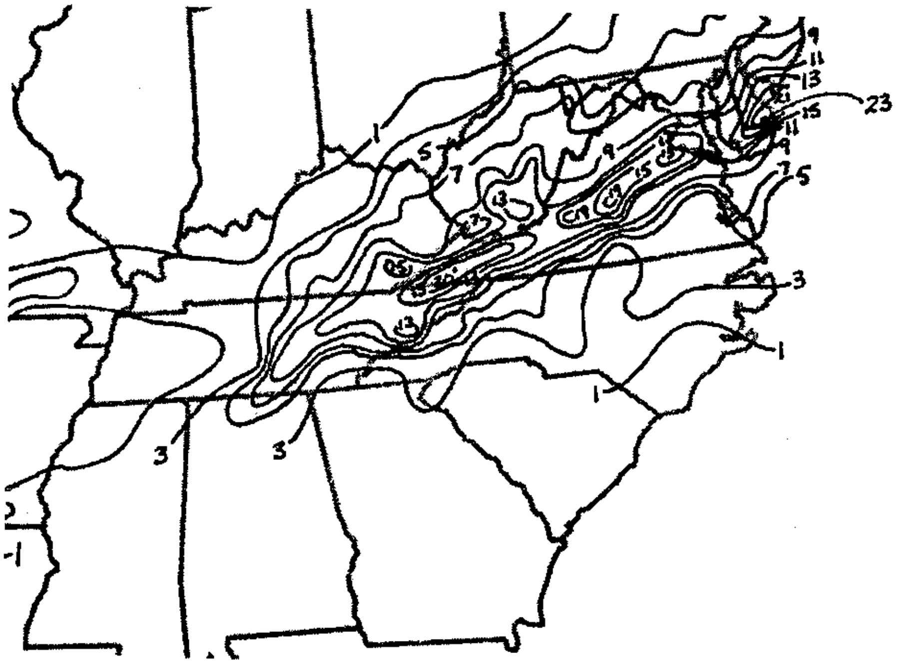
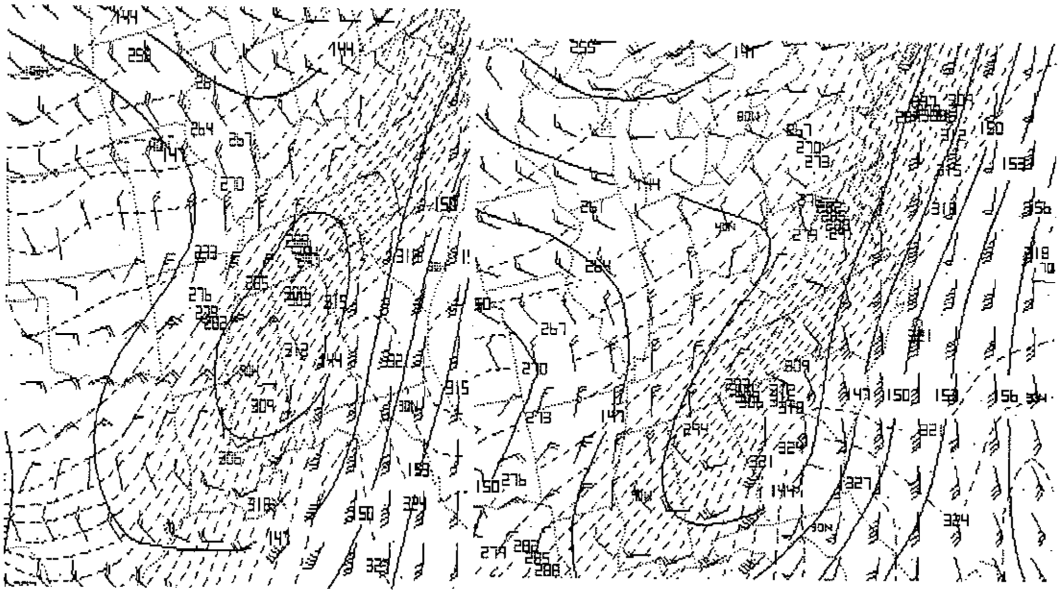


Figure 1: Snowfall (inches) for 1-3 Feb 1996 Mid-Atlantic Storm.

At the surface a very strong Arctic high pressure (1040 mb center) controlled the weather over the central portion of the country, pushing the freezing line (02/03Z) very far south (along a line through Houston, Jackson MS, Asheville NC, and Norfolk VA). Cold air reached the western Gulf and a storm started to develop along the main front. This storm moved along the Gulf coastline to Mobile AL by 02/15Z. One would think that based on the storm's position and movement the mid-Atlantic coast should be safe from accumulating snow. Forecasters had to use the Eta model and experience to help nail down the storm's intensification and movement.

Comparison of Lightning to Other Data/Output

Frequent CG lightning activity was occurring along the main cold front that extended from the



a) Eta 02/1200Z 6 hour forecast for 850-mb height (dm, black), theta-e (K, dashed), and winds (kt)

b) Eta 02/1200Z 12-hour forecast for 850 mb height (dm, black), theta-e (K, dashed), and winds (kt)

Figure 2.

low in the western Gulf to Savannah GA (early hours of 02 Feb). Lightning also occurred north of the front in areas where the surface temperature was near freezing (10-15Z). The persistence of lightning in areas along the 850 mb front told forecasters that lower level vertical motions along the surface freezing line were stronger than expected. *The Eta 02/12Z 6 and 12 hour forecasts* were used to help track the future movement and intensification of the storm system.

An 850 mb south-southwesterly jet of 45-50 kt was forecast to stretch from southern Georgia to the central section of North Carolina (6 hour forecast from 02/12Z Feb Eta run, Figure 2a). A strong 850 mb tongue (defined by the 321K contour) was to be well up into central Georgia, and the 850 mb θ_E gradient between Beckley WV and Cape Hatteras was to be very strong (282 to 318K, respectively). The main axis of the strong gradient extended from Mississippi to New Jersey (12 hour forecast from 02/12Z Feb Eta run, Figure 2b). This was a large area of potentially strong isentropic lift and frontogenetical forcing in the lower levels. Vertical velocities at 850 mb were predicted to be at least –4 μbar/sec over the Virginia-Maryland border increasing to –7 μbar/sec by the 12 hour forecast. All lightning activity ended up occurring along the strong 850 mb θ_E tongue (Figures 2a and 2b) with positive CG lightning further poleward than negative CG lightning. At 700 mb the model forecasted a strong southwesterly 60 kt jet to affect the region, with the highest vertical velocities (-6 to –7 μbar/sec) from southern Alabama to western NC. RH values at the 12 hour point were relatively low, between 75 and 80%, in an area of eventual convection.

