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Forecast verification of the Current Icing Potential (CIP) product to predict observed lightning in the vicinity of U.S. Spaceports

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FAA COMMERCIAL SPACE TRANSPORTATION (AST)

TASK 6:
CORRELATIONS OF ICING POTENTIAL INDEX TO TRIGGERED LIGHTNING RISK

A STATISTICAL ANALYSIS OF THE VIABILITY OF USING THE CURRENT ICING POTENTIAL TO DIAGNOSE THE THREAT FOR LIGHTNING ACTIVITY AT CURRENT AND FUTURE SPACEPORTS

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Abstract

Government spaceports employ extensive lightning detection networks that may not be available at commercial spaceports. As the number of commercial space operations increases, the Federal Aviation Administration identified the need for a method of diagnosing the threat of triggered lightning at commercial spaceports without in-situ measurements. Charge separation that produces lightning is generated by the existence of water in solid and liquid state interacting. This mixed phase environment is also conducive to structural aircraft icing. Anecdotal observations of the Aviation Weather Center's Current Icing Potential (CIP) numerical weather prediction model indicated a potentially high correlation between lightning activity and icing potential. Analysis of three years of USPLN lightning data at multiple spaceports across the country provided a measure of the lightning frequency at these locations. It was determined that existing facilities fall into three different lightning risk categories. Relatively high statistical correlations between the CIP and lightning activity in both space and time were discovered, but so were negative correlations. A forecast verification study and supporting representative case studies were conducted to quantify the CIP's ability to diagnose existing and future lightning hazards. The verification study, covering two years of lightning activity, determined the CIP's ability to diagnose lightning hazards was quite limited due to extensive over prediction. Case study analysis determined this method also failed to capture lightning initiation, a potentially greater weakness. Co-locating CIP and radar reflectivities over an eight-month period showed that this same over prediction problem is evident for areas of convection in general, without regard to

existing lightning. It is difficult to make any conclusions as to the validity of CIP for a predictor of lighting triggered by a launch vehicle.

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Chapter I

Introduction

As the United States commercial rocketry program grows in support of both federal and commercial demands, and the number of licensed and planned spaceports increases, a tool is desired to provide a regional assessment on the potential of lightning, or triggered lightning, for planning and safety assessment at these new spaceports. Figure 1 shows the locations of current and proposed spaceports across the United States as of 2011. Not included in Figure 1 are several other spaceports, mentioned later, that are currently inactive. Most of the new spaceports are much further inland, some nearer to population centers than the more traditional coastal spaceports such as Cape Canaveral Air Force Station (CCAFS) and Vandenberg Air Force Base (VAFB).

Triggered lightning events involving damage or destruction of launch vehicles have occurred, the most notable being Apollo 12 on November 14, 1969, and an unmanned Atlas/Centaur rocket on March 26, 1987. In both cases, the vehicles launched through weak cold fronts that were not producing any natural lightning, but triggered an electrical discharge between the upper charge region, the vehicle, its plume, and the ground. Apollo 12 was able to overcome system damage and loss and safely complete its mission, while Atlas/Centaur 67 experienced a computer failure, which resulted in the loss of the vehicle and payload.

There are a number of operational forecast products already in use to diagnose areas of aviation hazards associated with convective activity. Among these is the Current Icing Potential (CIP) operational system. The CIP is an operational weather forecast model that assesses the probability of super cooled liquid water in the atmosphere, which is conducive to structural aircraft icing. The existence of super cooled liquid water is usually indicative of a mixed water phase environment. These mixed phase environments generate the charge separation in thunderstorms that produce lightning. Given this relationship, the CIP might be able to serve as a publicly available tool for diagnosing lightning hazards at commercial spaceports. A suitable starting point for analysis is a statistical assessment of the CIP's ability to detect naturally occurring lightning.

Figure 1. Map of current and proposed United States Spaceports (FAA, 2011).

For this study, United States Precision Lightning Network (USPLN) data are used to represent areas of known lightning hazards. This network is able to identify cloud-to-ground strokes (with positive or negative polarity assignment) as well as cloud-to-cloud flashes. The USPLN lightning event counts have been assigned to 20 km grid boxes that match the grid boxes in the CIP model domain. The lightning data have been partitioned into *positive*, *negative*, *IC* (in-cloud), and *all* strokes events. Hourly counts of these events in the grid boxes were calculated. These events represent areas of known lightning hazards that are suitable for comparison to other forecast parameters that also represent environmental conditions that could support charge separation. The gridded lightning event data are suitable for the evaluation of operationally produced data sets for their determination of existing regional hazards to rocket activities.

Significance of the Study

Previous research conducted by the FAA and its contractors has noted that the mixed phase environment which produces super-cooled liquid water and ice particles conducive to aircraft structural icing are believed to be the same mechanisms for generating charge separation between clouds and the ground which ultimately produce lightning as shown in figures 2 and 3 **(Shelton-Mur & Walterscheid, 2010)**. Preliminary findings by the FAA indicated occurrences of lightning were highly correlated with the CIP index at the four spaceports analyzed over four years.

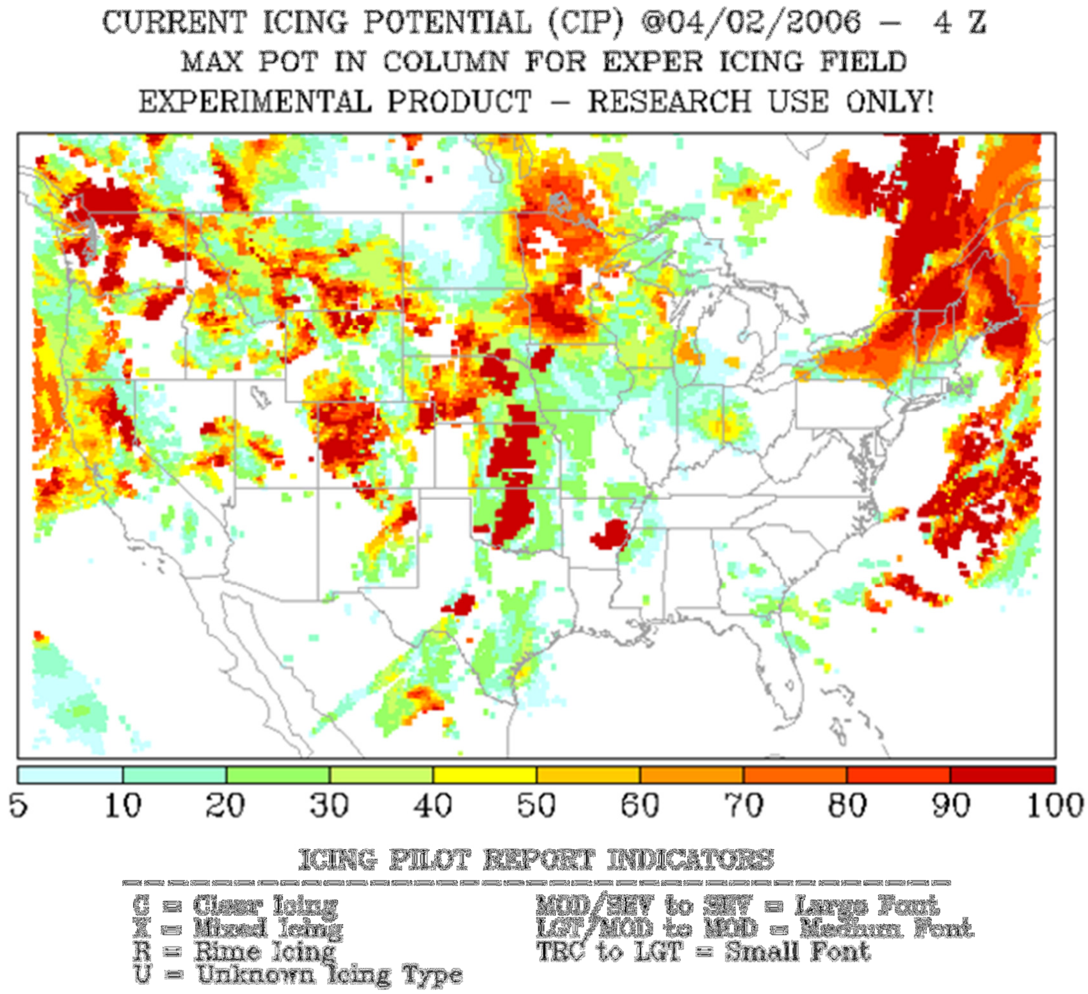

Figure 2. Maximum probabilities of CIP across the United States on April 2, 2006.

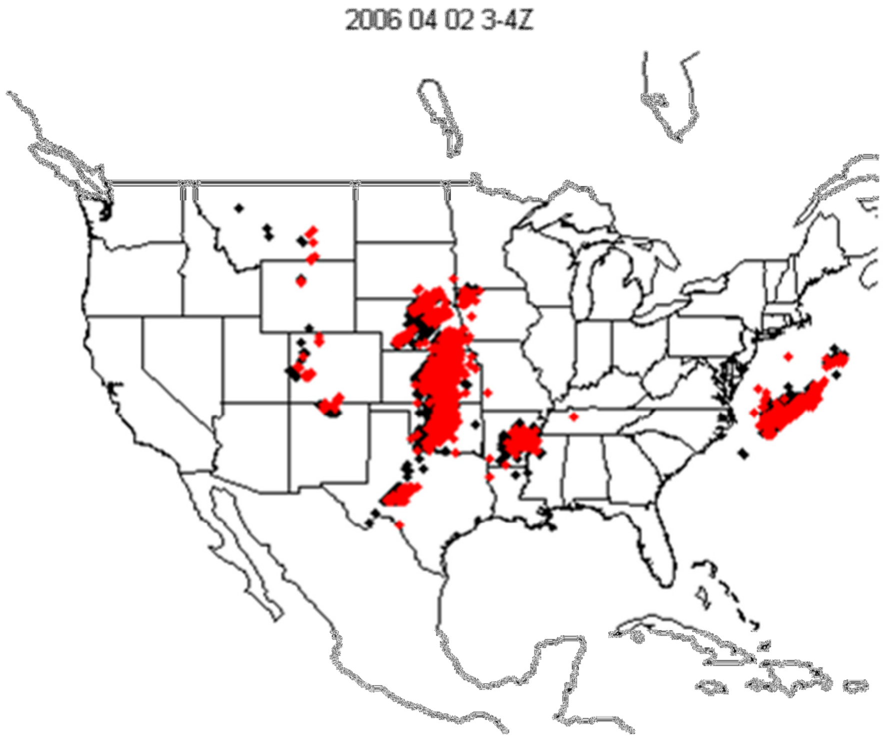

Figure 3. Cloud to ground lightning flashes for one hour following the CIP time.

Statement of the Problem

The FAA is uncertain what types of weather detection equipment and data, if any, future spaceports will have. Current government spaceports such as Kennedy Space Center (KSC) and CCAFS have extremely robust sensor networks for understanding the precise conditions in the boundary layer and aloft surrounding their support and launch facilities. Of these sensors, field mills are of particular interest because they can detect electrical fields that may generate lightning. We will determine, via statistical analysis, if the CIP can be used to diagnose the threat from (observed) lightning at commercial spaceports as an alternative to on site detection equipment from field mills.

Purpose Statement

The purpose of this study was to determine if the CIP can be used to diagnose the threat from (observed) lightning at commercial spaceports.

Data Delimitations

Existing national observing systems for lightning data are not government owned and can only be accessed by subscribing to the companies that operate the detection networks. Two private lightning networks cover the CONUS; these are the National Lightning Detection Network (NLDN) and the United State Precision Lightning Network. ERAU receives data from both networks in near real-time, while we have an internal archive of the USPLN for research purposes that dates back to 2009.

Archived CIP model data is freely available from the National Oceanic and Atmospheric Administration (NOAA) to the university community via the NOAA/National Model Archive and Distribution System (NOMADS). Other than modest amounts of missing data in the archive, the availability of CIP data placed no initial restriction on the period of analysis. In December 2010, NCEP (National Centers for Environmental Prediction) released an update to the CIP. This update changed the format of the archive data and was incompatible with the software developed for this analysis. This change in the CIP determined the end of the analysis period. Lightning data and compatible CIP data overlap from January 1, 2009 to November 30, 2010. Lightning data from January 1, 2009 to December 31, 2011 provide a limited lightning climatology for the various launch facilities. A proper climatology for any location should have decades of observations to be valid, so these results should not be considered as a result for such a study; however, this period does provide a sense of the overall lightning trends for the location and across the seasons.

There are additional limitations in the analyzed region in both time and space. The internal lightning data set contained 1,075 out of 1,095 days over the three year period. The 20 missing days do not present a significant weakness to this study. In addition, both the lightning data set and the CIP domain are limited to the continental United States (CONUS). As a result, any launch facilities outside this region, such as those in Alaska, Hawaii, or the Pacific Ocean, are not be included.

Limitations and Assumptions

Lightning data is received by ERAU in real-time in one minute packets. These reports contain all lightning events since the previous data block, or minute, before it. The lightning events have a spatial accuracy of about 1-2 km, which is well within the domain of the 20 km grid used for the creation of flash count densities. The CIP data is updated hourly, which is very rapid by Numerical Weather Prediction (NWP) standards, but results in 60 lightning data time blocks for each CIP hourly analysis. This required a scheme to be developed that would generate an hourly lightning data set that would match the CIP domain. The lightning data was processed into an hourly gridded data set with all times from 30 minutes (:30) before the hour through 29 minutes (:29) after the hour contained in a single file. This file was then treated as valid on the hour (:00).

The primary literature source for information on the location and status of spaceports and their license status is the FAA's U.S. Commercial Space Transportation Developments and Concepts: Vehicles, Technologies, and Spaceports. The latest available version of this document is January 2011. **(FAA, 2011)**.

Definitions of Terms

GRIB File	A binary file whose format is standardized by the World Meteorological Organization and is used for the storage and exchange of gridded fields.

List of Acronyms

BAK	Spaceport Indiana
CASP	California Spaceport
CCAFS	Cape Canaveral Air Force Station
CHUG	Chugwater Spaceport
CIP	Current Icing Potential
CPC	Climate Prediction Center
CONUS	Continental United States
CSM	Oklahoma Spaceport
ERAU	Embry-Riddle Aeronautical University
GOES	Geostationary Operational Environmental Satellite
IDV	(Unidata) Integrated Data Viewer
MARS	Mid-Atlantic Regional Spaceport
MASP	Mojave Air and Space Port
NCAR	National Centers for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCL	NCAR Command Language
NEXRAD	Next Generation Weather Radar WSR-88D Doppler Radar

NLDN	National Lightning Data Network
NOAA	National Oceanic and Atmospheric Administration
NOMADS	NOAA/National Model Archive and Distribution System
NWP	Numerical Weather Prediction
POES	Polar Operational Environmental Satellite
RUC	Rapid Update Cycle
SPAM	Spaceport America
SPWA	Spaceport Washington
SPWI	Spaceport Wisconsin
TDWR	Terminal Doppler Weather Radar
UCAR	University Corporation for Atmospheric Research
UPSLN	United States Precision Lightning Network
WSI	Weather Services International Corporation

Chapter II

Review of the Relevant Literature

A review of published literature regarding lightning formation and discharge, lightning forecasting, and associated numerical weather prediction (NWP) methods is provided with a goal of determining the feasibility of using NWP to diagnose lightning hazard to spaceports.

Numerical Weather Prediction

The CIP is an algorithm that uses observations from satellite, radar, the surface, lightning events (from the NLDN), and pilot reports along with forecast model output to diagnose the potential for icing and supercooled liquid water. The CIP was developed for the FAA to forecast short term icing conditions. The output is produced hourly in a three dimensional domain using methods developed based on forecast and research flight experience along with observations and model data. Historically, icing was forecast manually using a limited set of fields such as relative humidity, temperature, and vertical motion. The CIP utilizes these as well as other techniques to create a more complete picture and diagnose the potential for icing in different environmental conditions. The data sets are merged with the Rapid Update Cycle (RUC) model grid. The 3-D location of clouds and precipitation are determined by observations from sources such as satellite and radar. Next, the fuzzy-logic functions are performed, and then a decision tree is utilized. The decision tree ties in with the initial icing and supercooled large drop potential calculation for specific known icing situations. These icing situations are a single cloud layer, multiple cloud layers, cloud top temperature gradients, freezing rain, and deep convection. The final icing potential is then calculated by boosting the factors up or down. An upward boost is given to initial icing potential areas where icing is reported, or model upward vertical motion and/or model supercooled liquid water is forecast. Only model forecasts of downward vertical motion can decrease the icing potential. The paper presents four case studies of CIP performance in a single layer cloud, freezing rain, cloud top temperature gradient, and a poorly handled single cloud layer. The statistical performance of the CIP against pilot reports of icing is also presented where the CIP is shown to have a high degree of accuracy, particularly in certain ranges.

The RUC is an operational numerical weather prediction model used by the National Centers for Environmental Prediction. The RUC supplements longer range, longer update cycle models with a by using a shorter update cycle to achieve a more accurate short-range model. A shorter-range model with a faster update cycle has applications for fields sensitive to quickly changing weather conditions, such as thunderstorms and icing, which are of particular interest to aviation. At the time of writing, the operational RUC used a 20-km grid with a 1-hour update cycle and 50 levels using a hybrid sigma-isentropic vertical coordinate. The domain covered the continental United States, as well as adjacent Canada, Mexico, and the Atlantic and Pacific Oceans. Observational data for the RUC comes from high-frequency sources to facilitate the 1-hour cycle, which has to overcome significant challenges in order to remain stable, with spurious gravity waves and aliasing being a particular issue. A noise control process controls the gravity waves, while observation time windows select the data used for assimilation. The high frequency data sets and the quick update cycle of the RUC work well to maintain temporal stability but the infrequency of the RUC's primary data source (aircraft observations) leads to the aforementioned aliasing issues, as their spatial resolution is inconsistent in the vertical and horizontal model structure. Despite the challenges of data assimilation, the RUC has been statistically proven more accurate in short range forecasts than long-range models and short range persistence with the exception of a few fields. Improvements are planned to improve the grid resolution, introduce new data sources, improve the use of current sources, and develop a WRF-based successor. The newer version of this forecast model may provide better guidance of lightning potential than existing forecast tools allow and should be considered for future studies. Other modeling advancements are underway at NCEP that may provide a better assessment of storm-scale convective activity.

Lightning Formation

The fundamental cause of lightning formation is the electrical flow between separated charge regions in clouds and the ground. The lightning discharge is usually comprised of multiple individual strokes with the entire event being called a flash. Martin A. Uman did much of the foundational work to understand lightning formation; from his work, two books explore lightning basics and a more detailed analysis of the discharge.

In the book *Lightning*, Uman presents basic knowledge of lightning formation and the different types of common observed lightning discharges. These discharges can be grouped in three general categories based on the characteristics of formation: negative cloud to ground, positive cloud to ground, and cloud to cloud. A negative cloud to ground discharge occurs when charge separation between the ground and clouds results in the flow of electrons from the positively charged ground to the negatively charged cloud. A positive cloud to ground stroke discharge is similar to a negative cloud to ground discharge, but the electrons flow from negatively charged ground to a positively charged cloud. A cloud-to-cloud discharge is the flow of electrons across charge separation between clouds, never contacting the ground.

The specific characteristics of the different lightning polarities are further explored in *The Lightning Discharge*. Negative strokes and cloud-to-cloud strokes produce charges that are roughly on the same order, while a positive stroke will produce a charge three times stronger. The positive stroke will also move up to five times slower, affecting whatever it meets longer than a negative or cloud-to-cloud stroke.

Triggered lightning is an event where a disturbance helps create a channel between the separated electrical fields in the atmosphere allowing the transfer of charge. This produces a lightning discharge that might not have occurred naturally. While triggered lightning is a known hazard to rocket launches, we cannot speculate on how this hazard might relate to existing data presented in this study.

Lightning Forecasting

The National Weather Service (NWS) and academic institutions have conducted numerous studies in lightning forecasting, with statistical analysis being the dominant method for short- to long-term diagnoses of the threat for lightning.

The Storm Prediction Center's (SPC) efforts to forecast lightning, detailed by Philip Bothwell started in the early 2000s with the intent to forecast dry lightning strikes in support of fire weather forecasting. These efforts used lightning climatology and forecast model predictor fields to create a “perfect prognosis” forecast for lightning. The perfect prognosis assumes the NWP model is “perfect” and looks for conditions based on lightning climatology that have been statistically proven precursors to lightning activity. The output is created by applying equations to nearly 200 predictor fields in any model, long and short range, providing the perfect prognosis forecast out to the length of the forecast model. Over the years, the forecast system has been modified to include Alaska and other non-CONUS areas as well as forecast excessive lightning events in addition to dry lightning events.

Phillip E. Shafer and Henry E. Fuelberg (2005) used sixteen years of NLDN lightning data to produce equations that could be used to predict lightning onset. Their work showed very promising results for contained areas with not just onset but subsequent strikes. The most helpful contribution of this paper to lightning forecasting is the statistical analysis they performed, not necessarily their results. This publication is one of the newer in the subject and the last substantial analysis of the use of statistics for such a forecast. This work relied on data fields from weather balloons launched from different sites in Florida, including Jacksonville, Tampa, Kennedy Space Center/Patrick Air Force Base, and Miami.

Due to the inherent inability for lightning detectors to predict where lightning will be until after it has struck, many studies have been done to test the possibility of discovering weather radar signatures that would pre-empt the first strike and even allow for warnings. Michael S. Gremillion and Richard E. Orville (1998) investigated numerous warm season air-mass type thunderstorms around the Kennedy Space Center from 1992 to 1997 utilizing the NWS's WSR-88D (Weather Surveillance Radar 1988

Doppler) weather radar as well as the NLDN. Previous studies had indicated that charge separation occurred in storms with updrafts strong enough that they reached the negative ten to negative fifteen degree Celsius height where liquid and solid water was interacting. Using this as a baseline, they compared radar volume scans with lightning data to find that radar signatures of forty decibels at the negative ten degrees Celsius height can be used to predict the onset of lightning.

The publication by Kurt D. Hondl and Michael D. Eilts (1993) is very similar to Gremillion and Orville's, though Hondl and Eilts' work was published several years before. Once again, radar signatures are correlated with NLDN data to find signatures that would help indicate the onset of lightning. This is useful for data comparison as the papers are close enough in topic to confirm findings, while different enough to present different suggestions. For example, they both analyze data around Kennedy Space Center, but Hondl and Eilts additionally use data from Federal Aviation Administration Terminal Doppler Weather Radar in Orlando, Florida in addition to the WSR-88D in Melbourne, Florida. In addition to the signatures at the negative ten degrees Celsius level, they also examined convergence and divergence radar signatures in the proximity of the storms for correlations with lightning activity. While Hondl and Eilts performed highly detailed analysis of several individual events, most of the concentration was on initiation and the radar signatures associated with them.

Phillip E. Shaffer and Henry. E. Fuelberg (2007) also used several different weather models to try forecasting lightning using the perfect prognosis scheme. While their method was only moderately successful, their research regarding the application of models and lightning required a significant understanding of how the model was behaving and how it connected to real life. The results they obtained involved running local forecast models, as well as using operational forecast models, to predict the onset of lightning initiation at three to twelve hours before the storms formed. Unlike other papers that were purely statistical reviews, Shaffer and Fuelberg developed some of their own computations to post-process the existing data in the models and conform it to meaningful output regarding areas and time of lightning threat. Flow regimes remained very important to their understanding, as they play critical roles in the determination of where lightning will occur and the frequency of strikes.

In order to ensure that not all literature is number laden computer or radar analysis, some real world inclusion is necessary. Ronald M. Reap (1992) provides some of the early support for understanding lighting environments. Many of the previously mentioned publications reference Reap's work in analyzing synoptic patterns and the subsequent low-level wind flow regimes. At the time of the publication, like many others already described, the goal was to present some type of system for forecasting the timing and intensity of deadly cloud to ground lightning. Using different map types and different flow regimes, Reap was able to develop the concepts later used in many of the papers that relate the known lightning hotspots to the type of synoptic conditions that promote them. Much of this paper is outdated, as the forecast model used in the study is no longer operational and the NLDN was still fairly new, but the work lays the foundation for concepts regarding Florida lightning distribution.

Chris J. Theisen, Paul A. Kucera, and Michael R. Peollot's (2008) analysis *Florida Thunderstorm Properties and Corresponding Anvil Cloud Characteristic* is a potentially useful publication, though it doesn't actually discuss lightning. However, the composition of the particles and their location in a storm, including the anvil, is vital. Observations from radar and satellites were compared with data from aircraft flying near the anvil of the storms in a project called CRYSTAL-FACE (Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment) during 2002. Some of the findings are skewed away from natural occurrence, largely due to a bias toward storms with large anvils for the sake of better sampling. The result is information on: the intensity of a storm, how long it took to form and dissipate, and the characteristics of the anvil environment. This publication will likely serve very useful in filling gaps other publications, particularly those that focus on single data sources, leave behind.

Triggered Lightning Strikes on Aircraft and Spacecraft

Triggered lightning has been investigated by four instrumented aircraft, as well as two incidents where video was captured of commercial airliners triggering lightning strikes. These incidents, as well as Apollo 12 and Atlas/Centaur 67, are investigated by M.A. Uman and V.A. Rakov. The four, instrumented aircraft were intentionally flown into and around thunderstorms for the sake of understanding the aircraft's role in aircraft lightning strikes. These studies, plus data available on lightning strike accidents, support the conclusion that 90 percent of lightning strikes on aircraft and spacecraft are triggered by the craft itself.

Due to the strict weather launch criteria at current spaceports, the occurrences of triggered lightning strikes on spacecraft are rare. The two most notable lightning strikes on spacecraft are Apollo 12 in 1969 and an unmanned Atlas/Centaur in 1987, the latter serving as a reminder of the loss a lightning strike can cause. In both cases, the vehicles launched through weak cold fronts that were not producing noteworthy lightning. It was determined both spacecraft triggered an electrical discharge between the upper charge region in the cloud, the vehicle, its exhaust plume, and the ground. Apollo 12 was able to overcome system damage and loss and safely completed its mission, while Atlas/Centaur 67 experienced a computer failure, which resulted in the loss of the vehicle and its payload.

Atlas/Centaur 67

Christian, Mazur, Fisher, Ruhnke, Crouch, and Perala's article details the atmospheric conditions the produced the Atlas/Centaur 67 triggered lightning strike as well as the sequence of events. As with Apollo 12 a weak front, in this case a stationary cold front, was extending across Florida oriented southwest to northeast across the panhandle. The strongest convection associated with the front was being produced in a squall line that crossed the Florida panhandle into the Gulf of Mexico. This squall line was well north of Cape Canaveral at the time of the lightning strike. Conditions at the launch site were described (after the fact) as weak convective with thunderstorms in the area "in the broadest sense of the word". There was occasional lightning, dark clouds, and strong precipitation on the ground. No cloud to ground lightning was observed within five nautical miles of the launch site in the 42 minutes prior to the launch; though an undetected cloud discharge was observed by press 2 minutes prior to launch. Forty-nine seconds after launch there was a lightning flash observed below the cloud base. The vehicle was inside a cloud at an altitude of 12,000 feet where the temperature was 4 degrees Celsius, 2,400 feet below the freezing layer (14,400 feet). The radar echo of the cloud was only 10 dBZ, considerably lower than the 40 dBZ of thunderclouds in the area.

Apollo 12

M.A. Uman and V.A. Rakov analyzed the lightning strike triggered by Apollo 12 in 1969. The conditions were similar to that of Atlas-Centuar 67, though less is known about the environment due to the primitive weather sensing equipment at the time. A weak cold front was in proximity of KSC with no lightning reporting within six hours of launch. Shortly after launch, the vehicle triggered two separate discharges that damaged and disrupted spacecraft systems. Unlike Atlas-Centaur 67, Apollo 12 was able to overcome the system upsets to reach orbit safely.

Spaceports for this study

The following is a brief summary of the selected spaceports included in this study. Spaceports were selected based on a combination of present activity, anticipated activity, and spatial distribution across the CONUS.

Spaceport California. Located at 34.58 degrees north and 120.63 degrees west at the California coastline, this is the westernmost launch facility within the CONUS domain. Operated by Spaceport Systems International, this spaceport was the first to receive an FAA Commercial Space Launch Site Operator's License. It utilizes Space Launch Complex-8 at Vandenberg Air Force Base, part of the Western Range. The Western Range supports orbital and suborbital flights from the west coast, and launches from this complex are generally destined for polar orbits.

Cape Canaveral Spaceport. Located at an estimated position of 28.46 degrees north and 80.53 degrees west on the Florida east coast, Cape Canaveral Spaceport is one of the southernmost launch facilities within the CONUS domain. Operated by Space

Florida, this spaceport utilizes Launch Complexes LC-36, LC-46, and LC-47 for vertical launches and is co-located with CCAFS and Kennedy Space Center, all part of the Eastern Range. Cape Canaveral Spaceport also supports Space Exploration Technologies (SpaceX) launches at LC-40. The Eastern Range supports all orbital and suborbital launches from the east coast of the United States with numerous launch inclinations for polar, low, medium, geosynchronous, and high Earth orbits as well as Earth escape trajectories thanks to the added velocity from the Earth's rotation near the equator. Because Cape Canaveral Spaceport, CCAFS, and KSC are within 20km of each other, and are effectively one large launch complex, separate analysis would be a duplicate effort. Because Air Force personnel at CCAFS are responsible for supporting the entire launch complex, CCAFS will be used to identify all three organizations.

Chugwater Spaceport. Chugwater Spaceport is located at 41.67 degrees north and 104.78 degrees west. There has been little development of this spaceport since 2007, but analysis was determined to be worth conducting due to it being representative of inland northwest United States and located near United States nuclear missile silos. Chugwater Spaceport is a former Atlas missile base in Wyoming, which was purchased by Frontier Aeronautics in March 2006 who began maintenance work to bring the original hardware operational again. No further updates have been received since 2009.

Mid-Atlantic Regional Spaceport. Mid-Atlantic Regional Spaceport is located at 37.83 degrees north and 75.49 degrees west on the Virginia coastline, making it and Wallops Flight Facility the easternmost launch facilities in the CONUS. Operated by Virginia Commercial Space Flight Authority this spaceport operates two launch pads, 0-A and 0-B, which are co-located at Wallops Flight Facility. While Wallops mainly specializes in suborbital and balloon launches, the Mid-Atlantic Spaceport has developed facilities to support resupply missions to the International Space Station in low Earth orbit was well as lunar probes.

Mojave Air and Spaceport. Mojave Air and Spaceport is located at approximately 35.06 degrees north and 118.15 degrees west in California this spaceport is operated by East Kern Airport District and home to Masten Space Systems. As of January 2011 Mojave Air and Spaceport is not yet licensed by the FAA to conduct commercial vertical launches, but has the facilities to conduct vertical launch tests. Masten uses the facilities to design, build, and test reusable vertical take-off and landing vehicles for NASA contracts, as well as other vehicles such as The Spaceship Company's WhiteKnightTwo and SpaceShipTwo. Other companies use the current and upgrading facilities, including large runways, to test vertical and horizontal take-off vehicles.

Oklahoma Spaceport. Oklahoma Spaceport is located at approximately 35.34 degrees north and 99.20 degrees west in the state of Oklahoma, this spaceport is one of the few in the central United States, where coastal zones or expansive deserts are not available for use as ranges. Operated by the Oklahoma Space and Industry Development Authority, this spaceport utilizes a large runway and other facilities to support horizontally launched suborbital vehicles.

Spaceport America. Spaceport America is located at approximately 32.99 degrees north and 106.97 degrees west in New Mexico. Operated by New Mexico Spaceport Authority, Spaceport America is the world's first purpose built commercial spaceport currently capable of supporting vertical and horizontal suborbital launches. Spaceport America's proximity to the White Sands Missile Range to the east allows use of that range for launch and recovery operations. The spaceport has been used by commercial and government contractors for tests. However, it will most notably facilitate Virgin Galactic's WhiteKnightTwo aircraft and SpaceShipTwo spacecraft.

Spaceport Indiana. Spaceport Indiana is a proposed spaceport co-located at Columbus Municipal Airport near Columbus Indiana. It is located at approximately 39.2624 degrees north and 85.90786 degrees west, making it one of a few spaceports not near a coast or military ranges. In 2010 Spaceport Indiana was limited to education and hobby rocketry, but still has a proposed status as compared to an inactive. Education is facilitated by a partnership with Perdue College of Technology and the National Centre for Future Space Exploration, with the goal of providing the people of Indiana skills for employment in the growing commercial space flight industry.

Spaceport Sheboygan. Spaceport Sheboygan is a proposed spaceport in the city of Sheboygan, Wisconsin, on the shore of Lake Michigan. It is located at approximately 43.751 degrees north and 87.714 degrees west. In 2006, the Wisconsin Aerospace Authority was formed in order to establish a launch site for conducting sub-orbital launches to support space research and education. The current focus of this spaceport is to promote education in math, science, and rocketry, but also hopes to expand in the future. Spaceport Sheboygan has not applied for an FAA license as of 2011, but is still considered proposed rather than inactive.

Spaceport Washington. Spaceport Washington is a proposed spaceport that would be co-located at Grant County International Airport in Moses Lake, Washington. It is located at approximately 47.20 degrees north and 119.32 degrees west making it the furthest northwest spaceport of the CONUS. Already certified as an emergency shuttlelanding site, Grant County International Airport's facilities include a 13,452-foot main runway and a 10,500-foot crosswind runway, as well as 30,000 acres that could be developed into a vertical launch site. No action to develop this spaceport has been taken since 2007 and is considered inactive.

Chapter III

Methodology

The CIP product became operational in 2002 and now has a decade of use by the aviation community in conjunction with forecast SIGMET and AIRMET products issued by the Aviation Weather Center.

Lightning data from 2009 to 2010 archived at ERAU and archived CIP model data retrieved from NCDC for the same period were selected to perform an analysis between the two data sets to determine if there was a statistically significant correlation between the two. The analysis was conducted using software based on the National Centers for Atmospheric Research (NCAR) Command Language (NCL), providing a reliable infrastructure for computations made in the study. Statistical analyses for behavior of lightning at the CONUS and regional domains, around select spaceports, as well as the horizontal and temporal correlations with CIP data were performed to determine the value of the CIP data for assessing lightning hazards.

Selection Criteria

Lightning data networks, unlike most meteorological information infrastructure, are privately owned. The two detection networks, the National Lightning Detection Network (NLDN) operated by Vaisala and the USPLN operated by WSI, provide real-time and archived lightning data to subscribers and recent data on a time-delay publicly. The CIP uses the NLDN as the primary data source for determining the location of convective lightning, which makes NLDN and CIP data highly non-independent. WSI Corporation in cooperation with the Applied Meteorology program at ERAU participates in sharing data between universities through Unidata, a program within the University

Corporation for Atmospheric Research (UCAR). WSI and ERAU make USPLN data sets available to Unidata participants for educational and research purposes. The USPLN dataset was selected for the analysis of existing lightning hazards for the following reasons: ERAU's involvement with the academic distribution of USPLN data, the network's reporting of individual strokes, cloud-to-cloud events, strike polarity and, perhaps most important, data independence from the CIP product.

Data Retrieval

Retrieval of the data for this project was straightforward. The meteorology program at ERAU archives USPLN lightning data internally going back to 2009. NOAA's NCDC NOAMDS system makes all operational model data available to researchers for download.

Gridded Lightning Data Set

In order to perform the analysis of the data, lightning events, which occur at point locations and at specific times, had to be mapped to the CIP grid locations and into temporal bins, which best represent the lightning activity for a forecast/analysis hour. USPLN produces reports every minute containing the date/time, location, polarity, and other information for all detected lightning events that occurred since the previous data packet. A solution that used the latitude and longitude of a stroke to determine the CIP grid box of that lightning event was developed. The assignment of times, also in the software solution, was more complicated. While the CIP has a relatively high temporal resolution for NWP systems of one hour, lightning events occur rapidly with hundreds and even thousands of strokes during the same period. The lightning data would need to be set to hourly time intervals, but this created fundamental issues of which hour a lightning stroke is valid. Two options were available; (1) use bins starting on the hour where all stroke events from 00:00Z to 00:59Z are valid at 00:00Z, or (2) centered on the hour where all strokes from 23:30Z to 00:30Z are considered valid at 00:00Z. Though more complicated to process, the latter solution was selected as centering on the hour ensured none of the lightning data was off by more than 30 minutes. Using the former scheme a lightning strike at 00:59Z would have been valid for 59 minutes earlier at 00:00Z even though it occurred one minute before the next hour.

The data are also broken up into three categories based on lightning type reported by the USPLN: negative charged lightning, positive charged lightning, and cloud-to-could lightning. A fourth category totals the three separate lightning types. The partitioning of the strokes is consistent with looking for relationships in the differences of the physical processes producing the lightning stroke. Negatively charged lightning is produced when an electrical channel is established from the negatively charged lower regions of the cloud with the positively charged ground resulting in the transport of electrons from the surface to the cloud visibly seen as cloud-to-ground, or forked, lighting. Positively charged lightning events occur with the opposite current flow, often when upper-level clouds from a thunderstorm are transported downwind ahead of the storm carrying a positive charge in the cloud and inducing a negative charge at the surface. When an electrical channel is established electrons flow from the cloud, typically the anvil of a thunderstorm, to the surface. This positive discharge is approximately three times stronger and five times slower than that of a negative charge.

The positive stroke poses a particularly dangerous hazard to safety since it can strike "out of the blue" miles away from the active part of the thunderstorm with a much greater charge and exposure period than that of negatively charged lightning. Cloud-to-cloud lightning is produced when oppositely charged regions of clouds establish an electrical channel resulting in a discharge between clouds or within parts of a cloud. This discharge strength is approximately equivalent to a negative cloud to ground stroke.

The gridded stroke events were assembled into hourly GRIB files that matched the analysis/forecast times of the CIP files. Initial analysis of the CIP files with the gridded lightning data proved difficult when working with all the CIP levels. The level that matched lightning activity alternated from generally 4,000 to 6,000 meters depending on latitude and time of year. With no apparent pattern of lightning activity to the CIP vertical levels, the CIP data were processed to create a single value of the highest CIP value in a column for each grid across all levels, analogous to a composite reflectivity for RADAR data.

Analysis components of this study

Exploratory and statistical analysis of the gridded lightning data set are provided on the CONUS level and regionally around current and proposed spaceports, not classified as inactive. These spaceports include California Spaceport, CCAFS, Mid-Atlantic Regional Spaceport, Mojave Spaceport, Oklahoma Spaceport, Spaceport America, and Spaceport Indiana. These locations were selected based on current or potential commercial launch activity, vertical launch facilities, and previously established lightning climatology for select locations.

Lightning Data Analysis. An initial exploratory analysis was performed to provide an assessment of the gridded lightning data set to generate qualitative information on the differences in lightning activity between spaceports and across the country. Two methods of reading the lightning data were performed. The first method read through the GRIB files for each day of the year to determine the grid box that experienced the maximum lightning event counts for each category. This analysis proved to be a nonproductive effort as the results were not intuitive with limitations in analyzing when and where these maximums occurred, as well as discontinuities between the four categories. The second method also read through the GRIB files for each day of the year, summed the lightning events for each category at each grid box, and summed all the grid boxes producing a daily sum of all events for each category across the prescribed region. This method proved very informative to which days were active, which spaceports are more active than others, along with the seasonality of the lightning activity.

Regional analysis was conducted around California Spaceport, Cape Canaveral Spaceport, Chugwater Spaceport, Mid-Atlantic Regional Spaceport, Mojave Air and Spaceport, Oklahoma Spaceport, Spaceport America, Spaceport Indiana, and Spaceport Sheboygan by including only lightning events that occurred within five grid boxes north, south, east, and west of the grid box that contains the spaceport. This produces a region of eleven by eleven grid boxes, or 220 by 220 kilometers, covering an area of 48,480 square kilometers. The location of the spaceports, or in some cases specific launch facilities, was determined via Internet search for these facilities including the use of Geographical Information Systems such as Google Earth to identify the location and extent of ground facilities. For companies that only have a single vertical launch facility the exact coordinates of the tower were retrieved, while launch ranges and airports for horizontal launches used approximations based on a central part of the facility. With the exception of very large ranges such as White Sands in New Mexico, any error in the exact launch point estimation is far less than a twenty kilometer model grid box. Facilities considered active by the FAA and located in the model domain area (CONUS) are listed in Table 1 (with two exceptions noted as inactive). The actual analysis removes the following co-located spaceports Kennedy Space Center (see CCAFS), Wallops Flight Facility (see MARS), SpaceX (see CCAFS), Vandenberg Air Force Base (see CASP), Edwards Air Force Base (see MASP), and White Sands Missile Range (see SPAM).

Table 1

Locations and Status of CONUS Spaceports

	Inactive	Latitude	Longitude
Kennedy Space Center (KSC)[b]		28.61	80.60
Cape Canaveral Air Force Station (CCAFS)[b]		28.49	80.58
Wallops Flight Facility (WFF)[b]		37.84	75.48
White Sands Missile Range (WSMR)[b]		33.11	106.43
Edwards Air Force Base (EDW)[a]		34.95	117.88
Vandenberg Air Force Base (VBG)[a]		34.67	120.61
Mid-Atlantic Regional Spaceport (MARS)[b]		37.83	75.49
Oklahoma Spaceport (CSM)[a]		35.34	99.20
Spaceport America (SPAM)[c]		32.99	106.97
Mojave Air and Space Port (MASP)[c]		35.06	118.15
California Spaceport (CASP)[c]		34.58	120.63
Spaceport Washington (SPWA)[c]	Yes	47.20	119.32
Spaceport Sheboygan (SPWI)[c]		43.75	87.71
Chugwater Spaceport (CHUG)[c]	Yes	41.67	104.78
Space Port Indiana (BAK)[a]		39.26	85.91

[a] Abbreviated identifier used is based on FAA location identifier. These locations are airports or military bases
[b] Abbreviated identifier used is based on officially designated or industry standard conventions
[c] No identifier could be obtained and we created our own

In many cases, commercial companies used the preexisting vertical launch facilities at already established government spaceports such as CCAFS, Vandenberg Air Force Base, and Wallops Flight Facility. Other companies have, or had, spaceports loosely co-located with government facilities such as Spaceport America with White Sands, as well as Mojave Spaceport with Edwards Air Force Base. Figure 1 illustrates the close proximity of many spaceports. For this reason, we chose to focus on the commercially viable locations with current or shortly planned launch activity within the CONUS, taking advantage of co-located operations. However, spaceports that are considered inactive were still used to create regularly spaced analysis points across the CONUS.

Case Studies. In-depth analysis of each spaceport is beyond the scope of this research. Therefore, after the exploratory analysis, spaceports with current or well-established planned launch activity were examined more closely, and these locations are presented as location specific case studies of the viability of using the CIP to diagnose lightning threat. Cases with strong and weak correlations were selected to demonstrate how the CIP reacts before and during the onset of lightning activity.

False Alarm Rates. In 2009 ERAU Applied Meteorology developed a weather and aviation data server that could be used to query events which matched multiple aviation-centric criteria, such as CIP and rainfall (via radar reflectivities), across the CONUS or at specific locations **(Herbster, et al., 2010)**. The data covers about 8 months (243 days) from February 2009 to October 2009. This tool was used to generate false alarm statistics for CIP by identifying days where CIP probabilities indicated “likely” or “moderate” risk at all levels, and little to no radar reflectivities with coverage less than 10% and decibels (dBZ) less than or equal to “slight”. The results are days where CIP levels were high but convection did not occur, eliminating the possibility of lightning.

The database’s method for querying results in a region differs from the method used in the rest of the research. The gridded correlations used a region bound by 5 grid boxes north, west, south, and east of the grid box matching the coordinate of the spaceport which generated a box 48,400 square kilometers. The database on the other hand, uses a radius in set nautical mile values centered from a coordinate. These values were 10, 25, 50, 100, 250, and 500 nautical miles. The closest option to the 210 kilometers domain for each spaceport was the 100 nautical mile option, which converts to 185.2 kilometers. Between the circular search method and the radius limitations, the domain used for false alarm analysis ends up being smaller than the domain for correlation analysis.

Statistical Correlations. The statistical correlations were performed using software that directly compared the lightning and CIP gridded data sets. Two types of correlations were performed: temporal and spatial.

Horizontal correlations were calculated at each of the CIP’s vertical levels to investigate whether certain levels had a preferred performance. Additionally, to overcome our observation that peak vertical correlations were temporally and spatially variable the use of the “max-CIP” field was implemented. This choice had results that were more favorable than any single level provided. Max-CIP analyzes the entire column of grid boxes finding the maximum value of CIP observed in the column, which produces a single level “worst case scenario” atmosphere.

Temporal correlations were produced by keeping location (grid box) constant and varying time, while horizontal correlations were produced by keeping time constant and varying location. Correlations were calculated so areas of lightning and CIP would have high values; meanwhile, areas of CIP and no lightning (false alarms) and areas of lightning but no CIP (missed events) were not shown, as a zero field has no correlation with another data set.

During the correlation analysis, there were numerous instances of negative correlations. The nature of these occurrences were investigated by manually viewing the CIP and lightning data together, and it was found for cases where lightning occurred without CIP. Because lightning occurring without CIP would defeat the purpose of using the CIP as a lightning diagnostic, specific cases of negative correlations near current and proposed spaceports were selected for further review.

Chapter IV

Results

Lightning Data Analysis

An exploratory analysis of the gridded lightning data was conducted as an initial assessment of lightning activity at each of the spaceports as well as across the entire country. This analysis provided a novel assessment for comparing the differences in activity between spaceports and across the entire country. Some methods proved to be nonproductive efforts while others provided meaningful qualitative results.

CONUS Daily Maximum Event Counts

The daily maximum event counts were an initial exploratory analysis of the lightning data. The domain was analyzed to find the grid boxes with the highest event count for each category, a process that was repeated for each day of the analysis period. The effort proved to be nonproductive. Unfortunately, this analysis of the data provided no continuity between the lightning stroke types, and where/when they occurred. For example: grid box A might have the maximum count of total strokes/flashes on a day comprised on 205 negative strokes, 6 positive strokes, and 15 cloud to cloud flashes for a total of 226 events. However, the maximum daily count of cloud-to-cloud strokes occurred at grid box B that comprised of 80 negative strokes, 2 positive strokes, and 30 cloud-to-cloud flashes for a total of 112 events. These grid boxes could be in different regions of the CONUS driven by different forcing mechanisms. The real benefit of this effort was that it provided a measure of scale for what large values would be in the data set for various times of the year.

CONUS Daily Sum Event Counts

The daily sum event counts provides the sum of the four categories in each grid box, and then adds all the grid boxes to produce a total number of lighting strokes per day for the entire CONUS.

2009 Lightning Data Review

This year had the lowest total lightning activity of the three years analyzed with 52,802,485 total strokes across the CONUS. The complete daily sums for 2009 can be found in Table A1 in Appendix A. Table 2 shows the lightning activity for each month broken into the four categories; what percent of the year's activity each month contributed, what percent each type of lightning contributed to the total for all categories, and how much of the activity occurred during the summer (June, July, and August). Color-coding in all tables presented here indicates the relative rank of the date within the table, from green (low magnitudes), through yellow and orange, to red (high magnitudes). Nearly two-thirds (63.23%) of lightning activity for the entire year occurred during the summer months. The overwhelming majority, 89.66%, of recorded strokes were negative cloud to ground.

Table 3 contains a basic statistical analysis of the four lightning categories for 2009. The maximum events occurred on the following dates: Total and Negative were on August 6, 2009, Positive was on July 14, 2009, and Cloud-to-cloud was on August 17, 2009. The lightning data set was found to be highly skewed, as shown in Figure 4. The histogram shows that the distribution more closely matches a gamma distribution than a normal distribution.