At 500 mb most of the southeast was under the influence of weak vorticity and vorticity advection, which has been seen with many other winter storms. The 500 mb thermal ridge extended into the southeast from the Atlantic, creating a nice band of temperatures between –14 and –17 °C (very accommodating to large amounts of supercooled water and increased crystal growth). RH values as predicted by the model would be between 67 and 86%. At 300 mb North Carolina, Tennessee and Virginia were to be under the influence of the entrance region of a jet streak by 03/00Z. The strongest divergence was to be over southwest Alabama, upstream of where lightning would eventually occur along the low-level 850 mb tongue of moisture.

Instability over the southern Appalachians was expected to be relatively strong, indicating the high potential for elevated convection in the region. Total Totals were expected to reach 44-49, K-indices 24 to 32, and lifted indices from –2 to +3 (very strong for winter events). CSI was found to be weak at the 12 hour point; thus the majority of lift for this system came from frontogenetical and isentropic forcing. One of the strongest indicators for enhanced vertical motion was the Q-vector forcing at the lower levels. The model had a maximum of –8 to –10 over South Carolina, with long Q-vectors over northern Georgia and western South Carolina (signifying frontogenesis at the lower levels).

Moisture parameters were predicted to be very strong with the strongest moisture convergence over southeast Georgia (-70 to –80), 150-200 km upstream of the main lightning area. The average mixing ratio along the critical 296K isosurface (upstream of VA/NC/TN) was between 6 and 7 g/kg, indicating the potential for more than 8" of snow over the region. Model predicted precipitation from 02/12Z to 03/00Z along a line from southeast Alabama to western North Carolina was 1.2 to 1.5".

The lightning activity that occurred between 12Z and 22Z depicted atmospheric advection of moisture that the model could not. There were two very distinct impulses of lightning activity (11-15Z and 18-22Z) that broke off the main area of convection in Alabama, and then progressed northeastward toward eastern Tennessee, Georgia, western North Carolina and Virginia. Both of these impulses were associated with enhancement to the frozen precipitation rates in the downstream regions. Lightning activity also increased along the coast of the Carolinas where moisture convergence in the boundary layer was near +50 g/kg/hour. The area of lightning in North Carolina lay just 200 km and 4 hours upstream of the moderate to heavy snow that shut down most of western and central Virginia, eastern Maryland, and Delaware with 15+" of snow within 9 hours (from 03/00 to 03/09Z).

NEXRAD data, in the form of 8-km composite images obtained from MSFC and Level II raw data from NCDC (Knoxville and Norfolk/Richmond radars), were collected for this case. The 8-km NEXRAD images, when combined with abundant lightning data (as shown in Figures 3 and 4 for 02/14Z and 02/19Z, respectively), refined analyses of convection for forecasters in the Southeast. Examining surface data and the radar images at 02/0400Z (around northeast Texas and northern Louisiana) a forecaster in Tennessee would have thought that freezing rain was light with a melting zone causing enhanced reflectivities. Lightning activity along the same line would have foretold

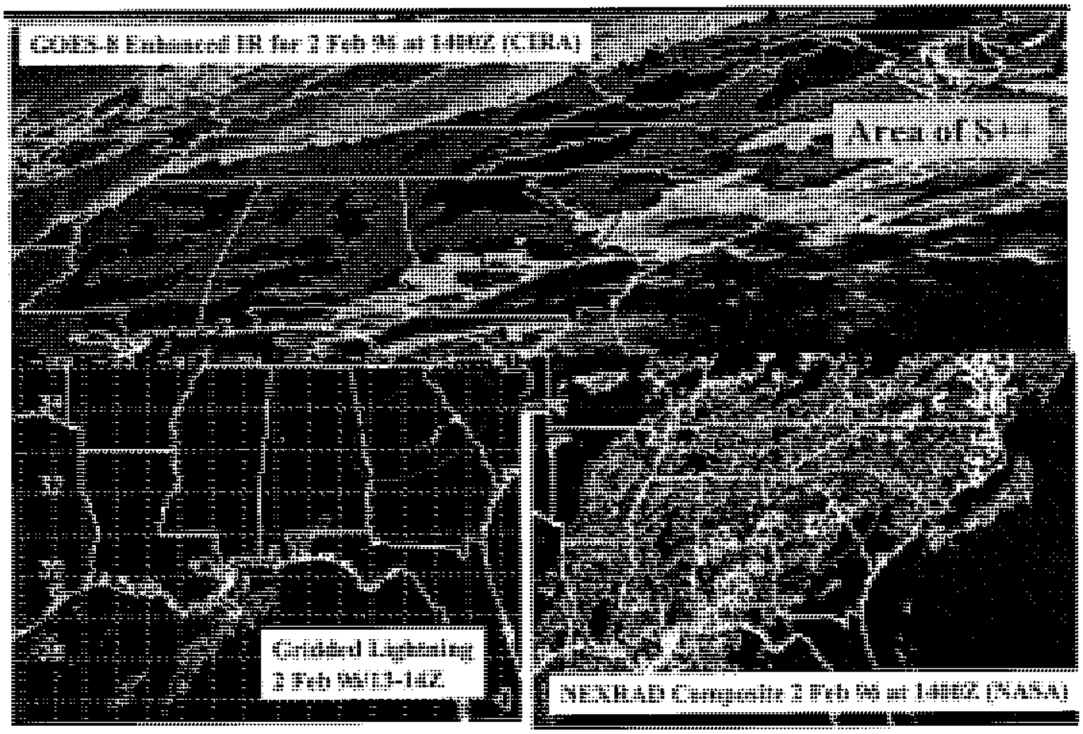


Figure 3: Comparison of lightning activity to satellite and radar data at 02/14Z.

forecasters of enhanced vertical motions within the freezing rain that would enhance precipitation rates downstream (which occurred 3-4 hours later over Tennessee and northern Alabama). Radar data portrayed activity over eastern Tennessee as heavy whereas surface data depicted light to moderate freezing rain and snow. The non-existence of convection (i.e., at least with no CG lightning) would have given an indication that radar images showed bright bands in eastern Tennessee.