Table 2

Monthly Lightning Activity for 2009

	% of Year	All Categories	Negative	Positive	Cloud-to-cloud
Jan	0.21%	108737	102624	1273	4825
Feb	0.80%	421108	384017	6272	30819
Mar	0.49%	259709	226834	4466	28409
Apr	4.87%	2570686	2324368	27347	218971
May	8.95%	4727637	4347936	40045	339656
Jun	17.41%	9192605	8487595	67414	637596
Jul	22.44%	11848109	10799571	269081	779457
Aug	23.38%	12346128	10126014	163829	2056285
Sep	12.13%	6405524	5938166	75825	391533
Oct	5.73%	3025895	2808206	38061	179628
Nov	1.67%	882305	839117	11844	31344
Dec	1.92%	1014042	956299	11846	45897
Summer	63.23%	33386842	29413180	500324	3473338
Total		52802485	47340747	717318	4744420
% of all categories			89.66%	1.36%	8.99%

Table 3

Daily Lightning Statistics for 2009

	All Categories	Negative	Positive	Cloud-to-cloud
Maximum	607461	568095	39157	151717
Third Quartile	263750	224582	2352.5	17168
Mean	150434.4	134873.9	2043.641	13516.87
Median	96372	86033	994	5161
First Quartile	11663	10922.5	160	519.5
Minimum (non-zero)	6	6	1	3
Standard Deviation	155586.7	138354.6	3659.743	22105.8
Interquartile Range	252087	213659.5	2192.5	16648.5

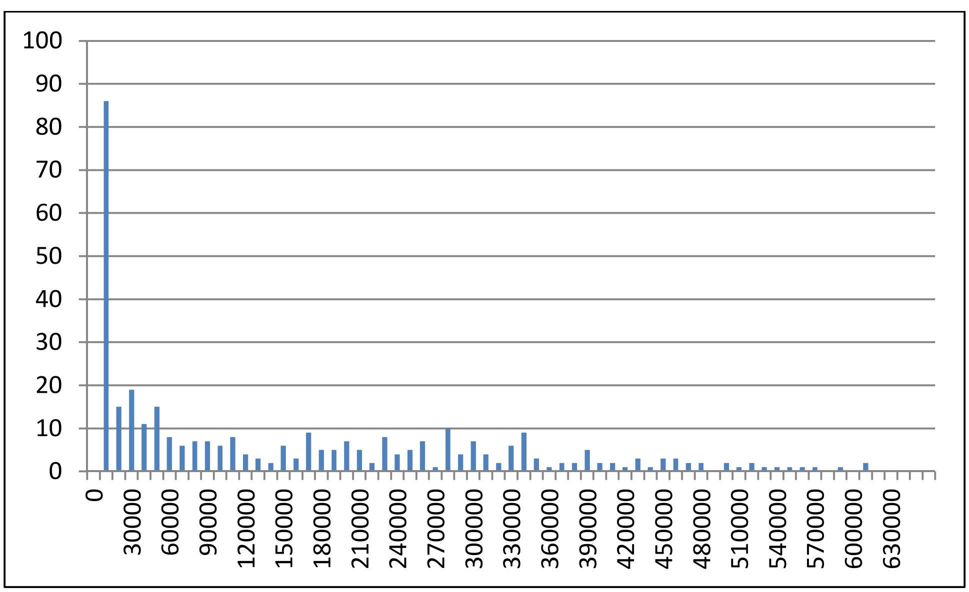

Figure 4. Frequency histogram of total lightning counts for 2009 showing the number of days with lower flash counts is more common.

2010 Lightning Data Review

This was the second most active year with 57,473,172 total stokes across the CONUS. The complete daily sums for 2010 can be found in Table A2 in Appendix A. Table 4 shows the lightning activity for each month broken into the four categories, and how much of the activity occurred during the summer (June, July, and August). Again, very nearly two-thirds (66.61%) of lightning activity occurred during the summer months and the overwhelming majority, 90.67%, of recorded strokes were negative cloud to ground.

Table 5 contains a basic statistical analysis of the four lightning categories for 2010. The maximum events occurred on the following dates: Total and Negative were on August 5, 2010, Positive was on May 24, 2010, and Cloud-to-cloud was on July 14, 2010. The lightning data distribution was again highly skewed, as was shown in Figure 4

Table 4

Monthly Lightning Activity for 2010

	% of Year	All Categories	Negative	Positive	Cloud-to-cloud
Jan	1.28%	737209	672061	15974	48946
Feb	0.72%	412466	374535	9507	28424
Mar	2.00%	1151824	1014013	32946	104865
Apr	4.56%	2623423	2320204	60503	242716
May	12.81%	7363147	6534138	161711	667298
Jun	22.37%	12854675	11670434	199936	984305
Jul	23.85%	13706851	12376036	208372	1122443
Aug	20.39%	11719448	10783410	129364	806674
Sep	7.26%	4173020	3855716	51163	266141
Oct	3.68%	2112453	1936036	29665	146752
Nov	0.77%	444646	412792	7705	24149
Dec	0.30%	174010	159261	4669	10080
Summer	66.61%	38280974	34829880	537672	2913422
Total		57473172	52108636	911743	4452793
% of all categories			90.67%	1.59%	7.75%

Table 5

Daily Lightning Statistics for 2010

	All Categories	Negative	Positive	Cloud-to-cloud
Maximum	733648	690514	14904	63268
Third Quartile	279666	253062	4017	19896
Mean	159205.5	144345.3	2525.604	12334.61
Median	76416	69391	1169	5566
First Quartile	8542	7449	218	542
Minimum (non-zero)	19	16	1	1
Standard Deviation	184818.1	168136.9	2954.774	14962.21
Interquartile Range	271124	245613	3799	19354

2011 Lightning Data Review

This was the most active year with 58,077,226 total stokes across the CONUS. The complete daily sums for 2011 can be found in Table A3 in Appendix A. Table 6 shows the lightning activity for each month broken into the four categories, and how much of the activity occurred during the summer (June, July, and August). Again, very nearly two-thirds (62.17%) of lightning activity occurred during the summer months and the overwhelming majority, 90.59%, of recorded strokes were negative cloud to ground.

Table 6 contains a basic statistical analysis of the four lightning categories for 2011. The maximum events occurred on the following dates: Total, Negative and Positive occurred August 1, 2011, and Cloud-to-cloud was on July 20, 2011. The lightning event data distribution was again found to be highly skewed, as previously shown in Figure 4.

Table 6

Monthly Lightning Activity for 2011

	% of Year	All Categories	Negative	Positive	Cloud-to-cloud
Jan	0.82%	474863	443605	10786	20252
Feb	0.70%	407507	348472	14835	44200
Mar	3.08%	1791578	1632496	36292	122790
Apr	7.73%	4487577	4043297	83663	360617
May	9.51%	5525819	4866601	120286	538932
Jun	16.83%	9776395	8747729	167261	861405
Jul	22.79%	13234443	11904092	227053	1103298
Aug	22.54%	13093146	12035358	194705	863083
Sep	10.51%	6103137	5695089	63706	344342
Oct	3.16%	1835142	1694643	30049	110450
Nov	1.87%	1083950	966129	20138	97683
Dec	0.45%	263669	234369	5943	23357
Summer	62.17%	36103984	32687179	589019	2827786
Total		58077226	52611880	974937	4490409
% of all categories			90.59%	1.68%	7.73%

Table 7

Daily Lightning Statistics for 2011

	All Categories	Negative	Positive	Cloud-to-cloud
Maximum	640343	544509	18239	79149
Third Quartile	284643	252524	4897	22364
Mean	159992.4	144936.3	2685.777	12370.27
Median	93654	85577	1423	5463
First Quartile	12264	10203	253.5	531
Minimum (non-zero)	3	3	1	2
Standard Deviation	168557.5	153028.1	2974.293	14326.55
Interquartile Range	272379	242321	4643.5	21833

Regional Daily-Sum Event Counts

Table 8 shows the sum of all stroke types at each spaceport for each year, the total for each spaceport for all three years, the percentage of lightning strokes each spaceport contributed to the total of all spaceport events, and the percentage each spaceport contributed to the total of all lightning strokes. The spaceports have been ranked based on the total lightning strokes over the three-year period with CCAFS being the most active and CASP being the least.

Table 8

Spaceports Ranked by Total Lightning Activity

	2009	2010	2011	Total	% of Spaceports	% of CONUS
CCAFS	573378	378184	526746	1478308	25.81%	0.88%
BAK	284555	514812	418872	1218239	21.27%	0.72%
CSM	357058	289424	257423	903905	15.78%	0.54%
SPWI	104787	288353	215865	609005	10.63%	0.36%
SPAM	181619	211772	170694	564085	9.85%	0.34%
MARS	209454	150436	171360	531250	9.28%	0.32%
CHUG	129493	109908	112522	351923	6.15%	0.21%
MASP	4680	18230	20581	43491	0.76%	0.03%
SPWA	10731	22968	6405	17136	0.30%	0.01%
CASP	345	3883	5397	9265	0.17%	0.01%
Total	1,856,100	1,987,970	1,905,865	5,726,607		3.40%
CONUS	52,802,485	57,473,172	58,077,226	168,352,883		

The spaceports can be loosely grouped into three categories, using linear bins based on CCAFS being the most active and CASP being the least active spaceports. Spaceports with high activity are (arbitrarily) those greater than or equal to 988,627 strokes, medium activity are those greater than or equal to 498,946 but less than 988,627, and low activity less than 498,946. Using this method CCAFS and BAK are categorized with high activity. Spaceports categorized with medium activity are CSM, SPWI, SPAM, and MARS. Spaceports categorized with low activity are CHUG, MASP, SPWA and CASP.

Characteristics of Spaceports with High Lightning Activity

CCAFS and BAK spaceports had the greatest lightning activity of all spaceports analyzed. Both spaceports accounted for 47.08% of lightning activity at all spaceports analyzed and 1.6% of all lightning activity across the CONUS during the analysis period.

Monthly lightning activity for CSAFS is shown in Table 9 and the basic statistical analysis is shown in Table 10. CCAFS had the highest lightning activity of all spaceports analyzed, with a total activity of 1,478,308 events for all three years. Lightning events accounted for 25.81% of activity at spaceports and 0.89% of activity across the CONUS. During 2009 and 2011, 73.96% and 72.92% of lightning activity occurred during the summer (June, July, and August). In 2010, the lightning activity did not match the normal summer pattern with only 49.33% of lightning activity occurring in the summer. This is the result of a considerably inactive July (28.22% in 2009, 7.56% in 2010, and 24.73% in 2011) and a much more active May (4.10% in 2009, 22.77% in 2010, and 5.58% in 2011). This can be attributed to the shift in precipitation patterns in Florida during El Nino years.

Table 9

Monthly Total Lightning Events for CCAFS

	2009		2010		2011		Total
	%	Strokes	%	Strokes	%	Strokes	
Jan	0.00%	6	1.79%	6779	1.26%	6661	13446
Feb	0.01%	29	0.74%	2810	0.00%	22	2861
Mar	0.05%	264	8.96%	33891	5.46%	28757	62912
Apr	2.55%	14616	4.35%	16453	4.17%	21953	53022
May	4.10%	23513	22.77%	86106	5.58%	29400	139019
Jun	17.98%	103071	28.67%	108443	18.87%	99390	310904
Jul	28.22%	161780	7.56%	28582	24.73%	130240	320602
Aug	27.77%	159230	13.10%	49533	29.32%	154458	363221
Sep	12.92%	74053	11.53%	43614	8.34%	43910	161577
Oct	4.76%	27289	0.47%	1782	2.21%	11638	40709
Nov	1.10%	6321	0.04%	133	0.00%	22	6476
Dec	0.56%	3206	0.02%	58	0.06%	295	3559
Summer	73.96%	424081	49.33%	186558	72.92%	384088	994727
Total		573378		378184		526746	1478308

The maximum lightning events at CCAFS occurred on the following days: June 23rd, 2009, September 28th, 2010, and July 15th, 2011. Each year had consistent storm days with 184 in 2009, 177 in 2010, and 190 in 2011 totaling 551 storm days. The number of annual thunderstorm days statistically implies the following probabilities of a lightning stroke occurring on any given day: 50.41% in 2009, 48.49% in 2010, and 52.05% in 2011. During the summer months (92 days from June 1 to August 31), the number of thunderstorm days were 90 in 2009, 86 in 2010, and 87 in 2011. The probabilities of a lightning stroke occurring on any given summer day was 97.83% in 2009, 93.48% in 2010, and 95.57% in 2011.

Table 10

Yearly Total Lightning Statistics for CCAFS

	2009	2010	2011
Maximum	30883	22050	34500
Third Quartile	1497	313	1042
Mean	1633.556	1047.601	1451.091
Mean Non-zero	3116.185	2136.633	2772.347
Median	1	0	1
First Quartile	0	0	0
Standard Deviation	3660.738	2910.774	3569.98
Interquartile Range	1497	313	1042
T-Storm Days	184	177	190
Daily T-Storm Probability	50.41%	48.49%	52.05%
Summer T-Storm Days	90	86	87
Summer Daily T-Storm Probability	97.83%	93.48%	94.57%

Characteristics of Spaceports with Low Lightning Activity

Monthly lightning activity for CASP is shown in Table 11 and a basic statistical analysis is shown in Table 12. CASP had the lowest lightning activity of all the spaceports analyzed, with the total activity for 2009, 2010, and 2011 combined (9625 events) less than monthly totals for many spaceports and even less than single days at CCAFS. CASP's lightning events accounted for 0.17% of activity at spaceports and 0.01% of activity across the CONUS. Lightning events on September 2011 accounted for 96.16% of activity in 2011. September 2011 also accounts for 53.29% of lightning activity at CASP during all three years with 5190 events. This activity was concentrated on September 10th and 11th with 2120 events for 39.28% of annual activity and 2439 events for 45.19% respectively. Other highly active events include May 2009 with 38.26% of annual activity, and October 2010 with 50.42% of annual activity.

Table 11

Monthly Total Lightning Events for CASP

	2009		2010		2011		Total
	%	Strokes	%	Strokes	%	Strokes	
Jan	0.87%	3	10.30%	400	0.00%	0	403
Feb	11.88%	41	1.21%	47	1.33%	72	160
Mar	1.16%	4	0.18%	7	0.22%	12	23
Apr	16.23%	56	0.03%	1	0.26%	14	71
May	38.26%	132	0.00%	0	0.54%	29	161
Jun	0.00%	0	0.00%	0	0.00%	0	0
Jul	0.00%	0	35.95%	1396	0.26%	14	1410
Aug	9.86%	34	0.00%	0	0.00%	0	34
Sep	0.00%	0	0.31%	12	96.16%	5190	5202
Oct	0.00%	0	50.42%	1958	0.04%	2	1960
Nov	0.29%	1	0.54%	21	1.00%	54	76
Dec	21.45%	74	1.06%	41	0.19%	10	125
Summer	9.86%	34	35.95%	1396	0.26%	14	1444
Total		345		3883		5397	9625

The maximum lightning events at CASP occurred on the following days: December 12th, 2009, July 11th, 2010, and September 11th, 2011. Each year saw less than

30 lightning days, with single highly active events changing the weight of an entire month.

Table 12

Yearly Total Lightning Statistics for CASP

	2009	2010	2011
Maximum	56	1392	2439
Third Quartile	0	0	0
Mean	0.945205	10.63836	14.7863
Mean Non-zero	11.89655	143.8148	234.6522
Median	0	0	0
First Quartile	0	0	0
Standard Deviation	5.183157	85.92915	171.264
Interquartile Range	0	0	0
T-Storm Days	29	27	23
Daily T-Storm Probabilities	7.95%	7.40%	6.30%
Summer T-Storm Days	5	2	3
Summer Daily T-Storm Probabilities	5.43%	2.17%	3.26%

Correlations of CIP and Lightning Data

By reviewing the CIP and lightning data together, areas were found for cases where lightning occurred with little or no CIP. Figures 5 and 6 show correlations between maximum CIP values and total flash counts. This particular case occurred on May 24, 2010, and May 25, 2010. Areas with no shading denote regions that contain no lightning, no CIP, or neither lightning nor CIP. Yellows, reds, and purple represent areas of increasing positive correlations, indicating lightning occurred with CIP. Shades of blue indicate areas of negative correlations, indicating either increasing lightning with decreasing CIP, or increasing CIP with decreasing lightning. During this analysis, there were numerous instances of negative correlations observed. These results are critically important because they represent conditions where CIP fails to indicate the true lightning hazard. In this first case, the areas of interest are Quebec and Ontario for multiple reasons.

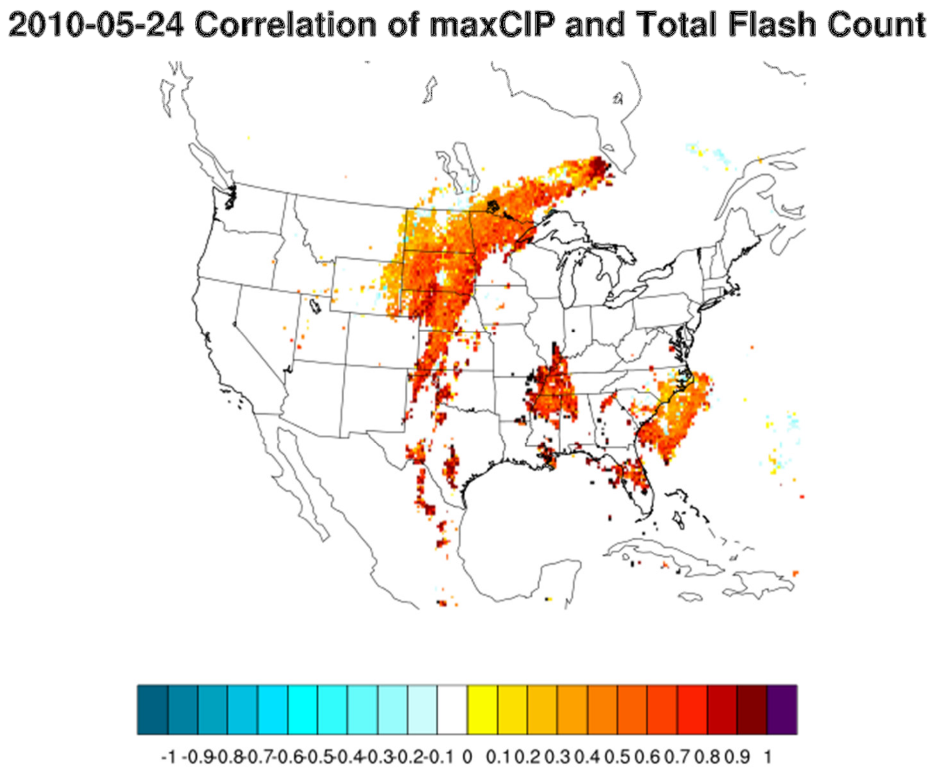

Figure 5. Lightning and maximum CIP correlations for the CONUS on May 24, 2010

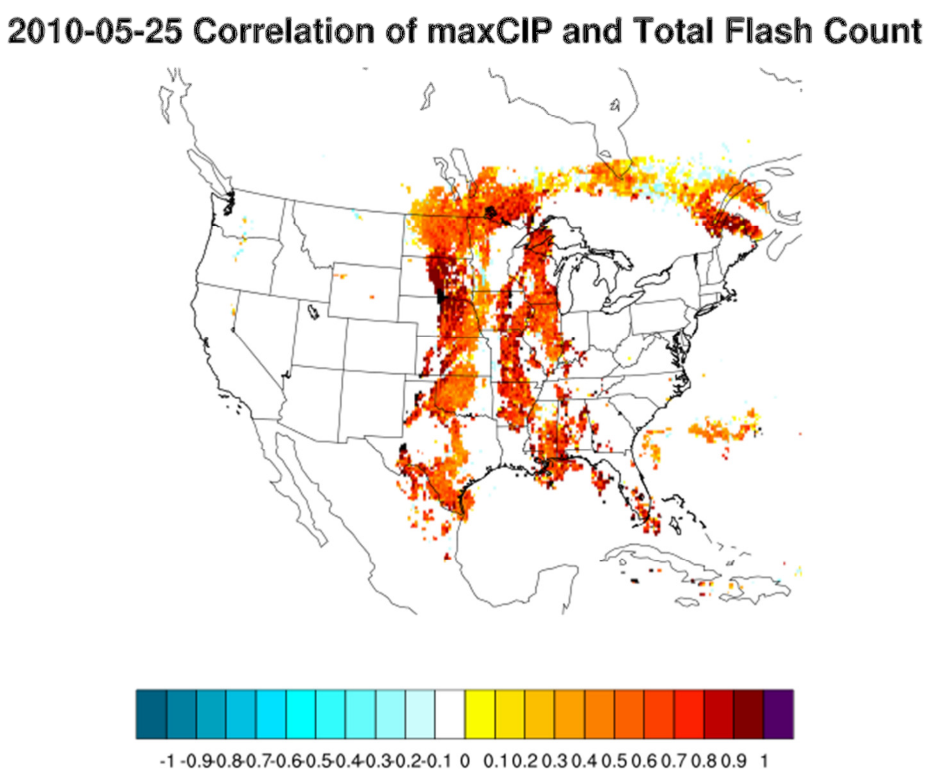

Figure 6. Lightning and maximum CIP correlations for the CONUS on May 25, 2010

Figure 7 is a display showing maximum CIP and lightning over the northeastern US and Canada on the same day as the correlations from Figures 5 and 6. CIP is colored using the same scheme as the operational CIP with blues and greens denoting lower probabilities of icing, increasing to yellows and reds for higher CIP values. Lightning uses a linear scaling from one stroke (black) blending into 366 strokes (blue). The CIP has a partial transparency so the lightning data or the CIP is not covered by the other data source. The result is lightning activity overlapping CIP will darken the CIP fields and add blue in cases of high lightning activity. An example of the latter result occurs in eastern North Dakota where high lightning activity (blue) and high CIP probabilities (red) generate purple as a new color not used on either of the scales.

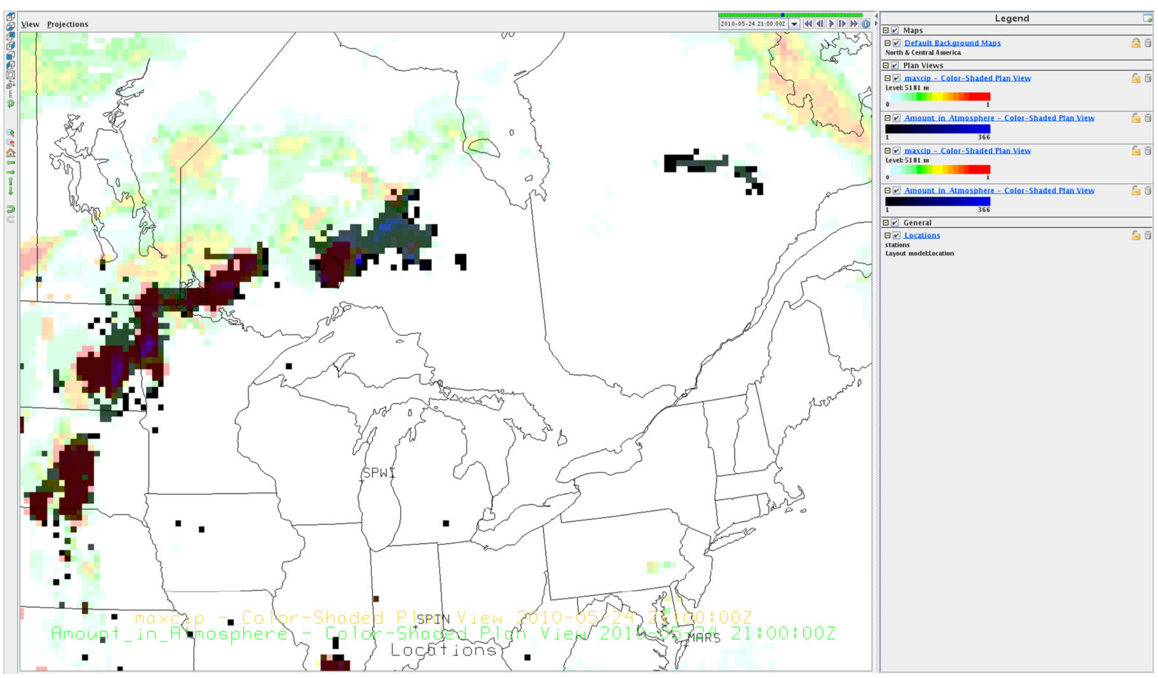

Figure 7. Intense lightning activity collocated with low CIP probabilities in Ontario and Quebec on May 24, 2010 at 21:00Z.

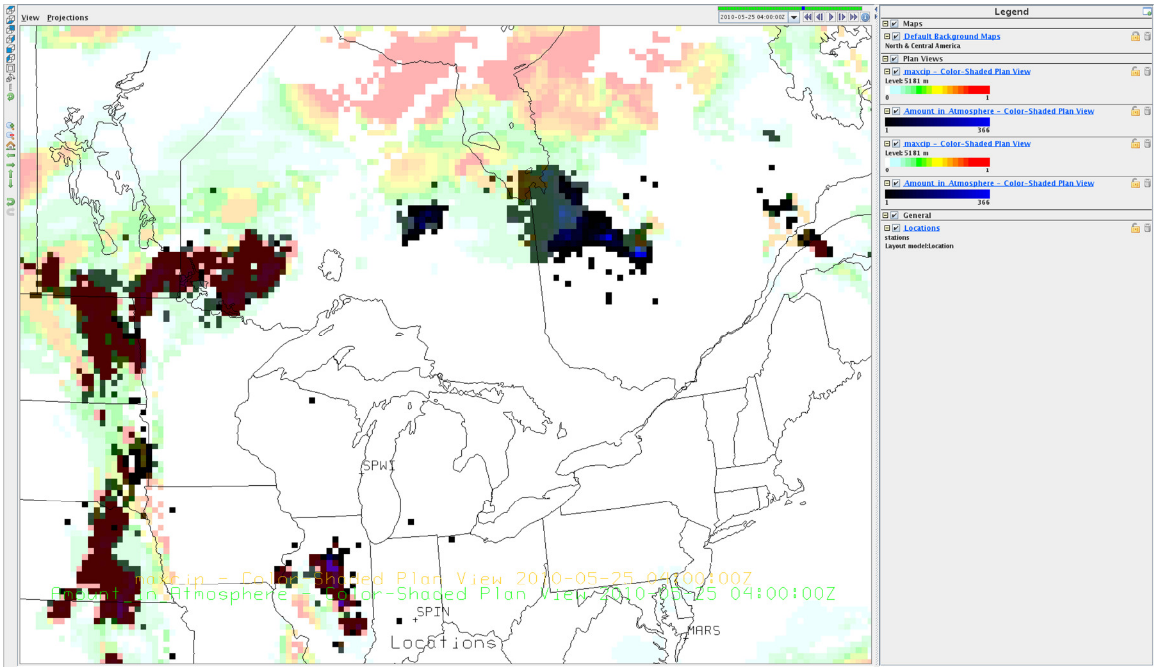

Figure 8. Intense lightning activity not being captured by CIP in Quebec on May 25, 2010 at 04:00Z; very high CIP probabilities with no lightning activity are just to the north.

The area of lightning activity in Quebec initiated on May 24, 2010, at 20:00Z and moved east towards New Brunswick through May 25, 2010. In this case, the area of light lighting activity initiated with very low CIP probabilities that also lacked spatial coverage. Detailed analysis at 21:00Z, when the lightning activity began to increase, showed 38 grid boxes with lightning activity, 33 grid boxes with CIP probabilities (all less than 40% and most less than 25%), and 18 grid boxes where the data sets over lapped. As the lightning activity continued to increase, up to 169 strokes per hour in one grid box, the CIP probabilities began to better match the activity spatially but the probabilities remained less than 40% until the hour after 169 stroke event when the CIP probability values jump to 80% or greater. This jump is most likely due to the NLDN observations of lightning in that area prompting an increase in CIP values.

Another area of lightning, this one much more active, developed in the central plains early on May 24, 2010, and moved northeast into Ontario. Throughout the day, up until 19:00Z, the lightning activity and high CIP probabilities (greater than 80%) were almost identically matched spatially. After 19:00Z lightning activity began to extend beyond the high CIP probabilities until 04:00Z on May 25, 2010. More than half of the lightning activity is detached from the CIP probabilities, as shown in Figure 8. In addition, the grid boxes that still had CIP probabilities in proximity to the lightning activity had decreased significantly to less than 40%. To the north, away from the lightning activity, CIP probabilities remained high at greater than 80%. Here we see a combination of missed-events and false alarms within the same synoptic scale feature.

Precipitation Based False Alarm Days

False alarm rates were determined by search results that matched moderate to likely risk for icing at any level as indicated by the CIP and little or no precipitation, ruling out convection that would support lightning. The database's archive was from February 13, 2009, to October 13, 2009 for 242 days of data. Table 13 shows the results for the spaceports analyzed as well as CONUS (CONUS has a false alarm rate higher than 100% due to the way number of days in the period was calculated being one less than the number of false alarm days returned).

Table 13

CIP False Alarm Data for Spaceports and CONUS

Spaceport	False Alarm Days	False Alarm Rate
BAK	91	37.60%
CASP	44	18.18%
CCAFS	123	50.83%
CHUG	102	42.15%
CSM	106	43.80%
MARS	83	34.30%
MASP	59	24.38%
SPAM	112	46.28%
SPWA	76	31.40%
SPWI	66	27.27%
CONUS	243	100%

Across the CONUS, there is effectively a 100% false alarm rate, which indicates every day there was moderate to likely risk for icing and no convection somewhere in the country. False alarm rates at individual spaceports vary from 50.83% (CCAFS) to 18.18% (CASP).

CIP – Lightning Forecast Verification Results

Forecast verification scores for the CIP ability to predict lightning were determined by building contingency tables. These tables provide a way to measure the question, “It was forecasted, did it occur?” For this assessment, a CIP value of 50% was used as the forecast predictor for lightning (i.e. 50% or greater is a forecast for lightning to occur). Given that half of the temporal period included in the hourly lightning counts was from the 30 minutes after the hour, there is a significant potential for lightning events without the NLDN observed lightning events triggering an increase in CIP. Daily calculations were generated for all spaceports, as well as the CONUS, for 2009 and 2010, the period of overlap for the lightning and CIP archives. Each spaceport was then also analyzed at monthly intervals. For comparison, forecast verification done by NASA’s Applied Meteorology Unit (AMU) at Kennedy Space Center is also included. The AMU developed a probabilistic lightning forecast tool to support operations at CCAFS and KSC, performing the same forecast verification procedure as this study.

The contingency table provides measures of “Hit” (H=CIP > 50% and lightning > 0), “Miss” (M=CIP < 50% and lightning > 0), False Alarm (FA=CIP > 50% and lightning >=0) and Correct Null Events (C=CIP < 50%, lightning = 0). Table 14 combines the location specific contingency tables to show the verification results for the seven active spaceports for the full years. Most spaceports had very similar results between the number of hits, misses, false alarms, and correct nulls. There were usually more hits than misses; in most cases, there were two to three times more hits. Spaceports where this was not the case include MARS in 2009 where missed events exceeded hits, while MASP and CASP in 2009 had very small numbers for both hits and misses, in similar magnitudes.

While the first row of results looks favorable for CIP as a lightning predictor, the False Alarm events exceeded both hits and misses. For all locations, the frequency of false alarms was several times greater than both the hits and misses, and in some cases orders of magnitude greater. It would be possible to reduce the False Alarm rate by increasing the threshold of CIP to something greater than 50%; however, doing this would increase the percentage of missed events. The problem of missed events is discussed in more detail in the case study section below, where lightning occurs with CIP values below the 50% threshold, along with other areas of false alarms.

Table 14

CIP-Lightning Forecast Contingency Table Results for Spaceports

		Forecast			
		2009		2010	
Spaceport	**Observed**	**Yes**	**No**	**Yes**	**No**
Site	**Yes**	**Hit**	**Miss**	**Hit**	**Miss**
	No	**False Alarm**	**Correct Null**	**False Alarm**	**Correct Null**
BAK	Yes	8344	2659	8641	3092
	No	176247	803014	118006	683381
CCAFS	Yes	10745	6835	8217	4281
	No	53047	919637	41470	759152
CSM	Yes	10216	2510	7616	2197
	No	69991	907547	67710	735597
MARS	Yes	6242	6835	3511	1427
	No	53047	919637	75864	732318
MASP	Yes	392	249	1325	360
	No	39819	949804	38599	772836
SPAM	Yes	7390	2696	8908	3643
	No	59604	920574	48280	752289
CASP	Yes	58	59	420	146
	No	37860	952287	39149	773405

There are many additional measures of forecast quality can be determined from these contingency table results. Tables 15 (2009) and 16 (2010) provide some of these forecast quality measures as a way to objectively determine the value of CIP as a predictor of a lightning hazard.

The quantities presented are defined as:

P = predicted events (H+FA),

E = total events (H+M),

T = total cases (H+M+FA+C),

F = frequency of the event (H+M)/C

False Alarm Rate = FAR = M/(H+FA) = FA/P,

Success Ratio = SR= H/(H+FA) = H/P = 1-FAR,

Probability Of Detection = POD = H/(H+M), and the

Critical Success Index =CSI = H/(H+M+FA).

The interpretation of the results can be simplified by recognizing that for POD, SR and CSI high values are better with a possible range of zero to one, while for the FAR lower is better for the same range. Low SR is due to a strong over prediction of the event, while a low CSI is due to high miss and/or false alarms in the forecast. The results are also provided graphically in annual groupings for interpretation and comparison.

Table 15

CIP-Lightning Forecast Verification Results for 2009

	BAK	CASP	CCAFS	CSM	MARS	MASP	SPAM
P:	184591	37918	63792	80207	125776	40211	66994
E:	11003	117	17580	12726	8585	641	10086
T:	990264	990264	990264	990264	990264	990264	990264
F:	0.0111	0.0001	0.0178	0.0129	0.0087	0.0006	0.0102
POD:	0.7583	0.4957	0.6112	0.8028	0.7271	0.6115	0.7327
FAR:	0.9548	0.9985	0.8316	0.8726	0.9504	0.9903	0.8897
SR:	0.0452	0.0015	0.1684	0.1274	0.0496	0.0097	0.1103
CSI:	0.0446	0.0015	0.1521	0.1235	0.0487	0.0097	0.1060

Table 16

CIP-Lightning Forecast Verification Results for 2010

	BAK	CASP	CCAFS	CSM	MARS	MASP	SPAM
P:	126647	39569	49687	75326	79375	39924	57188
E:	11733	566	12498	9813	4938	1685	12551
T:	813120	813120	813120	813120	813120	813120	813120
F:	0.0144	0.0007	0.0154	0.0121	0.0061	0.0021	0.0154
POD:	0.7365	0.7420	0.6575	0.7761	0.7110	0.7864	0.7097
FAR:	0.9318	0.9894	0.8346	0.8989	0.9558	0.9668	0.8442
SR:	0.0682	0.0106	0.1654	0.1011	0.0442	0.0332	0.1558
CSI:	0.0666	0.0106	0.1523	0.0982	0.0435	0.0329	0.1464

False Alarm Rates. False alarm rates (FAR) for 2009 and 2010 can be found in Figures 9 and 10, respectively. When calculated using data from the entire year, all spaceports measured FARs greater than 80%. Spaceports with lower lightning activity, such as CASP, had near 100% FARs while spaceports with higher lightning activity, such as CCAFS, tended to have slightly lower FARs. The AMU's findings at CCAFS indicated a wet season persistence forecast there has a FAR of 37% and their forecast equations 33%.

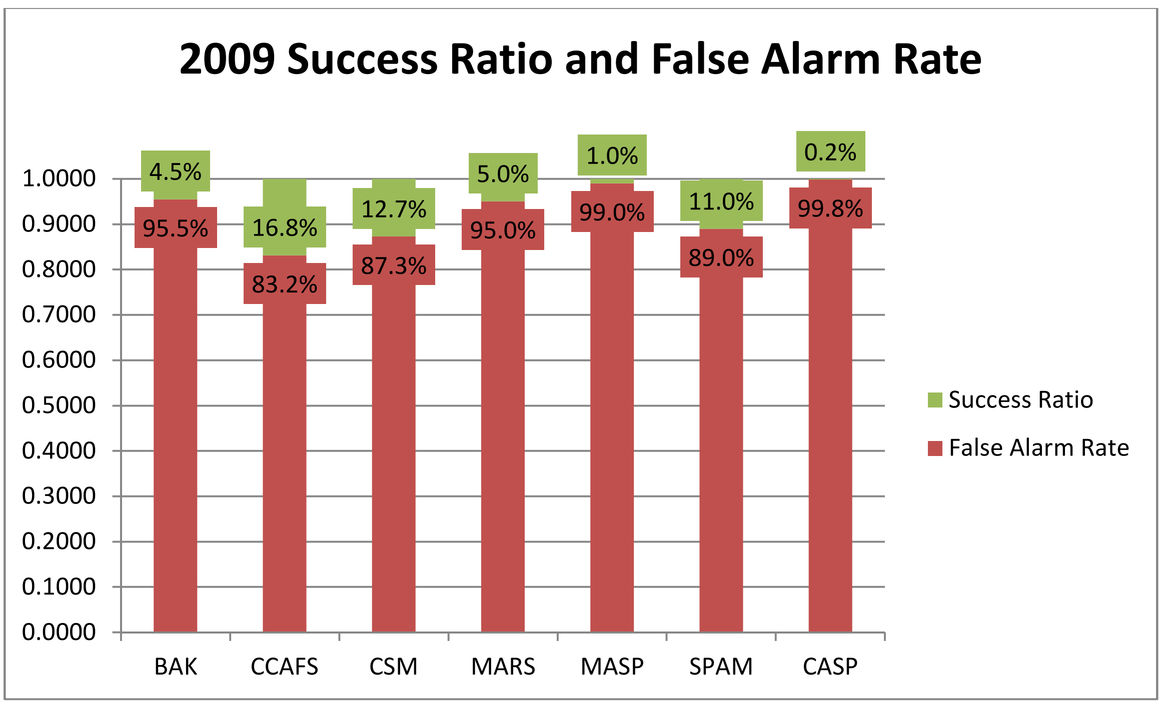

Figure 9. 2009 success ratio and false alarms rates of seven active spaceports.

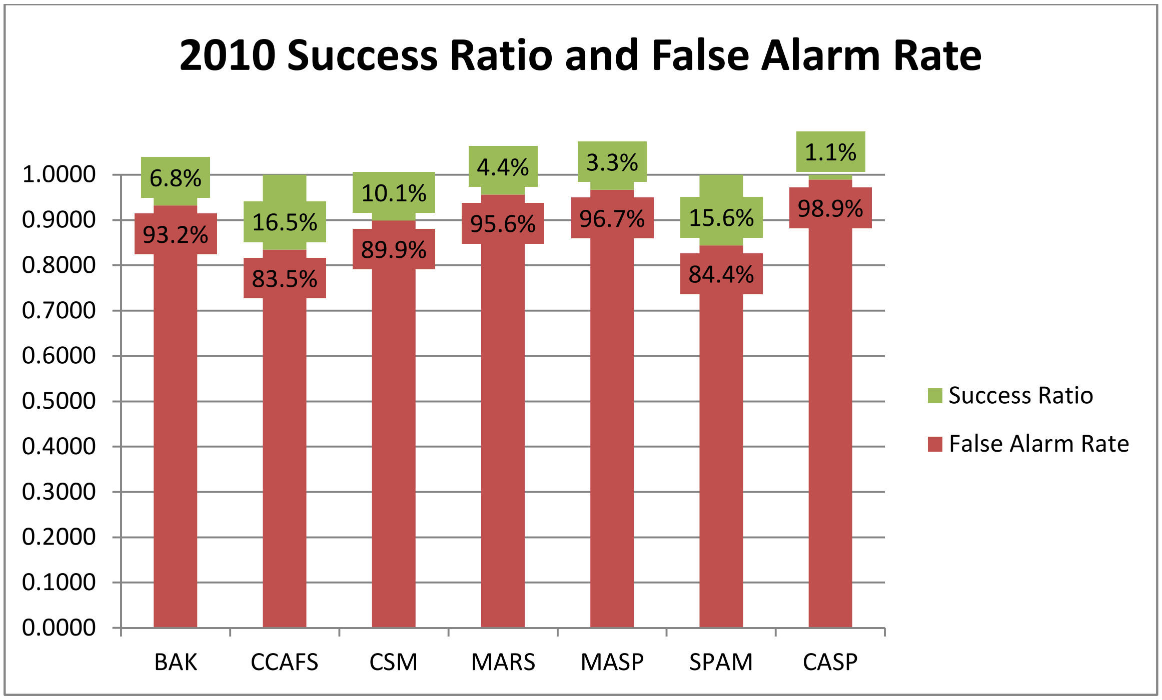

Figure 10 2010 success ratio and false alarms rates of seven active spaceports.

Probability of Detection. Probability of detection (POD) for 2009 and 2010 can be found in figures 11 and 12. When calculated using data from the entire year, POD seems to contradict the FARs. The POD is better than 0.50 for all spaceports, and better than 0.60 for all but CASP in 2009. In 2010 only CCAFS has a probability of detection lower than 0.70. However, high POD can come from over-prediction. POD does not penalize for how many total forecasts were made, and gross over prediction will inevitably capture more lightning events. Persistence forecasting at CCAFS in the wet season and the AMU's equation achieved similar PODs (0.67 and 0.75, respectively), but with much better performance in the other verification metrics.

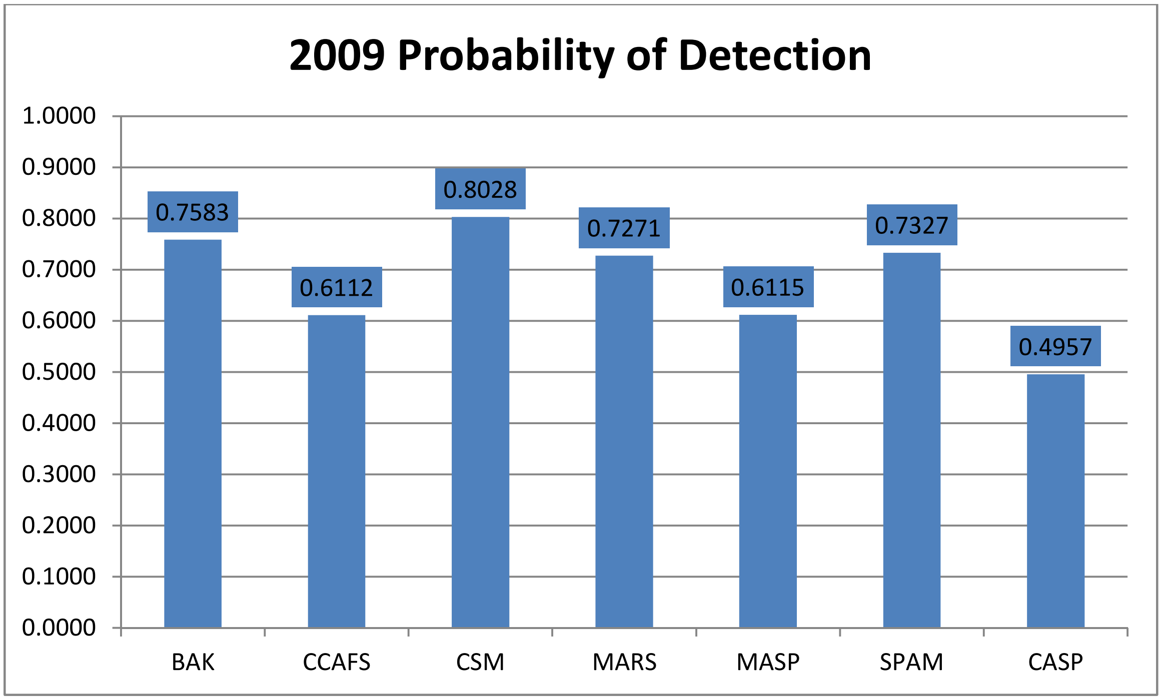

Figure 11. 2009 probability of detection of lightning using CIP at seven active spaceports.

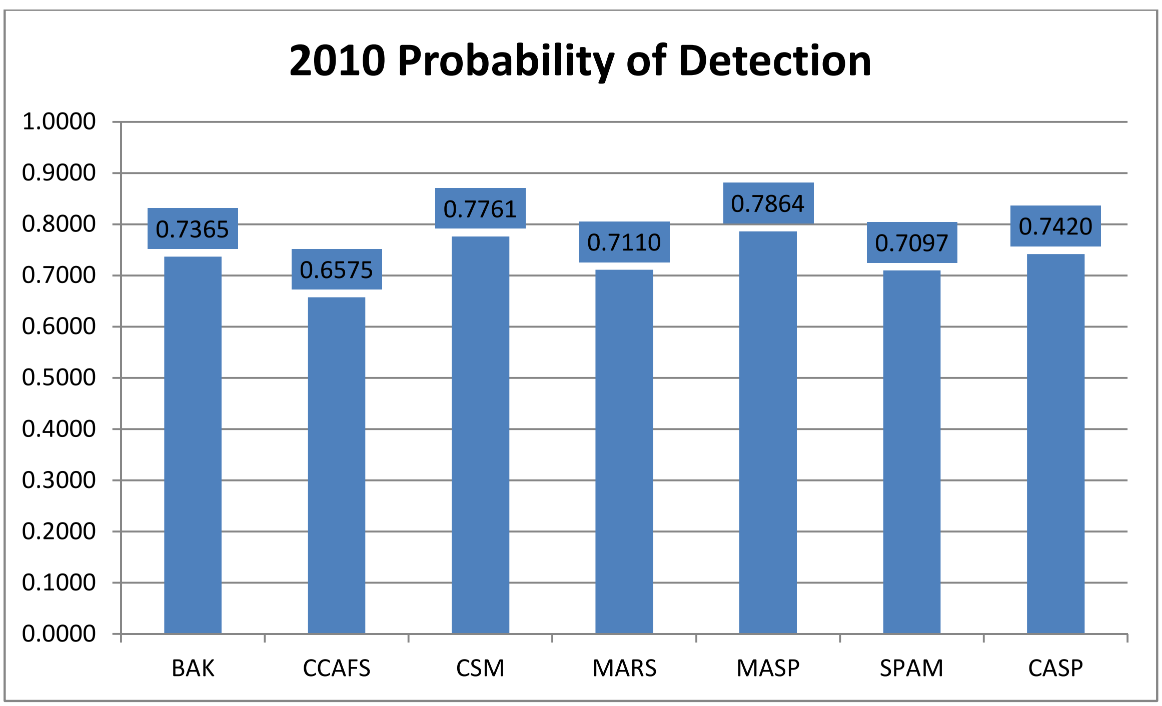

Figure 12. 2010 probability of detection of lightning using CIP at seven active spaceports.

Critical Success Index. The critical success index (CSI) scores for 2009 and 2010 can be found in figures 13 and 14. When calculated using data from the entire year, all spaceports CSIs lower than 0.16. Spaceports with higher lightning activity manager better CSI scores than spaceports with lower lightning activity. CASP and MASP are less than 0.001 in 2009 and only slightly higher in 2010. The AMU determined a wet season persistence forecast at CCAFS has a CSI of 0.48, and their lightning forecast equations had a CSI of 0.55. This suggests that the use of a persistence forecast at the spaceports with high lightning activity would have a CSI that is 3x to 10x the CSI of using the CIP for forecast guidance.