At 02/0600Z lightning activity in central Mississippi and Alabama was associated with moderate to heavy rain within reflectivity fields of 40-45 dBZ. Lightning in northern Louisiana was associated with light to moderate freezing rain (weaker 30-35 dBZ levels). A strong line of convection was growing from Mobile to the western Gulf of Mexico, from 02/06 to 02/10Z. The radar data did not pick up this activity over the Gulf well at all but lightning activity did (doing a better job of detecting moisture flow and instability). Lightning activity occurred also on the upwind side of moderate reflectivity cells (along the freezing line) where upward vertical velocities should have been strong. The radar did a very good job of picking up heavy snow in eastern Tennessee and West Virginia, where no lightning activity was detected.

At 1200Z the radar and lightning data detected the large thunderstorm cluster moving into Georgia with lightning on the upstream side. From North Carolina to Louisiana lightning activity depicted the location of the freezing line while radar data in North Carolina and Virginia depicted areas of freezing rain and developing bands of snow. Radar and lightning data could have been used to track an area of convection moving along the Appalachian chain into South Carolina.

The WSR-88D radar at Knoxville TN showed the results of the first wave of lightning along the conveyor belt as moderate snow occurred 200 km downstream (band from northern Alabama to southwest Virginia). The lightning and enhanced radar reflectivities offshore of North Carolina were related to increasing moisture flow from the Atlantic Ocean into North Carolina and Virginia. Another strong impulse of energy moved from the main line at 1600Z and progressed into South Carolina by 2000Z (on upstream side of 40-45 dBZ regime). Although lightning activity died off in South Carolina by 2300Z, moderate to heavy precipitation fell downstream in Tennessee and Virginia (snow from 03-11Z, as depicted via surface data and radar data from the Norfolk/Richmond WSR-88D).

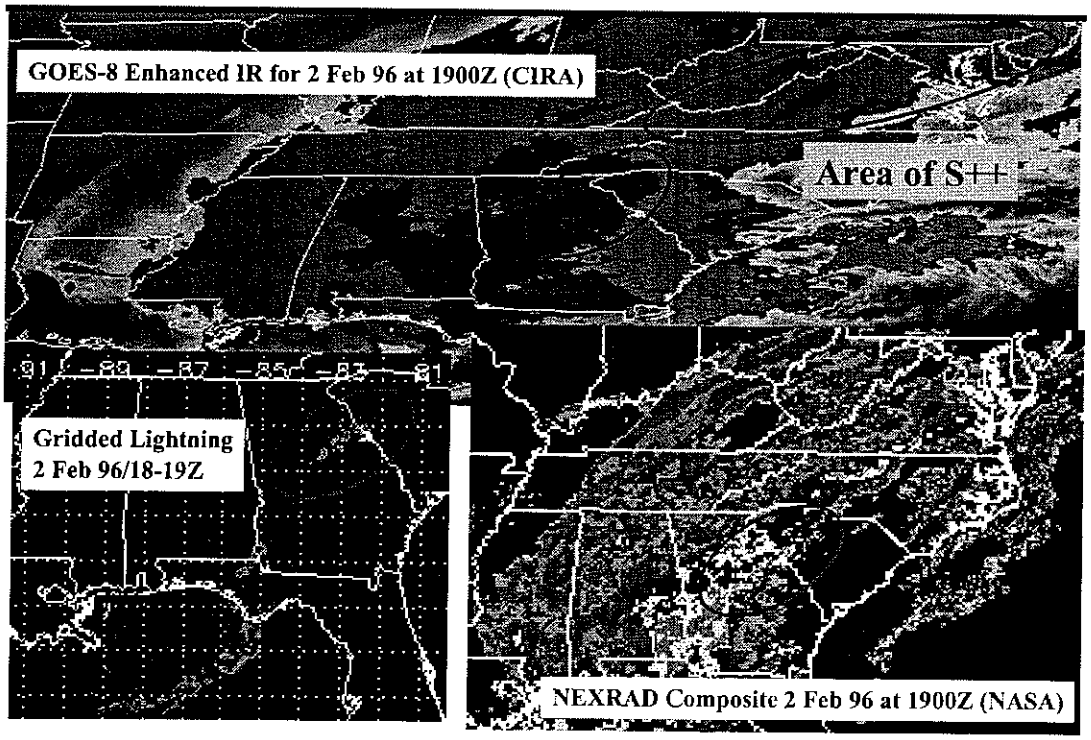


Figure 4: Comparison of lightning activity to satellite and radar data at 02/19Z.

GOES-8 satellite data were collected from the CIRA archive, sectorized to obtain imagery over the southeast United States and the displayed via IDL. During the early hours of 02 Feb lightning activity along the freezing line in northern Mississippi was on the southern edge of cold (-47 to –51 °C tops) IR shield. There were colder clouds over Tennessee but no CG lightning was associated with them. At 09Z lines of cold clouds (on enhanced MB images) over northern Louisiana and north-central Mississippi were just poleward of lines of lightning activity. An embedded thunderstorm in northern Georgia was detected with weak lightning activity as well as an isolated very cold cloud area amongst a large cirrus shield. From 12-15Z the area of convection that split off the main line in Alabama and progressed into North Carolina was noticeable on both satellite imagery and lightning fields.

Lightning activity occurred on the equatorward/eastern side of the coldest clouds (-45 to –50 °C). The satellite data show the direction of the winds that would pull upper level moisture from the dying thunderstorms (North Carolina to Virginia and Tennessee). The intensity/growth of the coldest cloud top areas decrease as the CG lightning subsides from 12-15Z (Figure 3 shows the comparison at 02/14Z). From 18-22Z a third round of convection broke off the main line in Georgia (Figure 4 shows the comparison at 02/19Z), as shown by lightning data but not by satellite IR fields (in which thunderstorms are too embedded as they progress into NC). The coldest IR fields (-51 to –58 °C) for the cloud tops did not cover the heavy snow area and most of snow was on equatorward edge.

GOES-8 3.9 micron imagery was examined for this system. Use of IDL with enhanced stepped color tables, did not detail areas very well that had CG lightning upstream of the enhanced snow. The second surge of lightning along the GA-SC border could not be correlated to varying 3.9-micron reflectivities for 18-20Z.

Final Analysis of the February 1996 Southeast Snow Event.