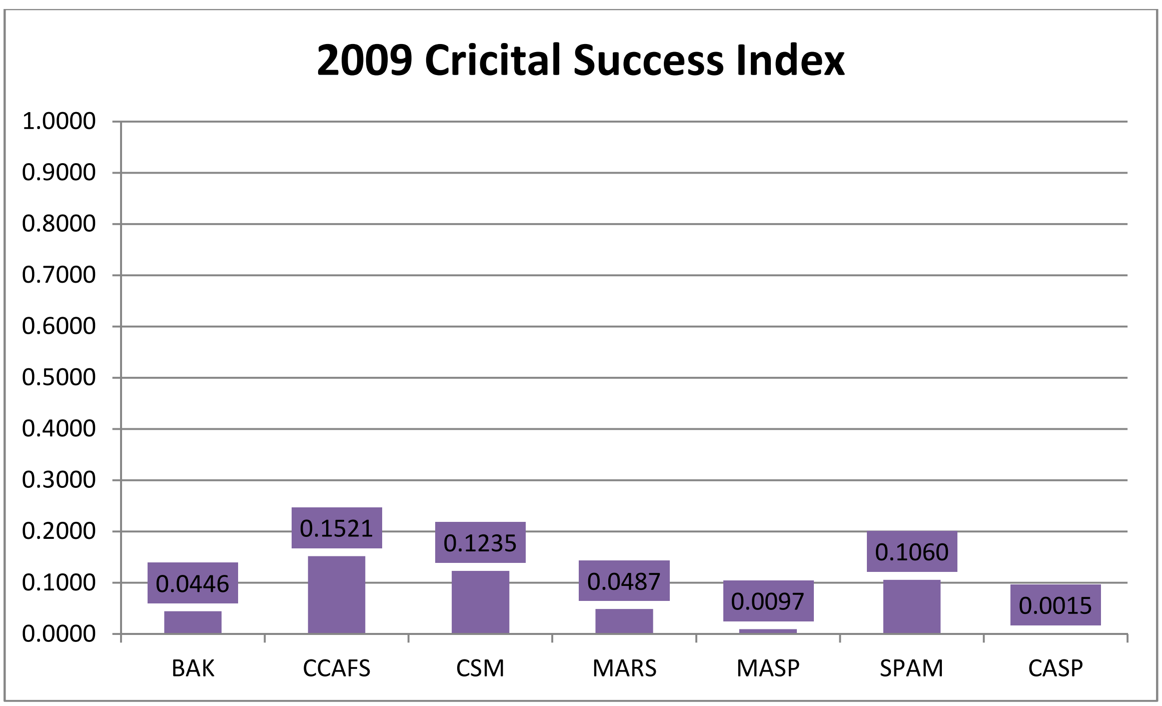

Figure 13 2009 Critical Success Index scores at seven active spaceports.

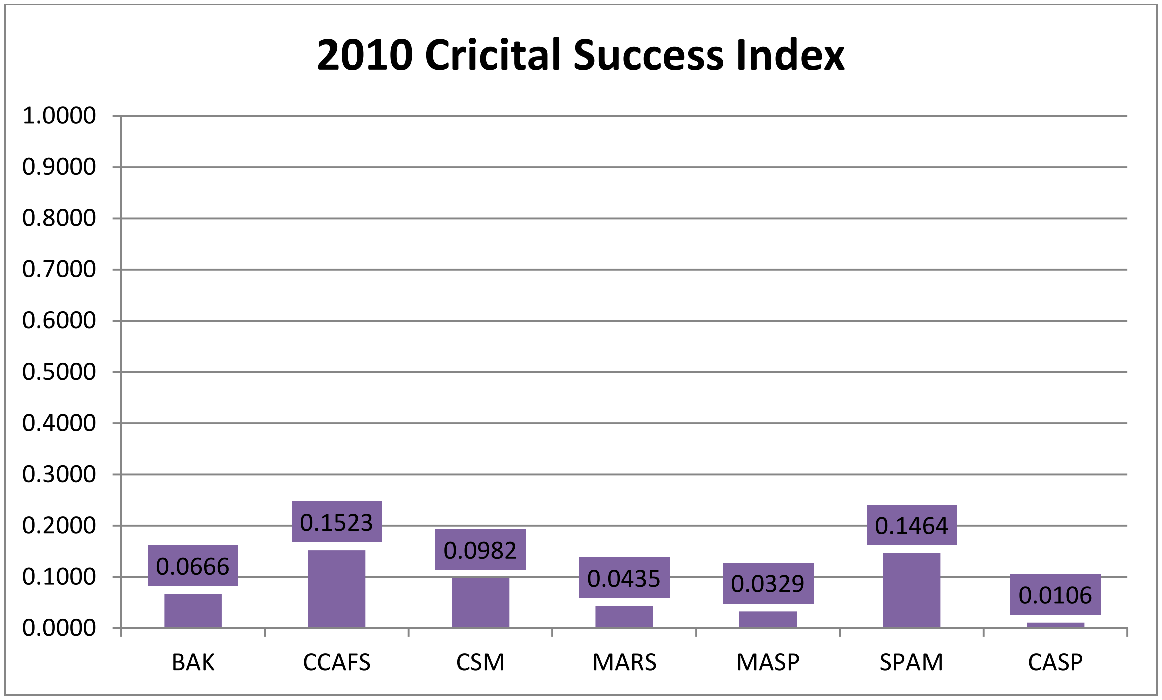

Figure 14 2010 Critical Success Index scores at seven active spaceports.

Chapter V

Case Studies

Cases of strong positive as well as negative (and weak positive) correlations were selected for an in-depth review of the behavior of lightning activity and CIP probabilities in close proximity to spaceports.

CCAFS July 9, 2009

Investigation of CCAFS on July 9, 2009, was selected by reviewing correlation analyses. Figure 9 shows numerous areas of low to negative correlations across North America, including Florida, the Atlantic Ocean, and Gulf of Mexico. In this case study a stationary front, as shown by the surface analysis in Figure 10, was positioned across the north Gulf coast and the Florida panhandle producing strong convection over central Florida and CCAFS.

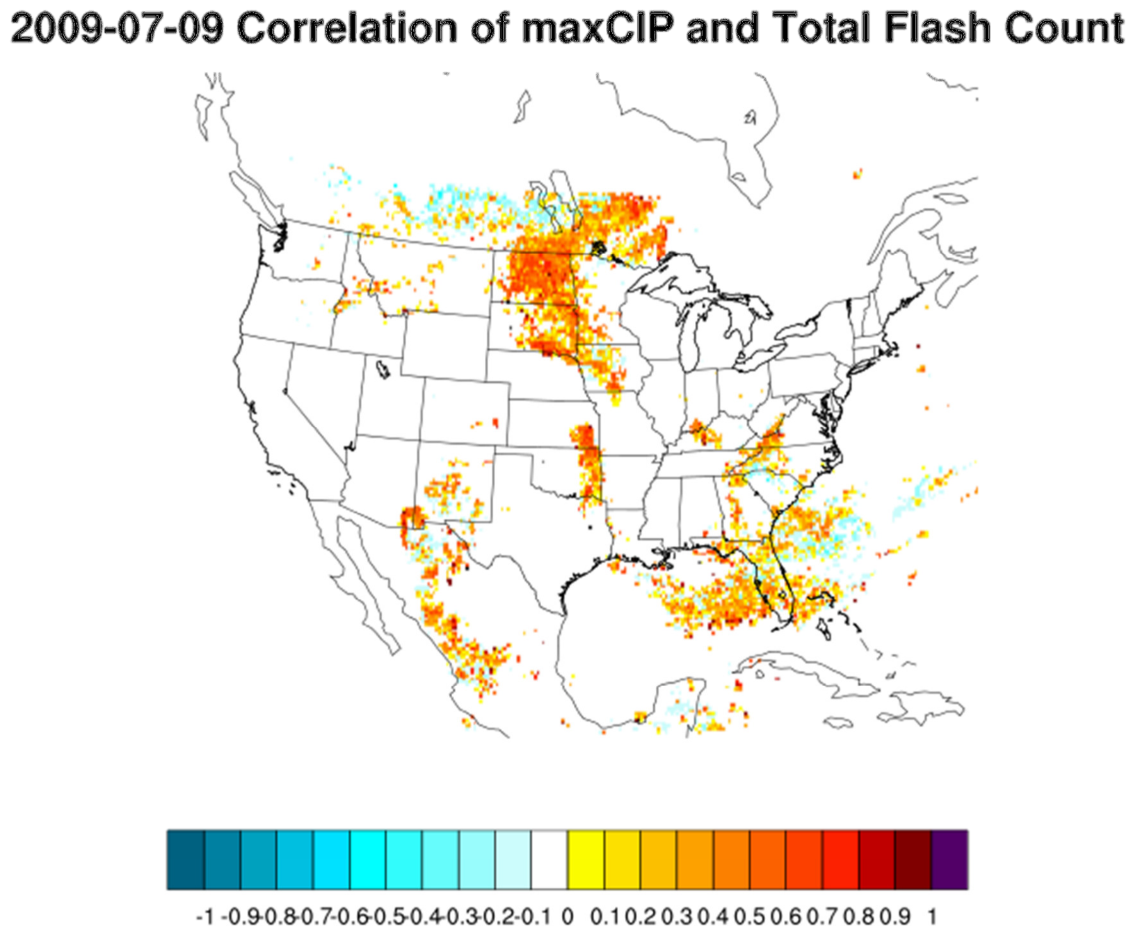

Figure 15. Surface analysis with satellite and radar imagery on July 9, 2009 at 22:30Z when lightning activity was closest to CCAFS.

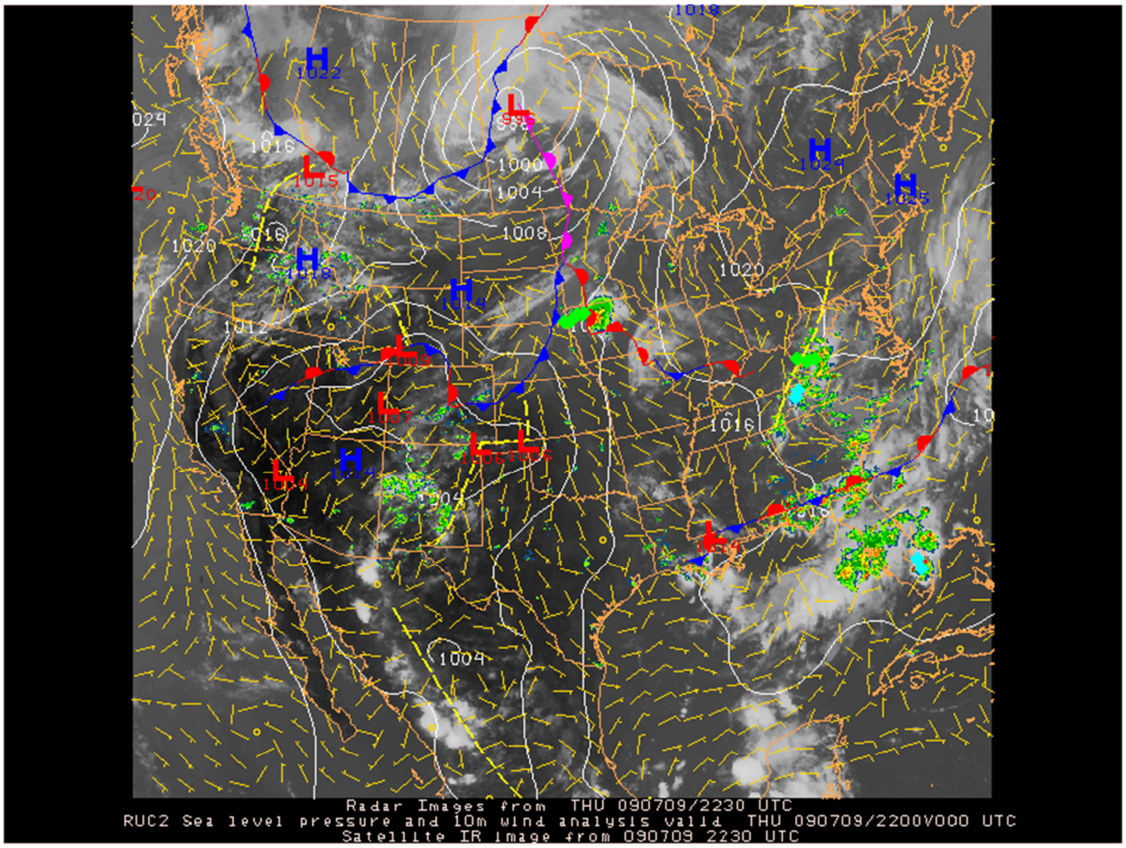

Figure 16. Surface analysis with satellite and radar imagery on July 9, 2009 at 22:30Z when lightning activity was closest to CCAFS.

The convection produced lightning throughout the day in the Gulf of Mexico, across Florida, and the Atlantic coast with activity inside the regional domain for CCAFS most of the day. From 00:00Z to 07:00Z the CIP covered a very large portion of the CCAFS domain, particularly in the northwestern, northeastern, and southeastern quadrants as shown in Figure 11 (range rings at 50 kilometer intervals centered over CCAFS have been added). This is contrast to the actual lightning activity, which was only in the southeastern quadrant for the first three hours before moving east into the Atlantic.

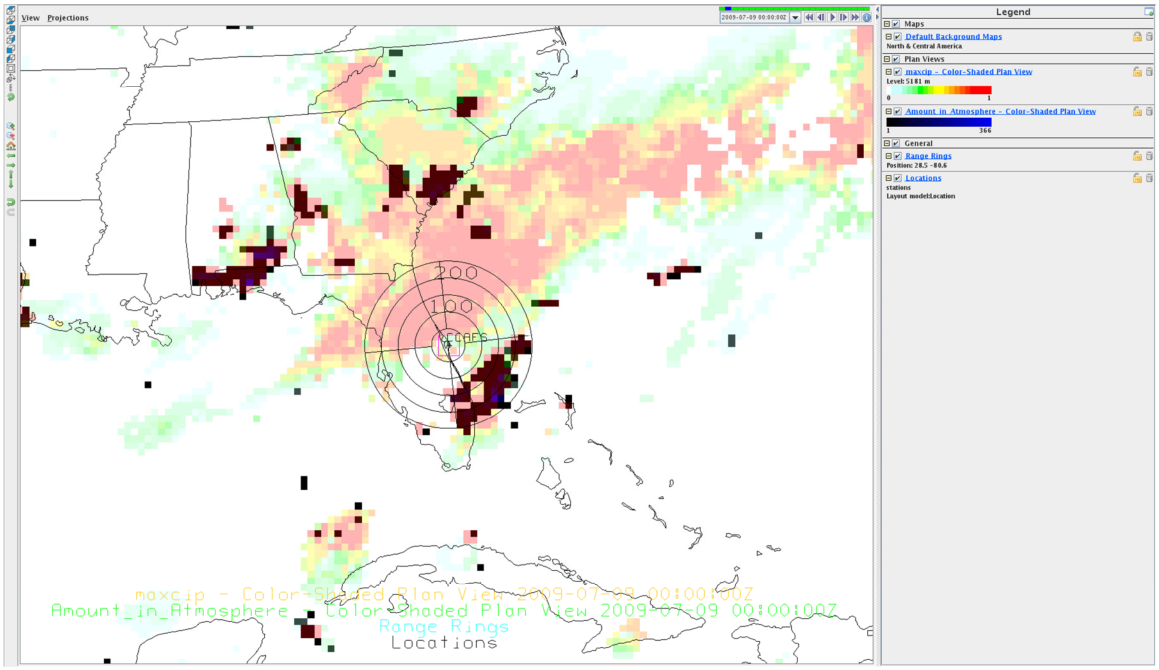

Figure 17. Very high CIP probabilities covering most of the CCAFS domain with lightning activity in only a quarter of the domain on July 9, 2009 at 00:00Z

By 11:00Z the large area of CIP probabilities had reduced back to well north and east of the CCAFS area, but in the northwestern quadrant a somewhat disorganized area of CIP probabilities was moving in from the Gulf of Mexico. Beyond that, there is some sporadic lightning activity and associated CIP probabilities in the Gulf of Mexico, shown in Figure 12. At 12:00Z, a large line of lightning activity initiates over the Gulf of Mexico in many areas there had previously been no CIP probabilities. The CIP fills in along this line with the lightning at the same time, shown in Figure 13.

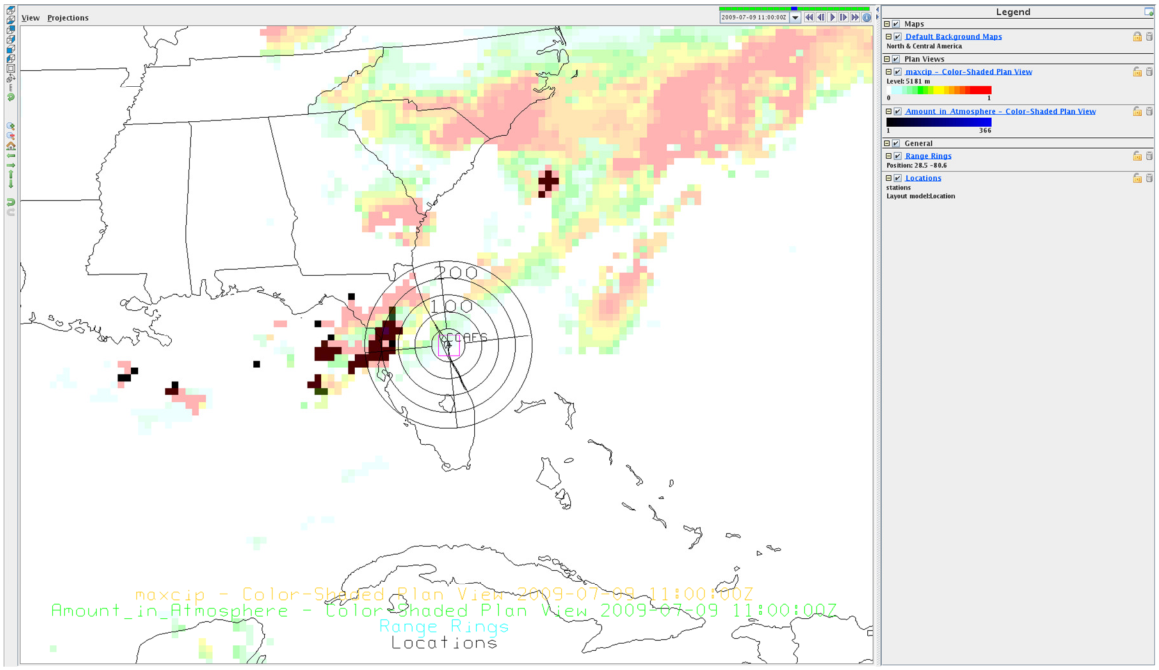

Figure 18. Unorganized CIP probabilities extending from western edge of CCAFS domain into the Gulf of Mexico on July 9, 2009 at 11:00Z

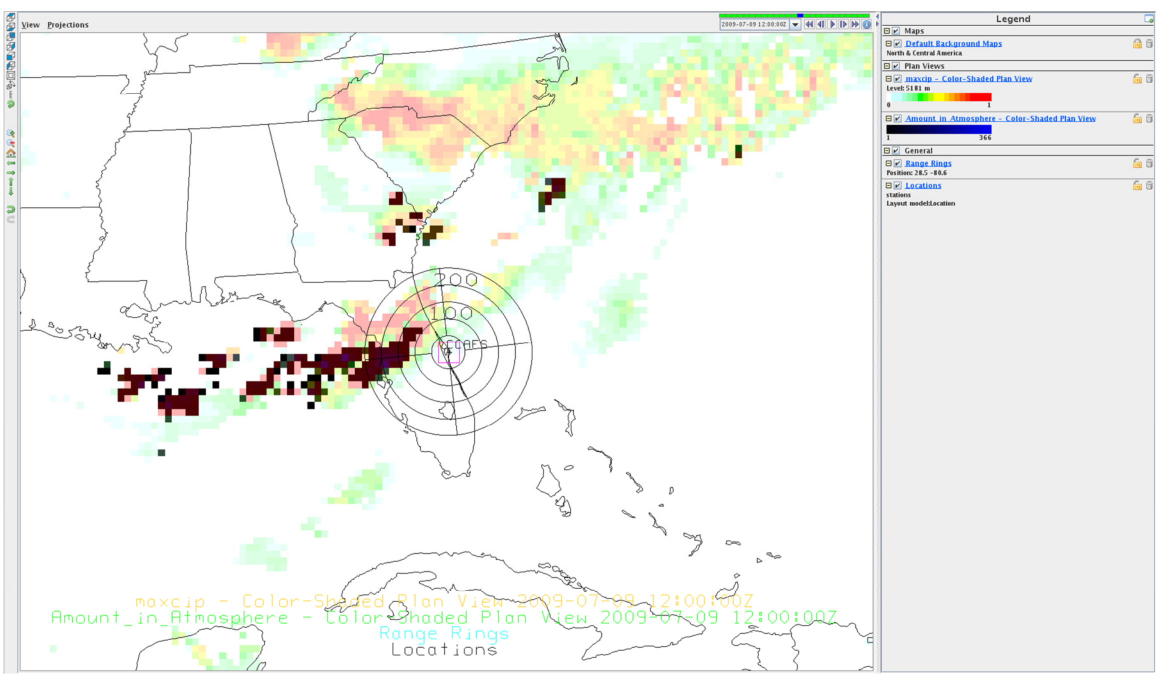

Figure 19. Lightning activity initiates in the Gulf of Mexico in areas where CIP probabilities had not existed the previous hour on July 9, 2009 at 12:00Z