Overall, the model handled this case fairly well; its only problem was that it insinuated that the system would be much weaker than it actually turned out to be. In the lower levels it had predicted a strong zone of frontogenesis with a strong conveyor belt (defined by a 45-50 kt jet and $\theta_E > 321$K tongue) that extended from the Gulf to southern Virginia. In the upper levels the mid-Atlantic Coast was to be under the influence of the entrance of a jet streak pattern with moderate divergence. On the contrary the model predicted vertical velocities were too weak to explain the heavy snow band from eastern Tennessee to Delaware (-5 to –6 µbar/sec at best).

Moisture convergence (70 to 80 g/kg/hour) and Q-vector convergence (8 to 10) were fairly strong upstream of the snow but not far north enough (and widespread) to explain the heavy snow in the Piedmont region (moisture convergence fell 150 km upstream of lightning). Lightning activity was unusually frequent for this case and there were two occurrences where packets of lightning moved off the main area of convection (in southern GA/AL) and proceeded northeastward into the mid-Atlantic region (could see with progression of NEXRAD cells of >35 dBZ). Satellite imagery also depicted this activity; gradation of cloud top temperature on IR imagery enabled forecasters to pick out storm movement and intensification.

RESULTS AND FORECAST METHODOLOGY

Quantitative Comparisons of Regions

To develop recommendations for how forecasters can best use lightning data in the nowcasting of enhanced frozen precipitation, the results of the regional analyses contained in the research had to be organized so that the comparison of certain important features could be ascertained. Typical ranges were determined for those specific parameters that were compared to ongoing lightning activity.

The make-up of Table I is described as follows. Specific model features are discussed (850 mb jet, 700 mb vertical velocities, etc.), as well as satellite imagery (changes in texture on visible imagery, concentration of cold IR cloud tops, etc.), radar reflectivity patterns (peak returns, etc.), and lightning rates (given in ranges of number per hour per region). The left-hand column of the table represents

Table 1: Regional comparison of parameters used in study of lightning in winter storms.

	850 mb Vert Vel µbar/s	850 mb Jet kt/dir	850 mb q_E ext. K	850 mb q_E grad K/km	850 mb Frtgen C/km	700 mb Jet kt/dir	700 mb Vert Vel µbar/s	500 mb PVA	500 mb Temps °C
West*	–1.5	10–20	300	0.040	0.020	10–25	–2.0	Weak	–17.0
Plains	–3.0	North	314	0.070	0.040	Var	–4.5	Strong	–22.0
N–C	–5.0	50 S	300	0.035	0.020	40	–7.0	Weak	–17.0
Plains	–8.0		312	0.065	0.036	S/SW	–11.0		–20.5
S Plns	–4.0	50 SW	304	0.055	0.022	50 SW	–5.0	Weak	–16.0
South	–6.0		320	0.070	0.030		–8.0		–19.0
North	–7.5	60 SW	297	0.030	0.020	50 S	–10.0	Weak	–17.0
East	–14.0		310	0.055	0.030		–17.0		–20.0

	300mb Jet Strk Max	Diverg 10^{-5} s^{-1}	Stblty Total Totals	Stblty Lifted Index	Stblty K– Index	Stblty CSI	Moist. Mst. Div g/kg/hr	Moist. Mxg. rat g/kg	Q–Vec Diverg.
West*	UL	+1.0	49.0	–2.0	25.0	Sfc	–10.0	3.5	–4.0
Plains	80	+3.0	53.0	0.0	31.0	700mb	0.0	7.0	–13.0
N–C	None	+0.5	40.0	+2.0	18.0	Sfc	–15.0	5.5	–3.0
Plains		+3.0	44.0	+7.0	23.0	700mb	–40.0	7.0	–11.0
S Plns	LR	+1.5	38.0	+4.0	21.0	850mb	–15.0	4.5	–4.0
South	125	+2.5	42.0	+8.0	25.0	500mb	–50.0	6.5	–6.0
North	LL	+1.0	37.0	+1.5	17.0	875mb	–15.0	4.5	–4.5
East	135	+4.0	46.0	+6.0	24.0	600mb	–50.0	7.0	–7.0

	Reflect. Snw DBZ	Reflect. Lgt DBZ	GOES Visible Text?	GOES IR Sn C	GOES IR Lgt C	GOES 3.9 mm Mxg?	Frq/hr CG (storm)	Frq/hr CG (10×10)
West*	33	36	Yes	–40	–36	Incon.	30	0.012
Plains	38	43		–50	–44		50	0.020
N–C	28	30	Yes	–42	–45	Incon.	60	0.024
Plains	37	42		–50	–50		80	0.032
S Plns	33	34	Yes	–44	–39	Incon.	90	0.036
South	40	43		–49	–44		120	0.048
North	33	31	No	–38	–36	Yes	5	0.002
East	40	40		–44	–42		25	0.010

the region of the country studied (Western Plains, Northern and Central Plains, Southern Plains and Southeast, and Northeast). Numbers represent average ranges ascertained in the analyses by region while other identifiers represent the most common feature found (e.g., UL for upper left of upper level jet in association with enhanced frozen precipitation and lightning activity). For the model products the regions differ somewhat in the lower levels. At the lower levels, the Western Plains (700 mb level for this area, 850 mb for the others) consistently had lower vertical velocities (-2.0 to –4.5 µbar/sec vs. –6.0 to –11.0 µbar/sec) and weaker jets (10-20 kt vs. 50-60 kt) than the other regions did. The strongest vertical velocities were in the Northeast (-10.0 to –17.0 µbar/sec) while the higher lightning rates occurred in the Southern Plains and Southeast (upwards of 90-120 flashes per hour (0.036 to 0.048 (bin))). The greatest variability as to the poleward extent of lightning up the 850 mb θ_E tongue occurred in the Southern Plains and Southeast.

The extent and character of lightning within the 850 mb tongue gives a forecaster an idea as to how the model is picking up the strength of moisture flow, a basic determinant of how far north heavy snow or ice will fall. Lightning often extended well beyond the equatorward base of where the 850 mb θ_E gradient would increase (in the southern portion of the country). The strongest 850 mb gradient occurred in the Southern Plains and Southeast (0.55 to 0.70 K/km) with the lowest in the

Northeast (0.30 to 0.55 K/km); isentropic lifting and frontogenesis play a big role in convective snow over the South.

Lightning and enhanced snow and ice often occurred in areas of weak or non-existent 500 mb positive vorticity advection and within the main thermal ridge where temperatures are accommodating to both large amounts of supercooled water and ice crystal growth. The 500 mb temperatures were consistent from region to region (ranging from –17.0 to –20.0 °C). Lightning and heavy snow tended to occur more within the upper left portion of strong 300 mb jet streaks in the Western Plains, the lower right portion of jet streaks in the South and in the lower left portion of jet streaks in the Northeast. There was no consistent tendency in the Northern and Central Plains. The fact that the convective snows occurred in an area of the jet streak where downward motion develops (Northeast) would alert forecasters to adjust model placement of upper level features (since the enhanced vertical motion should be occurring under the lower right portion of the jet streak.

The weaker stability indices in the Southern Plains and Southeast (values of 40 for Total Totals, 23 for K-Index) occurred in areas with relatively deep arctic air masses. Lightning and heavy snow/ice tended to occur in areas where overrunning was taking place; the convection actually occurred in areas where the depth of colder air (lower levels) would seem to prevent it. CSI tended to occur higher up in the atmosphere as one went eastward (surface to 700 mb over the west, 875 to 600 mb in the east); the most important finding was that lightning activity nearest the frozen precipitation would hardly ever extend beyond the poleward extent of CSI bands. Low level convergence indices differed greatly as one went from west to east. Moisture convergence in the lower levels was much stronger in the east (up to –50 g/kg/hr over the Northeast and Southern U.S.) than in the west and Q-Vector convergence played a dominant role in the Western Plains, as well as in the Northern and Central Plains. There was a wide range of reflectivity values for the snow/ice and areas of lightning near the enhanced frozen precipitation (all regions). Lightning activity occurred on the reflectivity gradient, upstream of the heaviest snow and ice (reflectivity values were 3-5 dBZ higher in areas of lightning near enhanced snow/ice than in regions of the enhanced snow/ice themselves).

In general the lightning activity occurred under cloud tops that were 4-6 °C warmer in temperature than the clouds under which heavy snow and ice fell. The variability of the cloud top temperatures is due to the fact that the lightning and adjacent snow/ice occurred along strong gradients of cloud top temperature. In three of the regions the texture on the visible satellite imagery could be used in conjunction with lightning activity to determine areas of heavy snow or ice. The relationship of 3.9 micron reflectivities to lightning activity and heavy snow/ice could not be ascertained. There were a few storms which exhibited some sort of mixing at the tops of clouds but for the most part the imagery did not show enough variance in reflectivity or strong evidence of the mixing of water and ice.

Forecaster Methodologies

Methodologies were developed based on experiences with the cases used in this work. They first address the model's handling of the systems, a first look at observations (satellite, radar, lightning and surface observations), an examination of the progression of convection into winter storms (with a cross comparison between the observations and model output), and a local (within 3 hours and 250 km) glance at oncoming convection and enhanced snow/ice.

Figures 5-9 depict the process by which the forecaster could use lightning data in forecasting enhanced frozen precipitation. Figure 5 illustrates the overall process, bringing a forecaster from the initial look at model output to the final forecast based on his/her examination and comparison of model output, and observations available. Figure 6 details the model output that the forecaster in a certain area would use to determine the potential for enhance snow or ice. The list is divided into primary and secondary model tools based on how the tools match up with lightning activity in regions around the U.S. in winter storms. All of the model tools are linked together since the forecaster would be examining them as one group, not separate entities. Figure 7 depicts the observations the

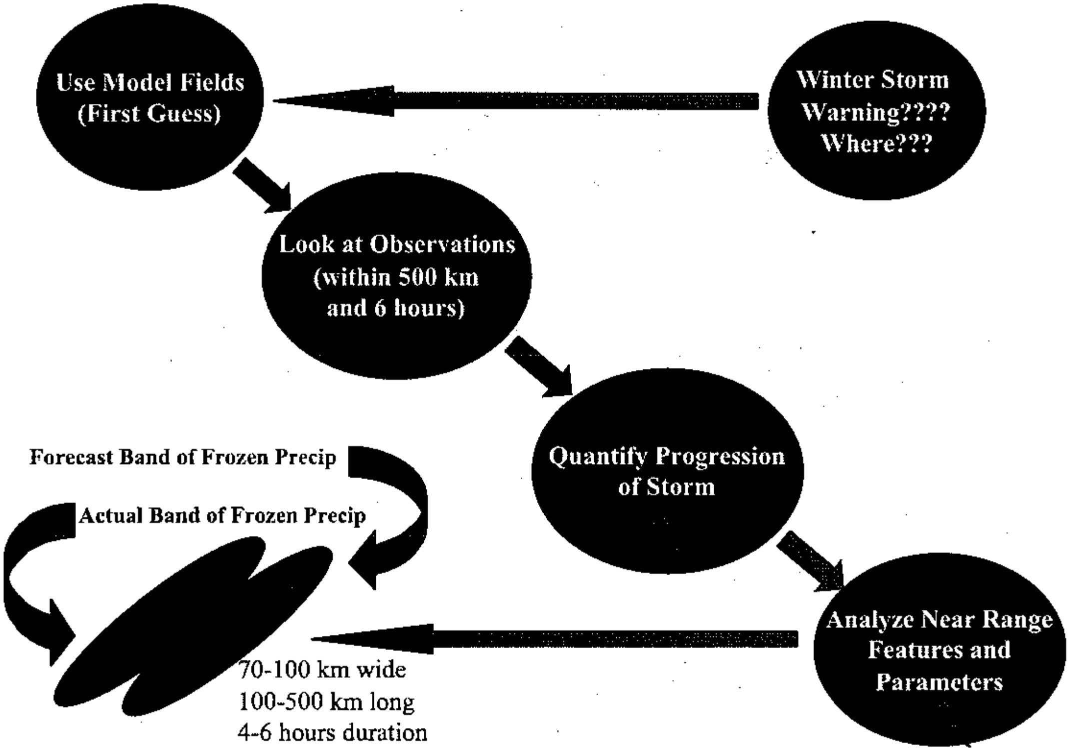


Figure 5: Overall process for enhanced frozen precipitation forecasting.