SPAM March 8, 2010

In this case study an occluding low pressure system, as shown in Figure 14, was positioned over southern California moving east across Arizona into New Mexico. Convection started out light at 00:00Z on March 8, 2010, in proximity of the cold and occluded fronts wrapping into the center of the low with additional scattered convection in New Mexico. The convection in New Mexico quickly intensified, and by 01:50Z severe thunderstorm warnings were being issued for southeastern New Mexico. Among the hazards such as hail and damaging winds normally associated with severe thunderstorms, cautions of cloud to ground lightning were included in the warning issued by the NWS in Midland/Odessa, Texas:

```
WUUS54 KMAF 080150
SVRMAF
NMC015-080245-
/O.NEW.KMAF.SV.W.0001.100308T0150Z-100308T0245Z/
BULLETIN - EAS ACTIVATION REQUESTED
SEVERE THUNDERSTORM WARNING
NATIONAL WEATHER SERVICE MIDLAND/ODESSA TX
650 PM MST SUN MAR 7 2010
THE NATIONAL WEATHER SERVICE IN MIDLAND HAS ISSUED A
* SEVERE THUNDERSTORM WARNING FOR...
  CENTRAL EDDY COUNTY IN SOUTHEAST NEW MEXICO...
* UNTIL 745 PM MST
* AT 646 PM MST...NATIONAL WEATHER SERVICE METEOROLOGISTS
DETECTED A SEVERE THUNDERSTORM CAPABLE OF PRODUCING QUARTER SIZE
HAIL...AND   DAMAGING WINDS IN EXCESS OF 60 MPH.  THIS STORM WAS
LOCATED 9 MILES   WEST NORTHWEST OF WHITES CITY...OR 20 MILES
SOUTHWEST OF CARLSBAD...MOVING NORTHEAST AT 15 MPH.
* THE SEVERE THUNDERSTORM WILL AFFECT THE FOLLOWING LOCATIONS...
  CENTRAL EDDY COUNTY...PRECAUTIONARY/PREPAREDNESS ACTIONS...
IN ADDITION TO LARGE HAIL AND DAMAGING WINDS...DEADLY CLOUD TO
GROUND LIGHTNING IS OCCURRING WITH THIS STORM. REMEMBER...IF YOU
CAN HEAR THUNDER...YOU ARE CLOSE ENOUGH TO BE STRUCK BY
LIGHTNING. SEEK SAFE SHELTER NOW.
&&
LAT...LON 3272 10444 3258 10403 3213 10441 3219 10465
TIME...MOT...LOC 0149Z 207DEG 14KT 3224 10451
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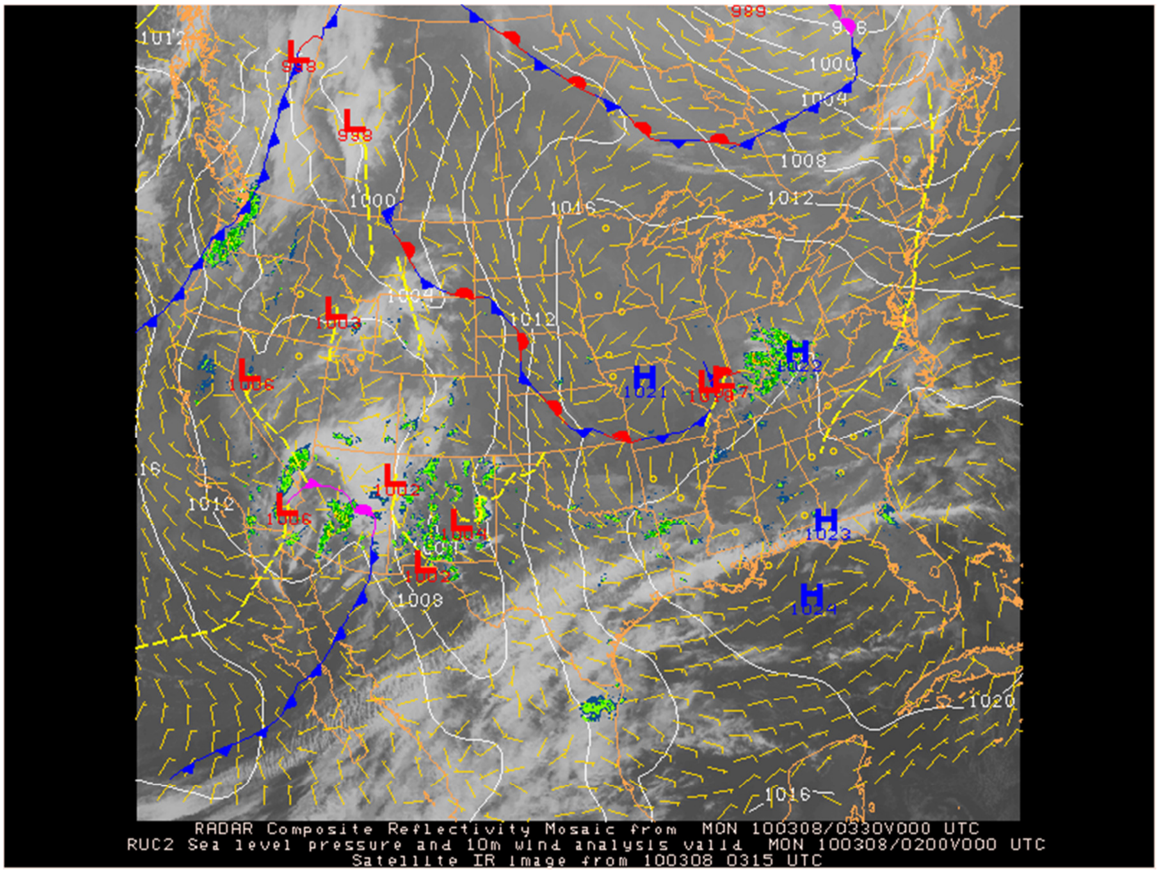


Figure 20. Surface analysis with satellite and radar imagery on March 8, 2010 at 03:15Z when lightning activity was closest to SPAM.

Lightning activity during the early hours of March 8 was low and located mostly in New Mexico including activity within the SPAM regional domain to the west, north, and east. The CIP probabilities were high in the northwest quadrant of the domain and low, transitioning to high, in the northeast domain as the distance from the spaceport increased. Figure 15 shows the initial lightning activity and CIP probabilities near SPAM as well as the rest of the southwestern and south central US, including a CASP, CSM, MASP, and CHUG. Note the large swath of high CIP probabilities in Texas, Oklahoma, Louisiana, and the Gulf of Mexico with no lightning activity.

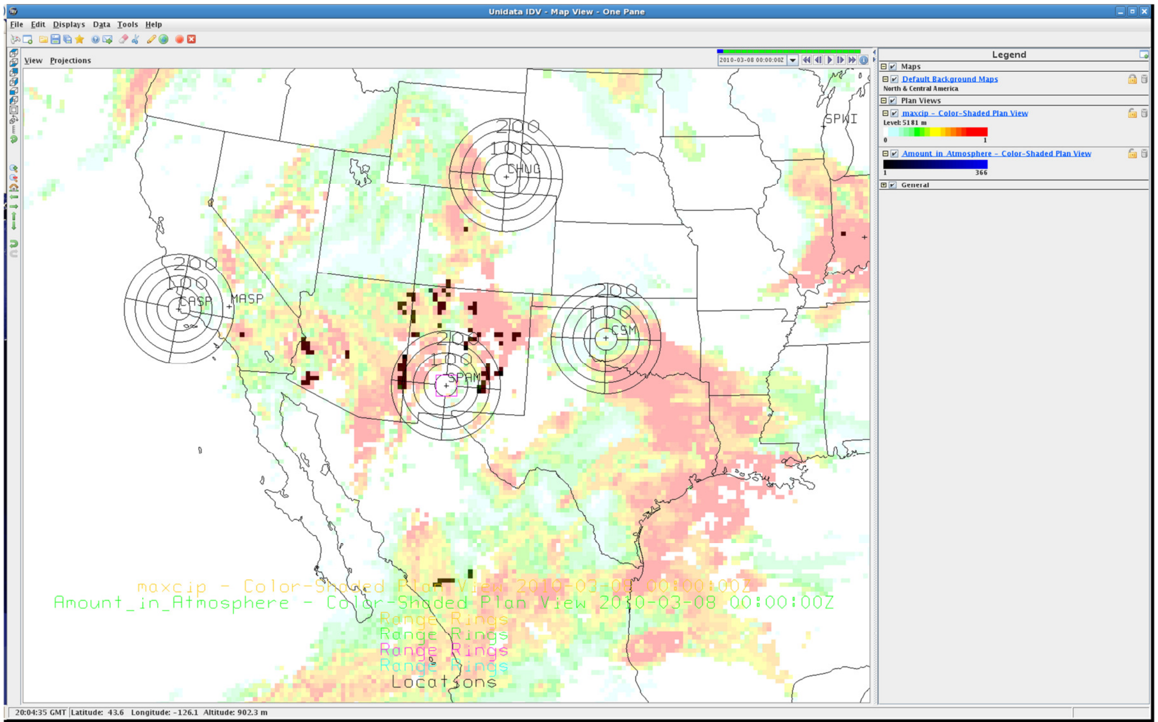
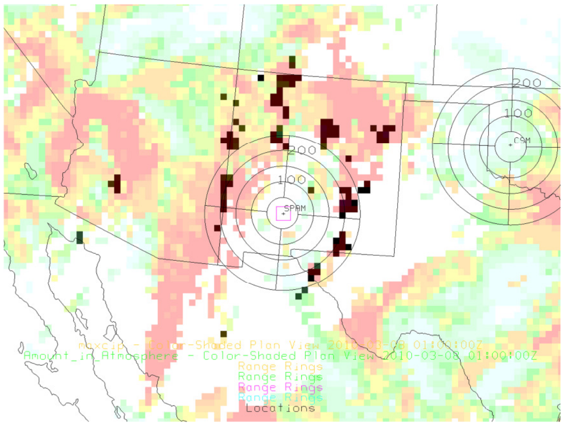
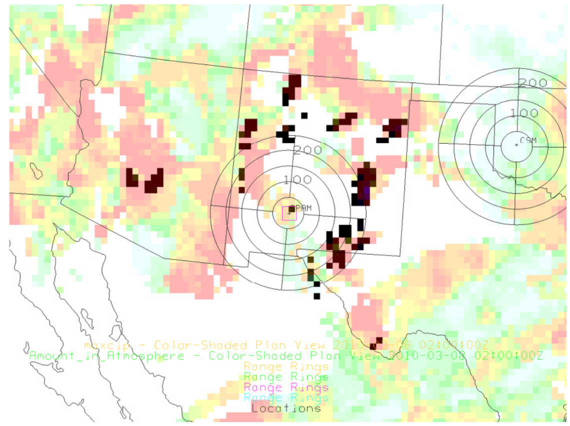


Figure 21. Initial lightning activity and CIP probabilities on March 8, 2010, over the southwestern and south central US including SPAM, CASP, CSM, and CHUG spaceports.

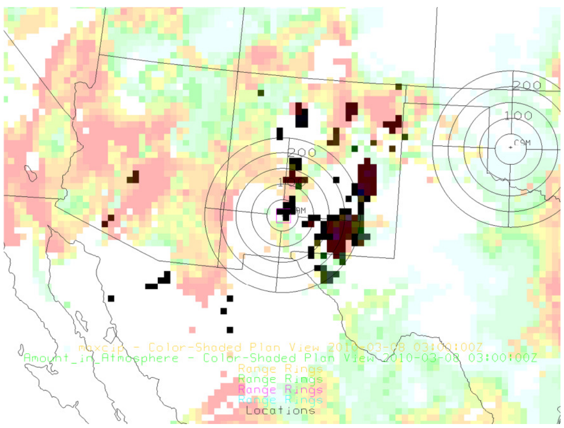
Until 04:00Z on March 8, 2010, CIP probabilities remained within the SPAM domain without probabilities higher than 75% (oranges) encroaching closer than about 100 kilometers. Lightning activity continued to circle SPAM from the west, through the north, and to east in a scattered manner until 02:00Z and 03:00Z when lightning activity was observed in the grids adjacent to and including SPAM. Figure 15 shows the progression of this lightning activity and the behavior of the CIP probabilities.



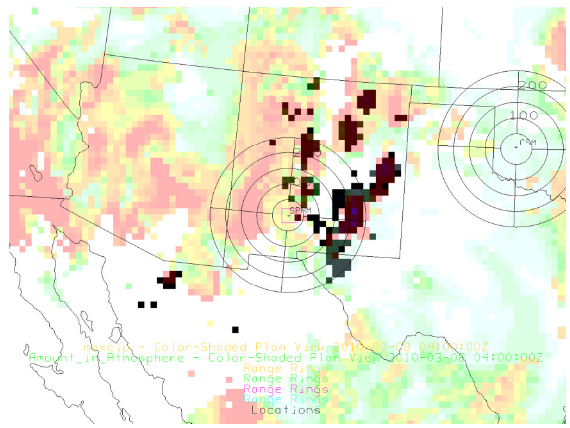
01:00Z



02:00Z



03:00Z



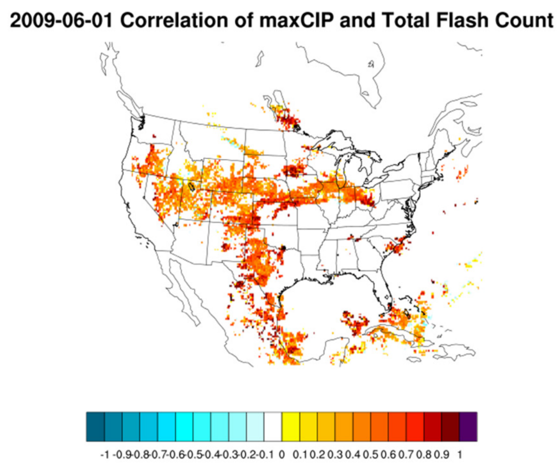
04:00Z

Figure 22. Sequence of lightning activity and CIP probabilities on March 8, 2010, starting at 01:00Z and ending at 04:00Z.

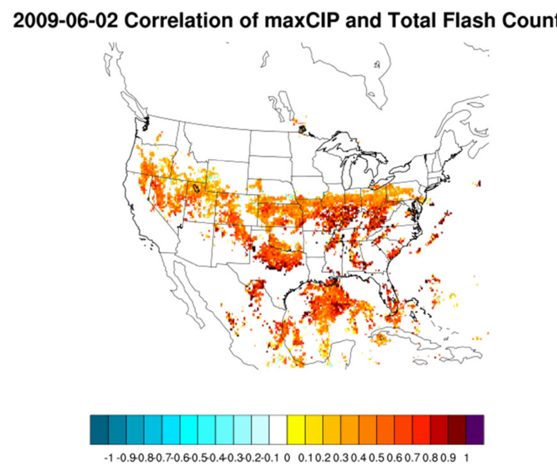
Intense lightning activity also initiated in the southeast quadrant of the SPAM domain. The lightning activity in the direct vicinity of SPAM and in the southeast quadrant developed in regions where CIP probabilities were either much lower or non-existent in the preceding hours. This was especially true when compared to the high background CIP probabilities in Arizona, Mexico, and California where little to no lightning activity occurred. In particular, the lightning activity over SPAM at 03:00Z initiated with only a few grid boxes within 50 kilometers of the spaceport indicating low to moderate CIP probabilities and none indicating high probabilities. During this period even greater lightning activity initiated in the southeast quadrant of the SPAM regional domain in areas where CIP probabilities lower and more sparse than in other quadrants such as the northwest and southwest.

BAK June 1-3, 2009

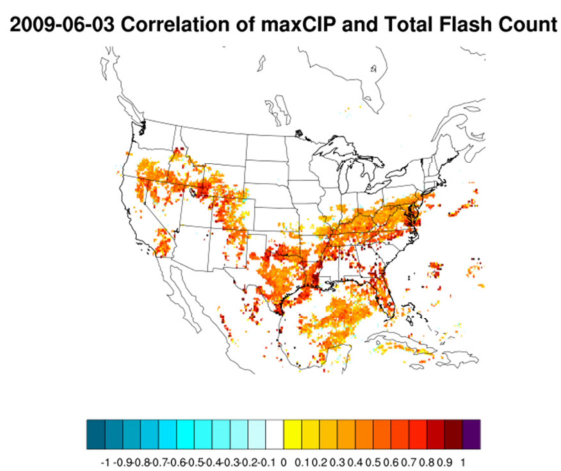