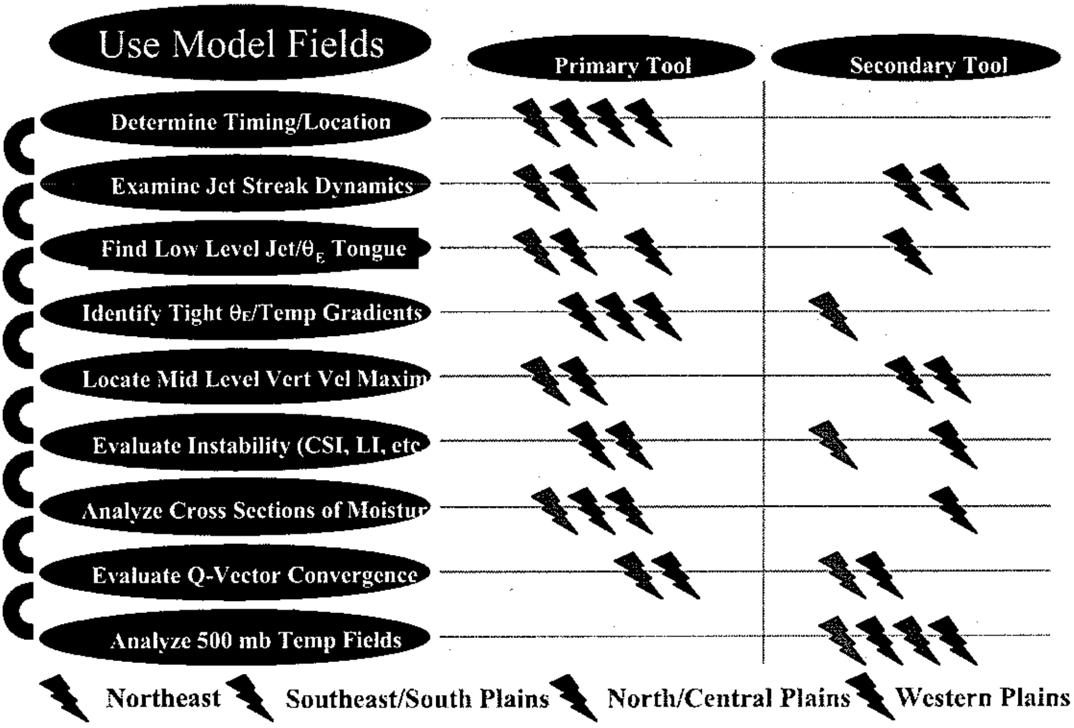


Figure 6: Model field analysis (Step 1)

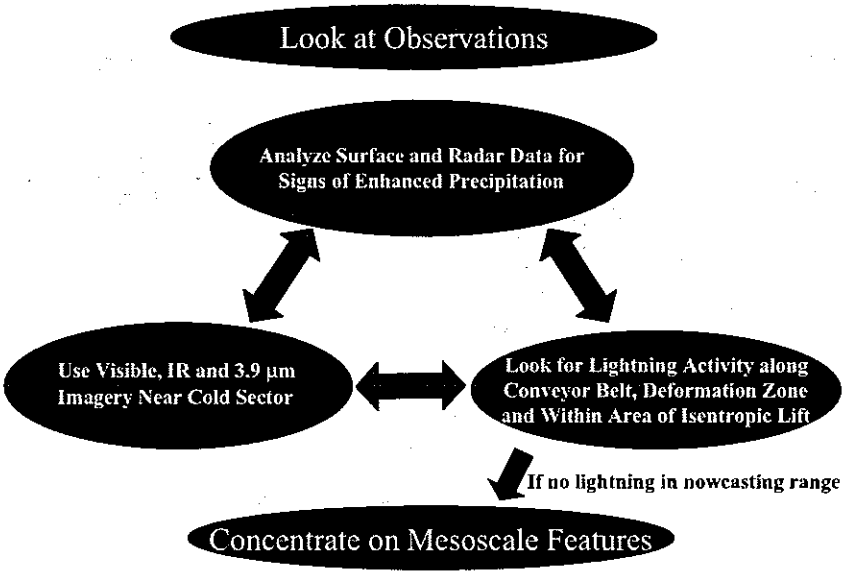


Figure 7: Analysis of static observations within 500 km and 6 hours.

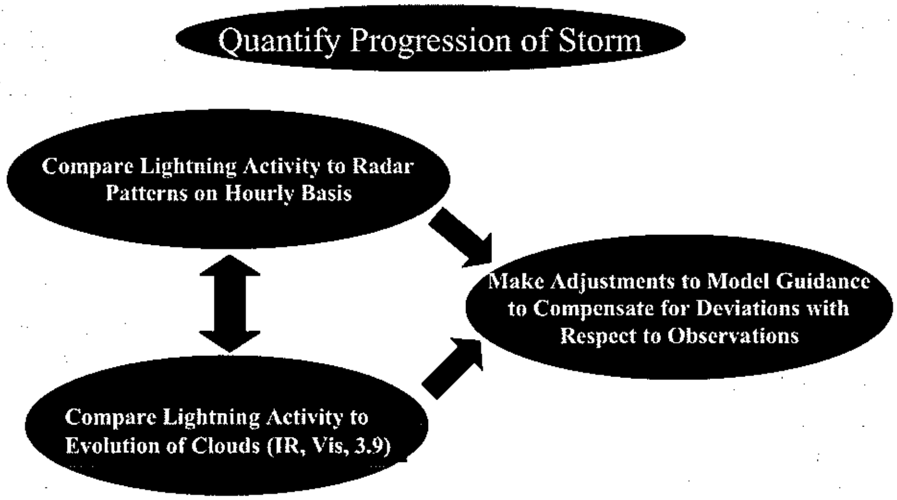


Figure 8: Analysis of progression of storm using radar, satellite and lightning

forecaster should look at within 500 km and 6 hours of a potential enhanced frozen precipitation band. These observations (radar, satellite imagery, and lightning) would be looked at on a static basis, and would be compared with each other in the process.

If there are no lightning flashes within nowcasting range of a forecaster deemed heavy snow or ice band, the forecaster would have to look at the system as one without much convection and fully concentrate on fine scale mesoscale characteristics based on other data. Figure 8 tells the forecaster to examine the storm via the analysis of the progression of lightning, radar and satellite data. The forecaster would compare the movement of IR-depicted clouds, radar cells, and lightning packets against model output. The final portion of the process (Figure 9) incorporates the near term comparison of observational data to arrive to as close a forecast as possible to actual occurrence.

CONCLUSION

The specific intent of this research was to investigate the potential of incorporating lightning data into the nowcasting of enhanced frozen precipitation in winter storms. "Incorporation" entailed the

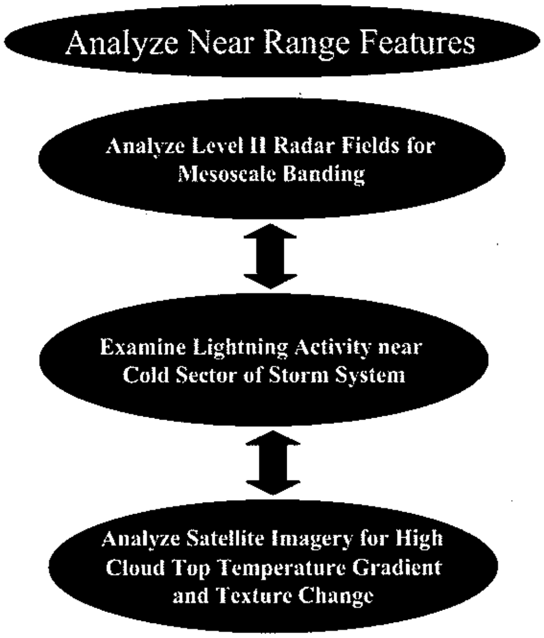


Figure 9: Near term analysis of all observations; fine tuning forecast of band

cross-analysis between lightning data and data/output from other platforms just as a forecaster would via a modern weather interactive processing system (e.g., AWIPS) as a storm approached their area of responsibility. As seen in the cases examined, the comparison itself is supported by various physical links between the precursors of lightning and enhanced frozen precipitation itself (i.e., lift, moisture, and instability).

MAJOR CONCLUSIONS

The following are the major conclusions from the analysis of the 26 cases of this study:

(1) Overall, using lightning to nowcast enhanced frozen precipitation helps in an increasing fashion as one proceeds from the East Coast to the Rocky Mountains. Winter lightning is most numerous over the Southern U.S., near the Gulf of Mexico and less numerous over the Northeast and Midwest. Lightning that was within nowcasting range (500 km and 6 hours) of actual banding of frozen precipitation occurred sporadically at the rate of about 6-10 flashes per hour (0.002 (bin)) for Northeastern storms while over the Western and Southern Plains rates exceeded 90 flashes per hour (0.048 (bin)).

It is over the Western Plains where lightning data provides the most benefit for nowcasting in winter storms. As seen with the cases in that region, vertical velocities output by the model are often too low (or in the wrong location) to explain lightning activity. Average vertical velocities output by the model for areas with eventual lightning were between –2.0 and –4.5 μbar/sec; in three of the Western Plains cases the location of the maximum vertical velocities was more than 400-600 km away from the lightning activity (nearest the enhanced frozen precipitation). Lightning rates (near the cold sector) during winter storms over the Northeast are not much less than those over the Western Plains. However, the Eta model outputs vertical velocities that are often half to as much as a full magnitude greater than those that it outputs over the Western Plains (values ranging from –10 to –17 μbar/sec). If one assumes that the model is handling vertical velocities well over the eastern U.S. then hourly rates of lightning activity can indeed be translated to lift and instability, and enhance the chances of the model to catch heavy snow or ice events in the short term.

(2) The most interesting finding was that in 11 of the 26 cases lightning activity represented packets (i.e., small areas of maxima) of moisture and enhanced instability that would break off the

main area of convection within the warm sector of the storm or in the deformation zone and progress into the snow or ice sector; within four hours and 400 km downstream, frozen precipitation rates would increase due to these packets of enhanced moisture, lift and instability. In the analysis of the many of these cases it was found that one could track the lightning packets (tracked on an hourly basis, ranging from 75-100 flashes per hour over a region about 2500 square kilometers in area, or 25 bins as defined in this study) against the convection as shown by enhanced satellite IR imagery and nationwide radar reflectivity plots. Bursts of lightning activity (where lightning flashes increase per bin by >5 per hour on an hourly basis as the packets progress) should be noted in this analysis. The GOES IR temperature readings were generally variable (-38 to –50 °C, depending on the region) in areas of lightning since for the most part lightning occurred along the tight IR temperature gradient on the upwind side of the cloud shield. All the data sources depict the movement of areas of enhanced vertical motion, moisture and instability that eventually merge with the frozen precipitation fields. The movement of lightning activity on an hourly basis occurred along the model-predicted track of the conveyor belt and strong q_E tongue.

(3) Lightning activity, especially over the Plains and Southeast, occurred mainly (20 out of 26 cases) along the main axis of the conveyor belt just upstream of the heavy snow or ice sector of the storm. There were seven cases, however, where lightning activity occurred along the strong low-level q_E gradient, adjacent to the path of heavy snow or ice; in some of these cases the conveyor belt was either weak or non-existent. This suggested a link between isentropic lift on the equatorward edge of the cold air dome and lightning activity (as induced high vertical motions associated with the enhanced upward motions provided by the isentropic lift). The gradients for q_E in the Southern U.S. were typically 0.055 to 0.070 K/km, twice as high as in the Northeast (0.030 to 0.055 K/km), where the potential for isentropic lift did not exist in areas of lightning and enhanced frozen precipitation. In this manner, the lightning activity helps to depict strong areas of low-level frontogenesis and isentropic lift that the model may not always portray. There were several instances where the lightning activity would extend into the model predicted cold sector of the storm, suggesting that the model was underestimating the strength of the moisture feed into the storm, and the northern extent of the strong low-level q_E gradient and frontogenesis.

(4) In analyses of satellite-derived cloud top temperature fields versus lightning activity it was found that lightning activity occurred on the upstream side of the coldest clouds in areas where the gradient of cloud top temperature existed. The cloud top IR temperatures varied greatly along this gradient and typical values for the regions ranged from –38 to –44 °C (Northeast) to –40 to –50 °C (Western Plains). This goes against the hypothesis that lightning activity should occur under the coldest clouds themselves where vertical motions would be greatest as clouds penetrate further up into the troposphere. Based on conventional knowledge of convection forecasters would think that lightning and enhanced snow and ice would occur under or near the coldest IR-depicted clouds. The aspect of lightning occurring along the cloud top temperature gradients is important since this is where enhanced frozen precipitation was found to also occur (all 26 cases). It also gives forecasters a better idea of where to look for enhanced lift upstream of heavy ice/snow amongst widespread cloud fields.

Reasoning for the occurrence of lightning and enhanced frozen precipitation along and near the strong IR gradients lies with the vertical structure of the wind field in strong winter mesoscale systems. Vertical shear is often high in winter storms, especially northwest of the maturing low. Whereas the winds near the surface are often northeasterly, winds in the middle and upper levels are southwesterly to westerly, approaching 80-100 kt. The winds in the upper levels transport ice crystals (associated with the convection) downstream. On a satellite image the downwind result appears as a widespread and relatively cold cloud shield.

(5) The analysis of radar data versus lightning data provided results that will be helpful to forecasters in winter storm situations. In many of the storms lightning activity occurred in areas where the radar depicted weak reflectivity returns and surface observations depicted moderate to heavy frozen

precipitation. The reflectivities where lightning and heavy snow/ice were occurring were typically 20-25 dBZ, much lower than one would expect for heavy snow/ice.

In one of the cases (the January 1995 Missouri snow storm) the main snow band occurred halfway between the Kansas City and St Louis radars. Both radars (with an elevation angle of 0.5°) overshot the heavy snow and the reflectivity returns were weak as compared to snow rates reported by observers in Columbia MO (2" per hour). The lightning activity in this one case occurred in the area of the heaviest snow. This gave forecasters a warning not only that snow rates should be heavier in the Columbia area (based on evidence of enhanced vertical motion) but also that snow rates downstream of Columbia (i.e., toward northeastern Missouri) would be enhanced also. The use of lightning data in cases like this one helps forecasters in situations where the radar is overshooting shallow convection.

In ten of the storms, mostly in the western and central plains, lightning activity occurred 1-2 hours before the radars would depict reflectivities indicating upstream convection. These situations involve the initial enhancement of frozen precipitation, and where reintensification of precipitation took place (reference the March 1990 and March 2-4, 1994 storms). In one of the cases (the April 1996 storm in Colorado) lightning data depicted convection and enhanced vertical motion over the mountainous areas southwest of Denver, while the radar data depicted low reflectivities (due to distance and blocking). With the lightning data the forecasters would have had better lead-time on the chance for heavy snow (as induced by the convection) for the Denver area and the northern face of the Palmer Divide. In 7 of the storms the lightning activity helped to identify areas of the storm system within or near the cold sector where bright bands would likely exist. Forecasters can sometimes determine where enhanced frozen precipitation can exist within enhanced radar reflectivity bands with the help of observations of surface precipitation intensity; they must be careful since these intensity readings are not always accurate and do not cover enough area. Lightning observations are of better use in these difficult situations.

In summary, twenty-three of the twenty-six cases studied had substantial lightning upstream of enhanced snow or ice (within the nowcasting timeframe); the other three had minimal activity upstream of enhanced ice or snow. Of the twenty-six, fifteen cases had lightning bands that were parallel in orientation to the frozen precipitation bands; in the other cases the lightning bands were almost perpendicular (and upstream of) to the frozen precipitation bands. In eleven of the cases, lightning occurred concurrently with the enhanced frozen precipitation, upstream of and parallel to future heavy ice or snow.

Lightning activity provides a valuable nowcasting tool for winter storms over the Southern and Central Plains, as well as over the Southeast. This is due to its frequency on an hourly basis. Secondly, it is due to the lightning's ability to enhance the ability of radar (which overshot winter convection in 40% of the cases observed) and satellite data (since lightning activity occurred upstream of or adjacent to heavy snow or ice on the equatorward edge of the coldest clouds (all cases)) to locate convection upstream of snow and ice. On a short time scale, models such as Eta have a very good handle on storms that affect the Northeast. Lightning data, as seen in the cases, can help identify or diagnose reintensification episodes and is also useful where the model does not have a firm handle on the placement of jet streak interaction, rain-snow lines, and general areas of enhanced lift.

Overall, the investigation of the incorporation of lightning data into the nowcasting of enhanced frozen precipitation has produced very favorable results for forecasters. Lightning data provide a useful tool when used in combination with both radar reflectivity charts and satellite imagery (based on the existence of lightning activity along IR gradients and in areas of questionable radar intensity returns). It also fills in the gaps associated with model output (especially in reference to vertical velocities near 700 mb, low-level moisture flow, and instability). The use of lightning data in winter storms is more of a benefit for forecasters as one proceeds from the east coast to the Rocky Mountains. Forecaster feedback on the usability of the forecaster methodologies is expected and encouraged; it will not be surprising that there are other "rules of thumb" regarding winter convection out there that could be incorporated into the forecaster methodologies.

Future Research

There are uninvestigated avenues regarding the use of lightning in winter storms whose potential findings may enhance already developed forecaster methodologies. These include in general those studies which focus on the climatology of winter lightning and improved satellite, radar and model techniques/technology which could improve the incorporation of lightning data into winter storm nowcasting by virtue of improved resolution and more identifiable physical links.

Tentative plans for future research include:

(1) An analysis of the correlation of sea-surface temperature (SST) patterns along the Gulf Stream and CG lightning activity associated with east winter storms. The purpose of this effort will be to investigate the interaction of sea surface and winter storm convection, i.e. to see if this interaction could be used on a consistent basis to more accurately predict snow and ice bands along the eastern seaboard;

(2) An extensive analysis of the climatology of CG lightning during the winter by month, year, and regions of the country (extension of Orville *et al.*, 1987 and Holle *et al.*, 1998);

(3) A detailed multi-parameter analysis of convective winter cells with lightning activity. This project will examine the ability of dual polarization radar to differentiate between the aggregates associated with heavy convective snow, and to help improve the radar detection of snow rates based on the amount of liquid water on accreting snow conglomerates;

(4) A more extensive effort to further populate and refine the table depicting the ability of lightning data to help forecasters in winter storm situations. This will involve the collection of more data sets (radar, satellite, lightning, pilot reports and model output) for a larger number of winter seasons. This will also involve false alarm determination;

(5) The assimilation of forecaster feedback into the forecaster methodologies. This will improve the use of lightning against other parameters in the nowcasting of frozen precipitation bands, and help refine the discriminators used in this regard. Forecasters could introduce new parameters that work well with lightning data (based on experiences with the data over a number of years).

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