This case study was selected by analyzing CIP correlations looking for cases of overwhelming positive correlations, shown in Figure 17, rather than negative correlations. The intent was to investigate the ability of the CIP to diagnose lightning activity in a case where correlation analysis seemed to support the original hypothesis. In this case, a well-organized severe weather outbreak developed across the Midwestern United States including Illinois, Indiana, Kentucky and Ohio within the BAK regional domain from June 1, 2009, to June 3, 2009, shown in Figure 18. The event was well forecast with the SPC's convective outlooks capturing the location, extent, and specific hazards for each day up to three days out. The one-day convective outlooks are shown in Figures 19 and 20. These storms produced damaging winds, hail, and tornadoes indicated by storm reports received by the SPC, shown in Figure 21 and Table 14. Table 14 further shows the total of events that occurred in states that intersect BAK's regional domain. The strongest weather near BAK occurred from 20:00Z on the first to 05:00Z on the second, and again from 18:00Z on June 2, 2009 to 00:00Z on June 3, 2009. In addition, June 3 also saw extensive lightning activity within the regional domain and directly over BAK, though there was less severity.



June 1, 2009



June 2, 2009



June 3, 2009

Figure 23. Sequence of lightning and maximum CIP correlations for the CONUS on June 1, June 2, and June 3, 2009.

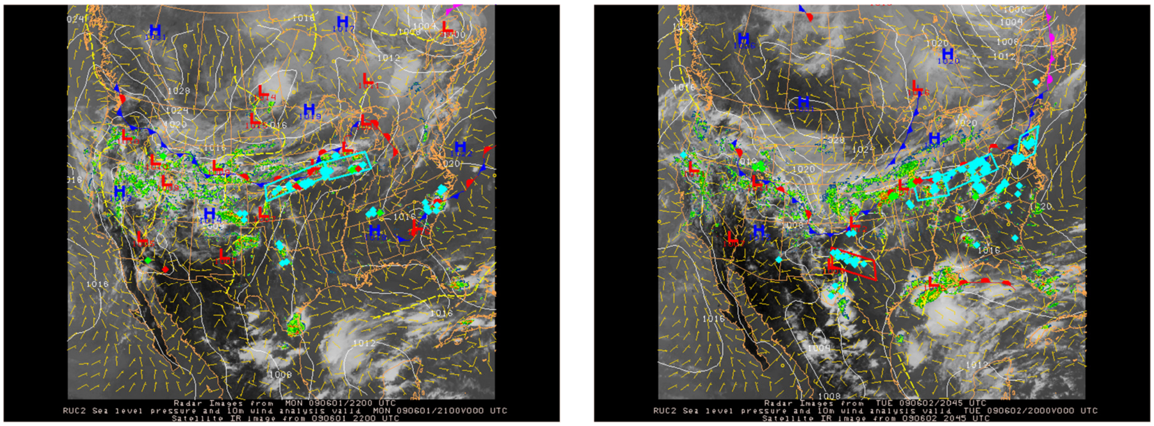
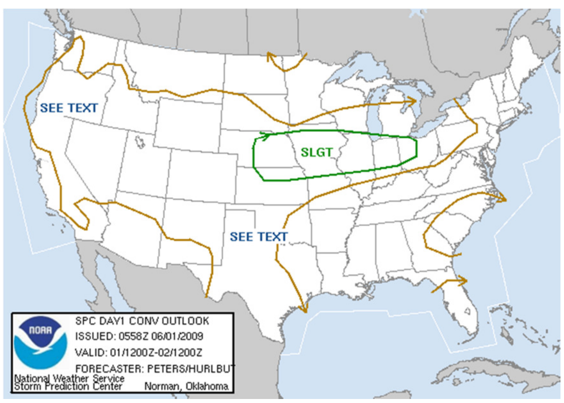
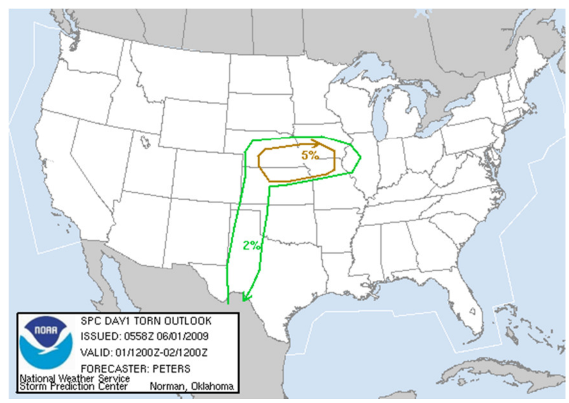


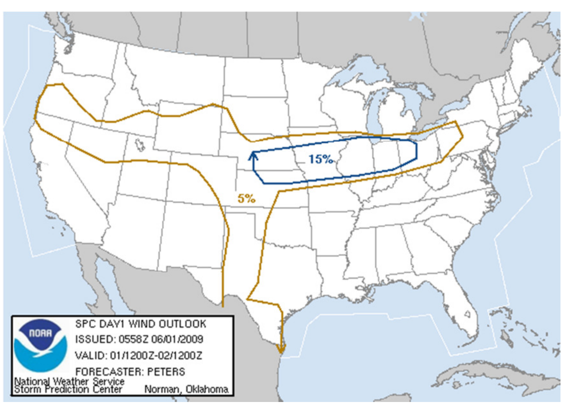
Figure 24. Surface analysis with radar, satellite, fronts, and warnings for June 1, 2009, at 22:00Z and June 2, 2009, at 20:45Z. Teal boxes are severe thunderstorm watches and red boxes are tornado watches. Teal diamonds are severe thunderstorm warnings and red diamonds are tornado warnings.



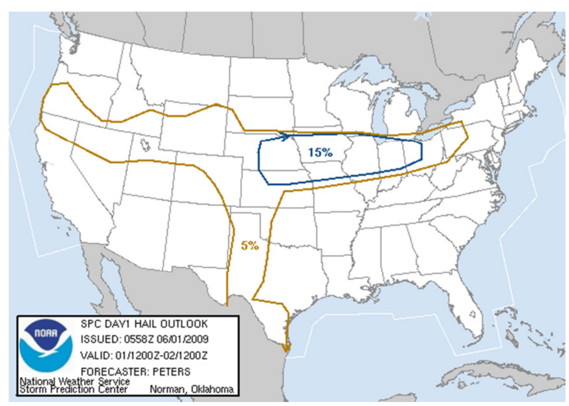
Categorical Convective Outlook



Probabalilstic Tornado Outlook

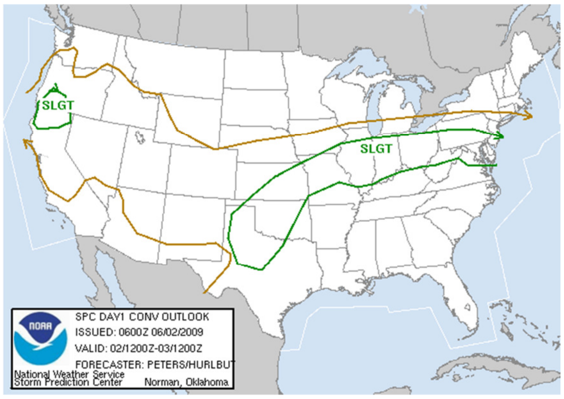


Probablistic Damaging Wind Outlook

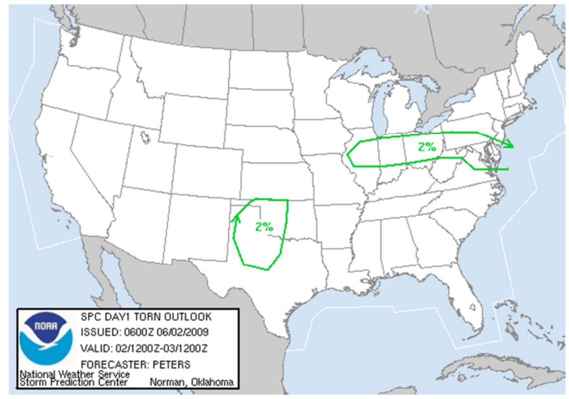


Probabalistic Large Hail Outlook

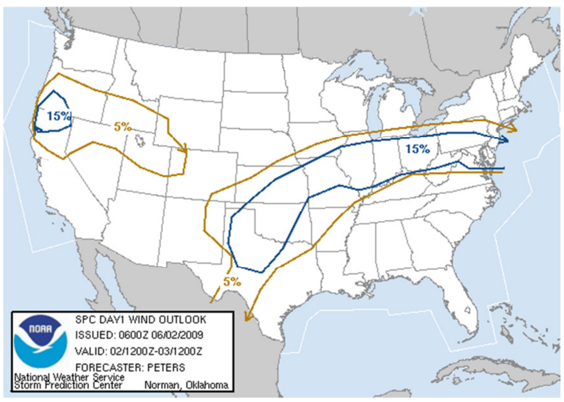
Figure 25. SPC Day 1 Outlooks issued at 05:58Z on June 1, 2009, and valid for June 1 at 12:00Z to June 2 at 12:00Z.



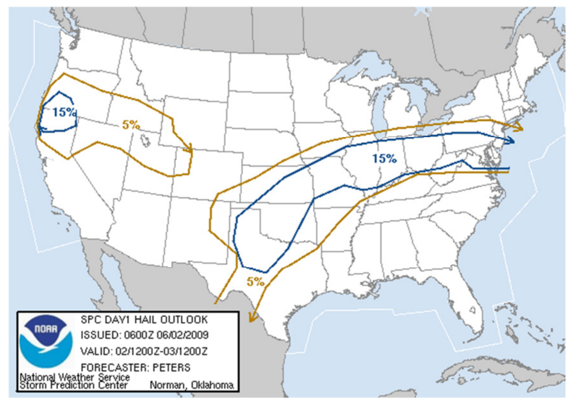
Categorical Convective Outlook



Probabalilstic Tornado Outlook



Probablistic Damaging Wind Outlook



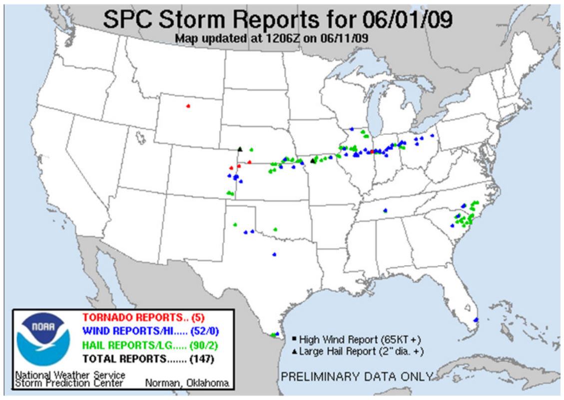
Probabalistic Large Hail Outlook

Figure 26. SPC Day 1 Outlooks issued at 06:00Z on June 2, 2009, and valid for June 2 at 12:00Z to June 3 at 12:00Z.

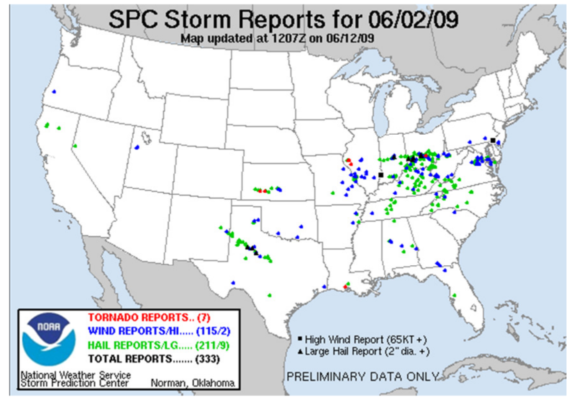
Table 17

Storm Reports for Indiana, Illinois, Ohio, and Kentucky from June 1, 2009, to June 3, 2009 – Daily Totals

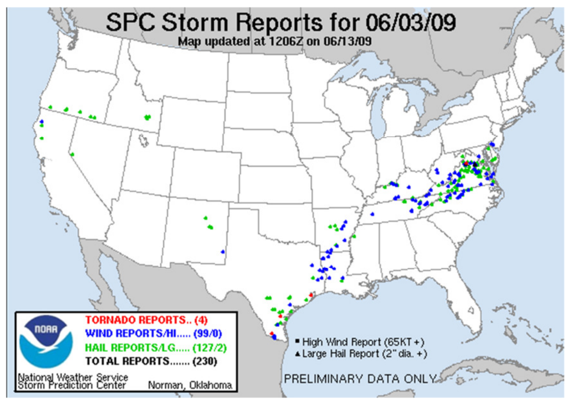
Day	Hail	Wind	Tornado	Total
June 1, 2009	27	31	1	59
June 2, 2009	98	39	4	141
June 3, 2009	6	7	0	13
72-Hour Total	131	77	5	213



June 1, 2009



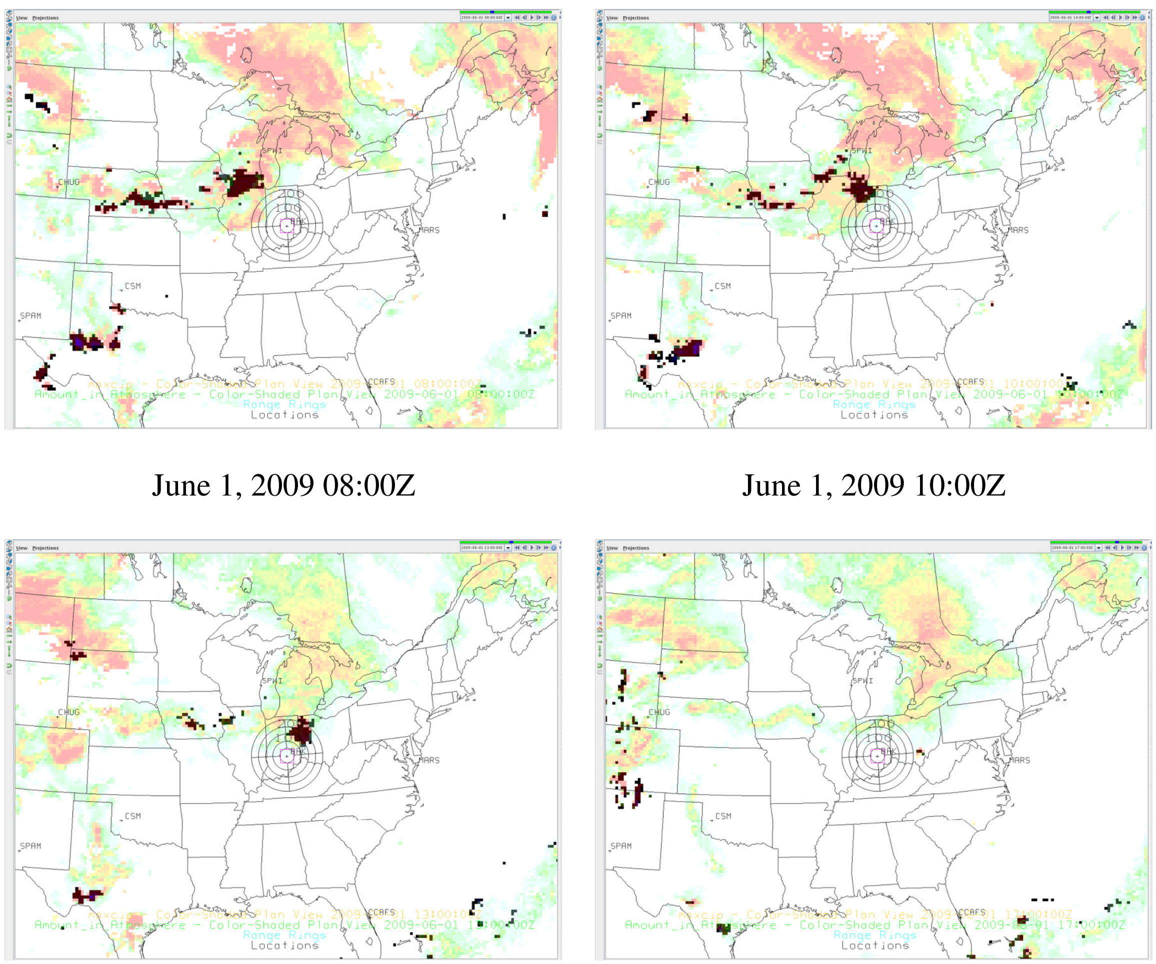
June 2, 2009



June 3, 2009

Figure 27. Archived SPC reports of tornadoes, wind, and hail damage for June 1, 2009, to June 3, 2009.

The first lightning activity to breach the BAK regional domain during this period was at 10:00Z on June 1. The activity initiated in Iowa and moved east crossing into the domain. The lightning was associated with an area of CIP that had crossed into the BAK regional domain two hours before. These initial CIP probabilities were very high, greater than 75%, but unassociated with any lightning activity. The lightning activity passed north of BAK through the regional domain by 1700Z when lightning activity almost entirely ceased and CIP probabilities across the Midwestern United States dropped off dramatically. Probabilities transitioned from blanketed values greater than 75% north and greater than 50% west of BAK to 60% or less. This behavior repeated all three days, June 1 to June 3, during this case study. This sequence of events is shown in Figure 22.



June 1, 2009 08:00Z

June 1, 2009 10:00Z

June 1, 2009 13:00Z

June 1, 2009 17:00Z

Figure 28. Sequence of lightning activity and CIP probabilities on June 1, 2009, starting at 08:00Z and ending at 17:00Z.

During this period, the CIP probabilities were highest across the Great Lakes into Canada with moderate to high probabilities extending southwest and then west into Illinois, Iowa, and Nebraska. The convective activity that entered the BAK regional domain started out scattered in Iowa where CIP probabilities were unorganized with flecks of high and low probabilities adjacent to each other with low spatial extent. As the lightning and convective activity increased, the CIP probabilities increased, matching the convective activity. The CIP then increased beyond the region of convective activity. One area in particular this occurred is the region of high CIP probabilities due west of BAK at 08:00Z that did not exist at 07:00Z, which entered the BAK regional domain ahead of the lightning activity, and never had any lightning activity directly associated with it.

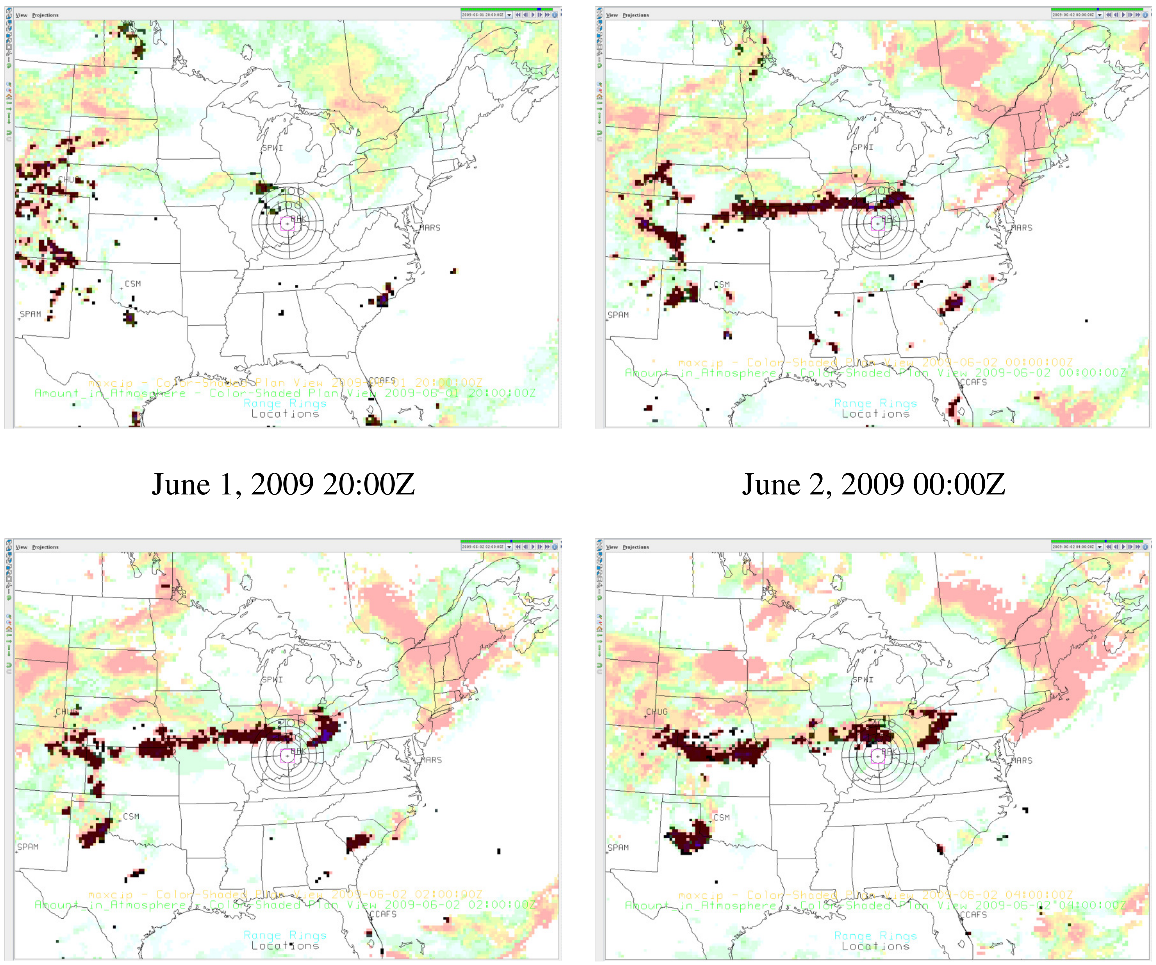
The next lightning activity to initiate began at 18:00Z in northwestern Illinois. This activity was associated with a long line of low to moderate CIP probabilities that extended from Nebraska to Ohio into the northeast and Canada. This line passed through the northern two quadrants of the BAK regional domain with CIP probabilities less than 50%, and most around 25%. At 19:00Z on June 1, 2009, lightning initiated about 150 kilometers northwest of BAK adjacent to CIP probabilities of 20%. In less than an hour, a severe thunderstorm warning had been issued for this storm by the NWS in Indianapolis:

```
WUUS53 KIND 011953
SVRIND
INC107-012045-
/O.NEW.KIND.SV.W.0054.090601T1953Z-090601T2045Z/
BULLETIN - EAS ACTIVATION REQUESTED
SEVERE THUNDERSTORM WARNING
NATIONAL WEATHER SERVICE INDIANAPOLIS IN
```

```
353 PM EDT MON JUN 1 2009
THE NATIONAL WEATHER SERVICE IN INDIANAPOLIS HAS ISSUED A
* SEVERE THUNDERSTORM WARNING FOR...
  MONTGOMERY COUNTY IN WEST CENTRAL INDIANA...
  THIS INCLUDES THE CITY OF CRAWFORDSVILLE...
* UNTIL 445 PM EDT
* AT 352 PM EDT...NATIONAL WEATHER SERVICE DOPPLER RADAR
INDICATED A
  SEVERE THUNDERSTORM CAPABLE OF PRODUCING QUARTER SIZE
HAIL...AND
  DAMAGING WINDS IN EXCESS OF 60 MPH.  THIS STORM WAS
LOCATED NEAR
  WAYNETOWN...OR 6 MILES WEST OF CRAWFORDSVILLE...AND
MOVING EAST AT
  25 MPH.
* THE SEVERE THUNDERSTORM WILL BE NEAR...
  NEW MARKET AROUND 400 PM EDT...
  CRAWFORDSVILLE AROUND 405 PM EDT...
  DARLINGTON AROUND 420 PM EDT...
  NEW ROSS AROUND 430 PM EDT...
THIS INCLUDES INTERSTATE 74 BETWEEN MILE MARKERS 23 AND 45.
LAT...LON 4012 8710 4014 8710 4019 8671 3992 8671
      3993 8710 4011 8710
TIME...MOT...LOC 1953Z 266DEG 21KT 4006 8700
$$
18/DRT
```

This storm was the first in a line of severe thunderstorms that passed through the BAK regional domain until 06:00Z on June 2. During the period from 20:00Z on June 1 to 06:00Z on June 2 storm reports to the NWS and SPC included 27 hail, 31 wind, and 1 tornado reports for a total of 59 events in Illinois, Indiana, Ohio, and Kentucky. Figure 23 shows the lightning activity and CIP probabilities that occurred during this period. Lightning activity ceased for the most part around 10:00Z on June 2 with only a few sporadic strokes observed in proximity to BAK and associated with the line of high CIP probabilities which had begun to drift north after having generally moved due east during the storm outbreak. As with June 1, from 10:00Z to 13:00Z CIP probabilities across the CONUS drastically decreased and one region in Quebec all but disappeared.

The lightning activity and CIP probabilities from 06:00Z to 15:00Z are shown in Figure 24.



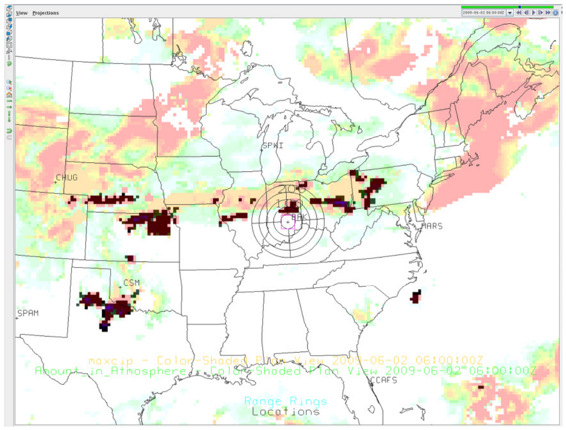
June 1, 2009 20:00Z

June 2, 2009 00:00Z

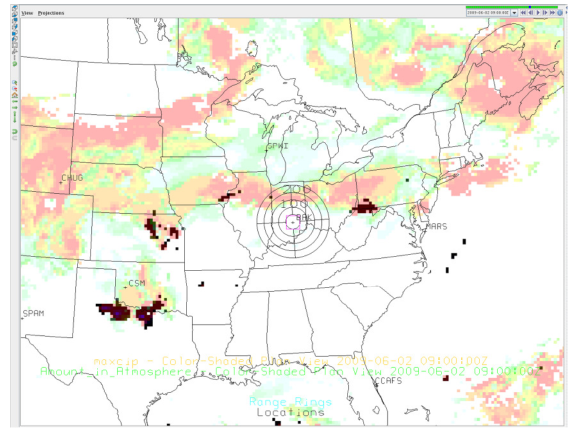
June 2, 2009 02:00Z

June 2, 2009 04:00Z

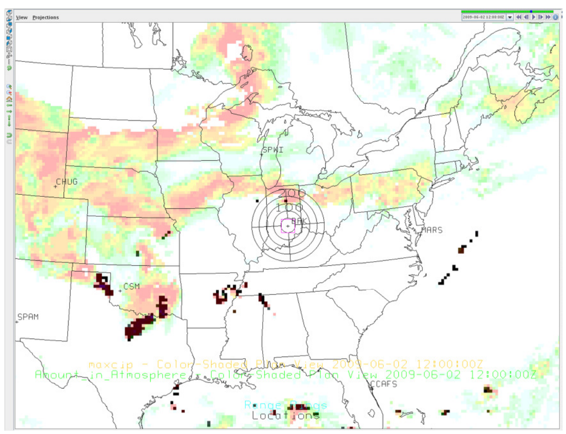
Figure 29. Sequence of lightning activity and CIP probabilities starting at 20:00Z on June 1, 2009 and ending at 04:00Z on June 2, 2009, showing the evolution of the lightning activity and CIP probabilities during the first wave of severe storms.



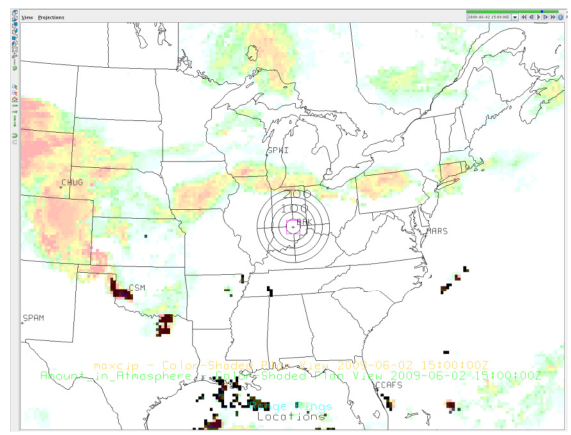
June 2, 2009 06:00Z



June 2, 2009 09:00Z



June 2, 2009 12:00Z

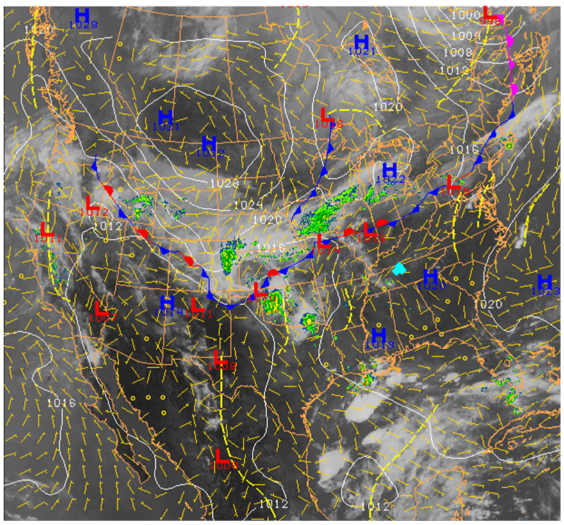


June 2, 2009 15:00Z

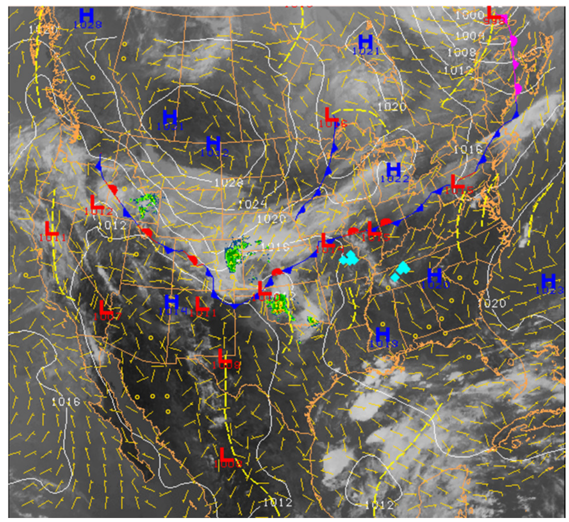
Figure 30. Sequence of lightning activity and CIP probabilities on June 2, 2009, starting at 06:00Z and ending at 15:00Z showing the trend of the two parameters.

At 16:00Z on June 2, 2009, the CIP probabilities were highest through the Great Plains with a line of CIP probabilities associated with the previous day's storms north of BAK across Wisconsin, Lake Michigan, and Michigan terminating with a couple "blobs" of higher probability CIP in Pennsylvania and New England. Between 16:00Z and

17:00Z storms began to form quickly across Tennessee and Arkansas in areas where there had previously been little to no CIP probabilities, with the first severe thunderstorm warnings being issued around 16:45Z, shown by the teal diamonds in Figure 25. From 17:00Z to 23:00Z severe thunderstorm coverage increased around and within the BAK regional domain as shown in Figure 26.

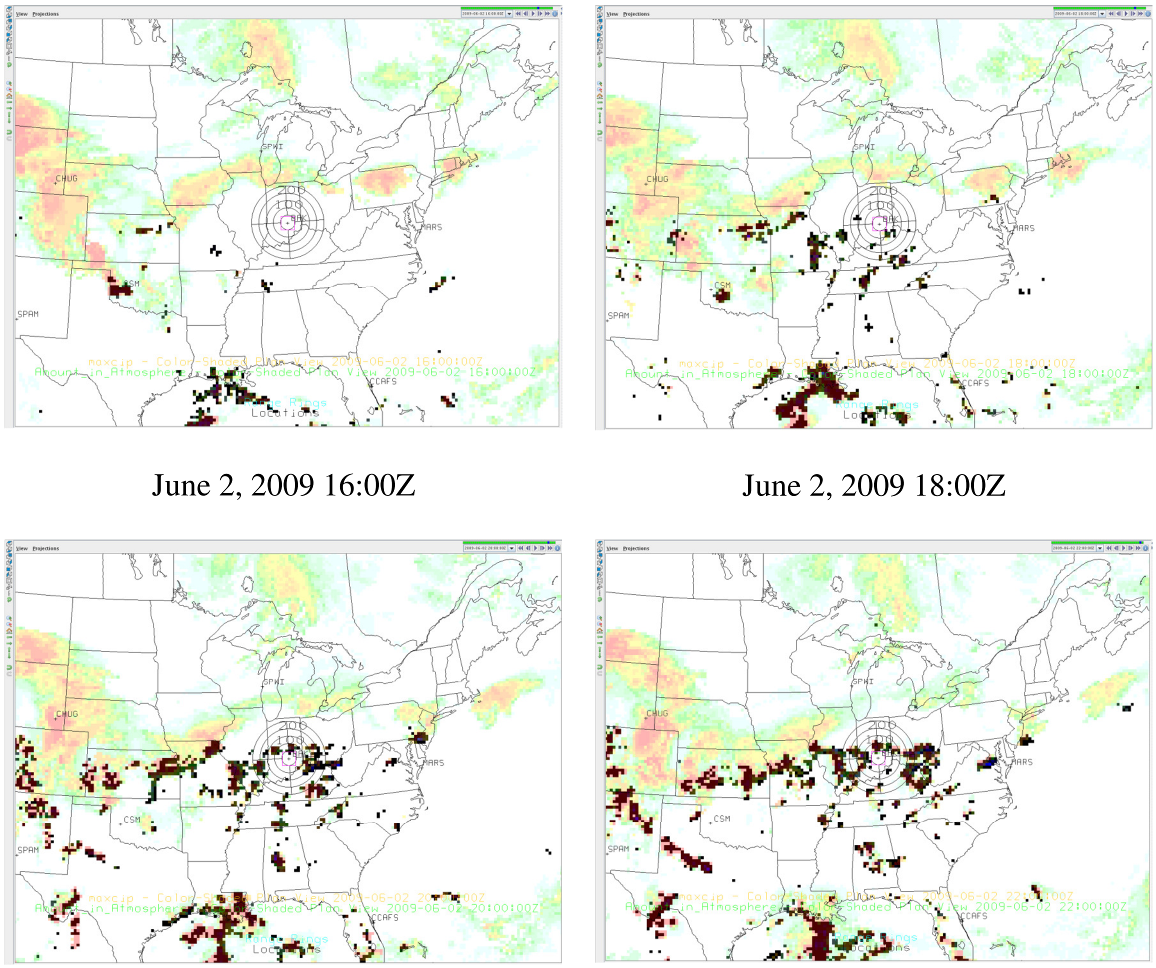


June 2, 2009, at 16:45Z



June 2, 2009, at 17:00Z

Figure 31. Surface analysis with radar, satellite, fronts, and warnings for June 2, 2009, at 16:45Z and June 2, 2009, at 17:00Z. Teal diamonds are severe thunderstorm warnings form storms forming in Tennessee and Arkansas.

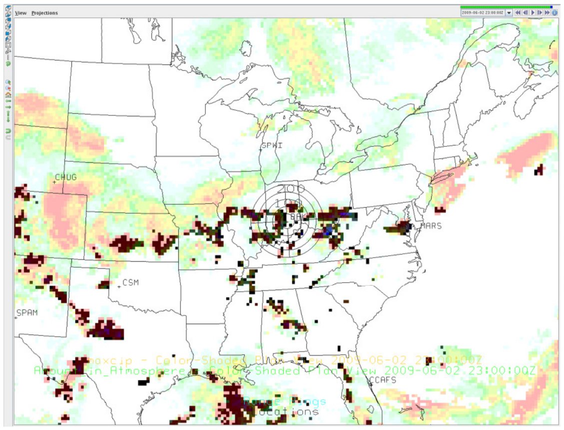


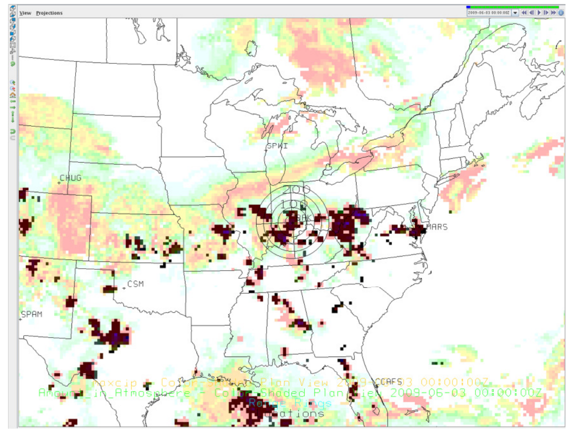
June 2, 2009 16:00Z | June 2, 2009 18:00Z

June 2, 2009 20:00Z | June 2, 2009 22:00Z

Figure 32. Sequence of lightning activity and CIP probabilities on June 2, 2009, between 16:00Z and 22:00Z. Note the trend of the lightning development and CIP probabilities.

At 00:00Z on June 3, 2009, the CIP across eastern North America jumped from relatively low probabilities much higher as shown in Figure 27. This shift in the CIP probabilities occurred one hour before the final storm report (a hail report) for Illinois, Indiana, Kentucky, and Ohio.





June 2, 2009, at 23:00Z June 3, 2006, at 00:00Z

Figure 33 Comparison of lightning activity and CIP probabilities on June 2, 2009, at 23:00Z and June 3, 2009, at 00:00Z.

The storms which formed during the period from June 2, 2009 at 16:00Z until June 3, 2009, and 01:00Z produced the most storm reports of this case study; more than three times as many as the day before as shown in Table 15 (hours with no report have been removed).

The single tornado on June 1, 2009, occurred in Illinois 203 kilometers from BAK at 2119Z. Three of the tornadoes on June 2, 2009, occurred in Illinois as well at 21:25Z, 21:35Z, and 22:225Z. These tornadoes were 441, 433, and 413 kilometers from BAK. The fourth tornado on June 2, 2009, and the last tornado event for this case study, occurred in Ohio at 21:45Z and was 276 kilometers from BAK. The Illinois tornado on June 1, 2009, occurred in the northwest quadrant of the BAK regional domain.

Table 18

Storm reports for Illinois, Indiana, Kentucky, and Ohio for June 1, 2009, to June 3, 2009 – Hourly Totals

Day	Time	Hail Count	Wind Count	Tornado Count
June 1, 2009	0100	0	4	0
	0200	0	3	0
	0400	0	1	0
	1300	2	0	0
	2000	3	0	0
	2100	1	1	0
	2200	7	6	1
	2300	11	8	0
Jun 2, 2009	0000	3	8	0
	0100	4	2	0
	0200	3	0	0
	0300	8	3	0
	0400	1	0	0
	0500	1	0	0
	1800	1	0	0
	1900	2	1	0
	2000	15	1	0
	2100	21	5	0
	2200	21	13	3
	2300	13	11	1
June 3, 2009	0000	8	3	0
	0100	0	1	0
	1900	0	1	0
	2000	3	1	0
	2100	0	2	0
	2200	3	2	0

Chapter VI

Discussion, Conclusions, and Recommendations

The purpose of this research was to determine the viability of using the CIP to diagnose the threat for triggered lightning strikes. The results showed that temporal correlations are very high but tainted by the CIP's use of NLDN's lightning data as the primary source for identifying deep convection and convective icing, while spatial correlations are very low due to the amount of icing probability generated by non-convective mixed phase clouds. Climatological analysis of regions around select spaceports demonstrated consistent seasonal variation in activity as well as the susceptibility of certain spaceports to frequent lightning activity.

Forecast Verification

Though the POD of the CIP's lightning forecast is reasonably high, this comes at the cost of a very high FAR. This is analogous to predicting lightning on most days, with a FAR roughly 9 out of 10 days. A common threshold for a skillful forecast system is to establish a CSI of 0.60 or greater; i.e. do better than a coin toss. The CIP as a lightning forecast tool does no better than 0.15, and frequently less than 0.10.

Over-prediction

The primary reason for the high FAR, and low CSI, when using the CIP to forecast lightning is the gross over-prediction of lightning hazard regions. Case study analysis showed CIP coverage areas covering an area of whole states that then failed to capture the lightning initiation.

Lightning Climatology

The CONUS analysis of lightning climatology from the gridded data set showed relatively consistent seasonality between 2009, 2010, and 2011 with the winter months less active compared to peak activity in the summer months. Activity remained elevated during the spring and fall months, with some variation between the years and categories. Spaceports could be grouped into three categories based on the amount of lightning experienced over the course of the year. Spaceports with high activity experienced up to 200 lightning days, while spaceports with low activity might see as few as three storms a year. The variability in lightning activity demonstrates the need for detailed analysis of lightning hazards at each spaceport.

CIP and Lightning Correlations

The CIP is highly correlated with lightning activity because the CIP uses NLDN data to diagnose deep convection and convective icing. Lightning flashes detected by the NLDN fifteen minutes prior to the model valid time are assimilated into the CIP. The lightning is use as a predictor of a mixed phase cloud that will include super cooled liquid water.

Conclusions

There is no substitution for in-situ measurements of the local charge in the atmosphere during lightning sensitive operations. Forecast verification showed the CIP would generate a false lightning forecast 9 out of 10 days and possess less skill than any other lightning forecast method in operational use. Those lightning forecasting methods that are in operational use still fail to achieve the desired 0.60 CSI. Case study analysis showed the CIP largely over-predicts the extent of lightning (icing too, for that matter) and generally fails to capture lightning initiation.

Recommendations

As numerical forecast systems gain higher resolution, storm formation is becoming a better-resolved part of the forecast. Where and when storms will form is a better diagnostic for lightning threat than looking for mixed water phase environments, humidity levels at various altitudes or equations used to parameterize lightning. Continued development of models capable of fully resolving thunderstorms is essential to lightning forecasting.

There is also no information for determining the CIP's ability to diagnose triggered lightning hazards. Studies agree a vehicle passing through a charged region could trigger the lightning stroke, but there are only a handful of cases of this occurring. These few cases do not provide enough evidence to draw any conclusions about the environment in which a vehicle may trigger a lightning stroke. More studies of rocket plume conductivity and environmental charge sensitivity need to be conducted to address the volume of questions that remain.

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Appendices

Appendix A

Tables

Appendix A1 2009 Lightning Data – CONUS Sums
Color-coding indicates the relative rank of the date within the calendar year, from green (low events), through yellow and orange, to red (high events). Cells outlined borders indicate data values greater than three standard deviations above the mean.

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
1-Jan-09	1594	1570	11	13
2-Jan-09	1936	1894	9	33
3-Jan-09	26172	25226	100	846
4-Jan-09	29316	26994	392	1930
5-Jan-09	5674	5265	87	322
6-Jan-09	2855	2661	32	162
7-Jan-09	3735	3401	59	275
8-Jan-09	1153	1094	16	43
9-Jan-09	14293	13920	249	124
10-Jan-09	2031	1765	68	198
11-Jan-09	1499	1463	11	25
12-Jan-09	486	473	4	9
13-Jan-09	481	467	3	11
14-Jan-09	112	111	1	0
15-Jan-09	55	55	0	0
16-Jan-09	31	30	1	0
17-Jan-09	6	6	0	0
18-Jan-09	1346	1296	10	40
19-Jan-09	6767	6591	39	137

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
20-Jan-09	4598	4286	96	216
21-Jan-09	485	455	6	24
22-Jan-09	861	818	21	22
23-Jan-09	844	757	6	81
24-Jan-09	168	137	0	31
25-Jan-09	478	375	12	91
26-Jan-09	137	96	12	29
27-Jan-09	351	219	18	114
28-Jan-09	44	38	2	4
29-Jan-09	457	414	8	35
30-Jan-09	155	155	0	0
31-Jan-09	617	592	15	10
1-Feb-09	618	584	3	31
2-Feb-09	40627	39447	356	824
3-Feb-09	29491	29167	184	140
4-Feb-09	1328	1242	34	52
5-Feb-09	1793	1742	15	36
6-Feb-09	69	47	2	20
7-Feb-09	76	64	1	11
8-Feb-09	2009	1739	34	236
9-Feb-09	6000	5269	207	524
10-Feb-09	6796	5364	91	1341
11-Feb-09	52393	45415	979	5999

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
12-Feb-09	164	124	15	25
13-Feb-09	1445	1311	8	126
14-Feb-09	11252	10687	50	515
15-Feb-09	4414	4163	31	220
16-Feb-09	711	657	17	37
17-Feb-09	687	658	12	17
18-Feb-09	16215	13242	398	2575
19-Feb-09	59716	53434	994	5288
20-Feb-09	1125	1114	6	5
21-Feb-09	6049	5897	12	140
22-Feb-09	36370	36077	242	51
23-Feb-09	23	19	1	3
24-Feb-09	207	189	1	17
25-Feb-09	326	243	19	64
26-Feb-09	36382	30929	645	4808
27-Feb-09	80332	73550	1352	5430
28-Feb-09	24490	21643	563	2284
1-Mar-09	61164	56287	784	4093
2-Mar-09	28737	28331	137	269
3-Mar-09	1648	1343	31	274
4-Mar-09	506	427	11	68
5-Mar-09	675	543	18	114
6-Mar-09	245	211	2	32

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
7-Mar-09	13483	11834	344	1305
8-Mar-09	51447	40068	1554	9825
9-Mar-09	4072	3178	91	803
10-Mar-09	21914	18887	428	2599
11-Mar-09	41107	34752	691	5664
12-Mar-09	13608	12151	161	1296
13-Mar-09	5733	4767	79	887
14-Mar-09	2182	1912	20	250
15-Mar-09	2815	2492	14	309
16-Mar-09	2013	1872	27	114
31-Mar-09	8360	7779	74	507
1-Apr-09	45249	42048	398	2803
2-Apr-09	141057	132110	1418	7529
3-Apr-09	98699	91934	927	5838
4-Apr-09	34325	33797	139	389
5-Apr-09	26850	21190	766	4894
6-Apr-09	78834	75722	483	2629
7-Apr-09	36659	36279	47	333
8-Apr-09	9387	8939	83	365
9-Apr-09	8761	7323	303	1135
10-Apr-09	96900	86033	1669	9198
11-Apr-09	104459	99443	826	4190
12-Apr-09	188597	174162	1307	13128

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
13-Apr-09	149073	135368	1310	12395
14-Apr-09	201417	191261	1243	8913
15-Apr-09	63861	62544	333	984
16-Apr-09	72661	66613	825	5223
17-Apr-09	171696	156173	1615	13908
18-Apr-09	76947	70183	576	6188
19-Apr-09	85114	78875	681	5558
20-Apr-09	57405	53430	579	3396
21-Apr-09	34290	32083	405	1802
22-Apr-09	15049	13968	261	820
23-Apr-09	27897	25400	524	1973
24-Apr-09	40135	35435	608	4092
25-Apr-09	80863	68474	1487	10902
26-Apr-09	154935	130482	2885	21568
27-Apr-09	155770	131083	1687	23000
28-Apr-09	43792	39489	466	3837
29-Apr-09	166420	142175	1987	22258
30-Apr-09	103584	82352	1509	19723
1-May-09	1059	953	13	93
2-May-09	162064	147907	1330	12827
3-May-09	127391	117906	638	8847
4-May-09	96372	90775	633	4964
5-May-09	115795	104993	1068	9734

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
6-May-09	170088	151217	1442	17429
7-May-09	83969	71622	1331	11016
8-May-09	224492	208000	2223	14269
9-May-09	190283	167445	1523	21315
10-May-09	112383	99213	1082	12088
11-May-09	167362	153297	1170	12895
12-May-09	155917	142343	1135	12439
13-May-09	168426	141621	3141	23664
14-May-09	165860	145763	1912	18185
15-May-09	146346	130847	2344	13155
16-May-09	183838	168112	2420	13306
17-May-09	74221	70113	539	3569
18-May-09	58515	55944	480	2091
19-May-09	75192	72616	557	2019
20-May-09	26247	25099	193	955
21-May-09	97060	93166	839	3055
22-May-09	65784	62104	365	3315
23-May-09	137711	127745	1030	8936
24-May-09	223323	204149	1823	17351
25-May-09	208696	191083	1705	15908
26-May-09	237896	221223	1515	15158
27-May-09	277010	259486	1468	16056
28-May-09	282957	267913	1572	13472

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
29-May-09	197601	184159	1475	11967
30-May-09	252417	245593	1190	5634
31-May-09	241362	225529	1889	13944
1-Jun-09	247676	222309	3270	22097
2-Jun-09	302519	274667	3409	24443
3-Jun-09	316191	295058	2030	19103
4-Jun-09	209997	194826	1464	13707
5-Jun-09	198997	186982	1417	10598
6-Jun-09	192770	177743	1859	13168
7-Jun-09	192503	176656	1692	14155
8-Jun-09	221997	198824	1997	21176
9-Jun-09	298329	260660	3011	34658
10-Jun-09	376429	338156	3143	35130
11-Jun-09	349690	316296	2294	31100
12-Jun-09	258462	221349	2823	34290
13-Jun-09	278710	257727	1611	19372
14-Jun-09	417267	391025	2354	23888
15-Jun-09	290001	260075	3271	26655
16-Jun-09	296730	270682	2604	23444
17-Jun-09	221876	197337	1623	22916
18-Jun-09	460592	418247	3679	38666
19-Jun-09	320547	301977	2082	16488
20-Jun-09	210836	201121	1505	8210

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
21-Jun-09	250650	237009	1600	12041
22-Jun-09	393186	374976	1804	16406
23-Jun-09	342409	314737	2391	25281
24-Jun-09	335662	312415	1788	21459
25-Jun-09	331449	313867	1875	15707
26-Jun-09	374765	354591	2667	17507
27-Jun-09	383962	366796	1698	15468
28-Jun-09	388459	363133	1780	23546
29-Jun-09	323412	304403	1588	17421
30-Jun-09	406532	383951	3085	19496
1-Jul-09	298654	279002	3217	16435
2-Jul-09	330741	312120	2363	16258
3-Jul-09	345991	330473	2097	13421
4-Jul-09	302043	281050	2751	18242
5-Jul-09	325797	303664	2351	19782
6-Jul-09	321326	302104	2237	16985
7-Jul-09	275758	252731	3586	19441
8-Jul-09	237350	211114	6815	19421
9-Jul-09	339398	268741	29307	41350
10-Jul-09	276426	243218	10624	22584
11-Jul-09	385386	345315	8534	31537
12-Jul-09	421429	384990	6544	29895
13-Jul-09	464206	408996	21017	34193

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
14-Jul-09	447929	371084	39157	37688
15-Jul-09	338715	295319	10887	32509
16-Jul-09	436886	408630	3599	24657
17-Jul-09	381972	359009	2888	20075
18-Jul-09	281004	268629	1683	10692
19-Jul-09	337941	320571	1961	15409
20-Jul-09	498998	450962	15421	32615
21-Jul-09	404978	374599	4035	26344
22-Jul-09	339871	304458	8146	27267
23-Jul-09	304485	281390	6549	16546
24-Jul-09	357358	315247	15788	26323
25-Jul-09	516239	469137	9245	37857
26-Jul-09	563924	518851	11280	33793
27-Jul-09	551928	507729	12270	31929
28-Jul-09	525139	483188	9814	32137
29-Jul-09	513469	473545	6143	33781
30-Jul-09	424516	394707	4680	25129
31-Jul-09	298252	278998	4092	15162
1-Aug-09	285456	265626	5073	14757
2-Aug-09	267757	235196	8894	23667
3-Aug-09	334886	297054	10319	27513
4-Aug-09	584482	532062	11394	41026
5-Aug-09	505848	469218	6495	30135

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
6-Aug-09	607461	568095	9445	29921
7-Aug-09	441813	416761	4272	20780
8-Aug-09	389801	363376	4327	22098
9-Aug-09	600839	515606	9357	75876
10-Aug-09	538188	483730	7456	47002
11-Aug-09	364492	338437	3110	22945
12-Aug-09	422734	394860	3393	24481
13-Aug-09	453545	402846	4464	46235
14-Aug-09	445392	341889	8128	95375
15-Aug-09	451940	339097	11024	101819
16-Aug-09	279344	202257	3684	73403
17-Aug-09	451279	295915	3647	151717
18-Aug-09	470682	326318	4269	140095
19-Aug-09	476705	364612	4870	107223
20-Aug-09	542612	386593	4534	151485
21-Aug-09	496991	410436	5309	81246
22-Aug-09	259678	206685	2501	50492
23-Aug-09	233591	162503	1840	69248
24-Aug-09	392873	297941	5867	89065
25-Aug-09	274570	208845	2821	62904
26-Aug-09	273432	191249	3128	79055
27-Aug-09	320565	219099	2943	98523
28-Aug-09	277138	206342	4116	66680

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
29-Aug-09	294066	190292	1926	101848
30-Aug-09	274933	205393	2256	67284
31-Aug-09	333035	287681	2967	42387
1-Sep-09	242764	229123	2301	11340
2-Sep-09	168673	156258	2015	10400
3-Sep-09	222297	203927	3109	15261
4-Sep-09	254904	236620	2950	15334
5-Sep-09	259743	242034	3702	14007
6-Sep-09	281739	264158	2726	14855
7-Sep-09	244711	223635	3216	17860
8-Sep-09	364719	334430	5370	24919
9-Sep-09	321137	294252	4466	22419
10-Sep-09	306157	290035	2592	13530
11-Sep-09	293660	269728	4441	19491
12-Sep-09	193404	179926	2220	11258
13-Sep-09	226695	212917	1790	11988
14-Sep-09	277339	251791	3196	22352
15-Sep-09	160652	147300	2141	11211
16-Sep-09	186316	174483	1747	10086
17-Sep-09	209964	191924	2686	15354
18-Sep-09	174251	162540	1941	9770
19-Sep-09	165473	155230	1570	8673
20-Sep-09	182168	166333	2445	13390

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
21-Sep-09	318901	294367	4061	20473
22-Sep-09	237507	221389	2305	13813
23-Sep-09	113971	108108	1065	4798
24-Sep-09	87725	81587	977	5161
25-Sep-09	90773	86271	934	3568
26-Sep-09	100485	91061	1738	7686
27-Sep-09	101747	89373	2420	9954
28-Sep-09	191574	172431	2462	16681
29-Sep-09	208935	196035	1913	10987
30-Sep-09	217140	210900	1326	4914
1-Oct-09	258919	243503	2385	13031
2-Oct-09	227470	217911	2031	7528
3-Oct-09	143688	138243	1458	3987
4-Oct-09	142362	124079	1900	16383
5-Oct-09	36336	30243	811	5282
6-Oct-09	144924	126930	2399	15595
7-Oct-09	111856	95594	2009	14253
8-Oct-09	161164	143387	3066	14711
9-Oct-09	108410	98785	1996	7629
10-Oct-09	80265	76082	816	3367
11-Oct-09	108443	103418	884	4141
12-Oct-09	80633	75638	1037	3958
13-Oct-09	67230	61181	1086	4963

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
14-Oct-09	21130	18901	369	1860
15-Oct-09	96646	86922	1607	8117
16-Oct-09	241995	222288	3208	16499
17-Oct-09	179129	172000	1500	5629
18-Oct-09	177208	174245	674	2289
19-Oct-09	107418	104758	426	2234
20-Oct-09	49140	45235	568	3337
21-Oct-09	48431	44013	975	3443
22-Oct-09	54296	51863	401	2032
23-Oct-09	26962	25709	335	918
24-Oct-09	46407	42908	2168	1331
25-Oct-09	40237	38578	312	1347
26-Oct-09	101811	93721	1510	6580
27-Oct-09	44339	42183	466	1690
28-Oct-09	11215	10014	216	985
29-Oct-09	43682	39323	640	3719
30-Oct-09	42431	39255	685	2491
31-Oct-09	21718	21296	123	299
1-Nov-09	5154	5030	54	70
2-Nov-09	5688	5564	36	88
3-Nov-09	4719	4528	32	159
4-Nov-09	16717	16195	101	421
5-Nov-09	20187	19155	360	672

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
6-Nov-09	9651	8435	571	645
7-Nov-09	4731	4065	353	313
8-Nov-09	13031	11819	337	875
9-Nov-09	15333	14212	246	875
10-Nov-09	32691	30665	827	1199
11-Nov-09	5876	5232	148	496
12-Nov-09	22762	21461	249	1052
13-Nov-09	57455	56178	373	904
14-Nov-09	45524	44804	214	506
15-Nov-09	9738	9196	112	430
16-Nov-09	1883	1452	90	341
17-Nov-09	264	205	33	26
18-Nov-09	182	143	15	24
19-Nov-09	8721	7995	150	576
20-Nov-09	123213	117530	2067	3616
21-Nov-09	44273	43523	224	526
22-Nov-09	31930	28789	627	2514
23-Nov-09	32183	30237	368	1578
24-Nov-09	188347	180582	1788	5977
25-Nov-09	121677	117513	868	3296
26-Nov-09	24689	23928	164	597
27-Nov-09	8084	7304	279	501
28-Nov-09	8752	7700	337	715

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
29-Nov-09	5404	4155	198	1051
30-Nov-09	13446	11522	623	1301
1-Dec-09	134183	130717	808	2658
2-Dec-09	228559	219790	1974	6795
3-Dec-09	75962	70967	935	4060
4-Dec-09	15558	14057	272	1229
5-Dec-09	39203	36859	423	1921
6-Dec-09	1438	1392	11	35
7-Dec-09	3382	3298	14	70
8-Dec-09	23184	21097	405	1682
9-Dec-09	36712	31575	935	4202
10-Dec-09	28845	27606	196	1043
11-Dec-09	5145	4802	85	258
12-Dec-09	4548	4217	85	246
13-Dec-09	17916	16458	356	1102
14-Dec-09	61674	57365	827	3482
15-Dec-09	67769	61863	1186	4720
16-Dec-09	25396	23472	350	1574
17-Dec-09	42238	41379	159	700
18-Dec-09	59493	57233	489	1771
19-Dec-09	14160	13534	126	500
20-Dec-09	849	822	8	19
21-Dec-09	243	233	1	9

Date	Total Strokes	Negative	Positive	Cloud-to-cloud
22-Dec-09	932	683	40	209
23-Dec-09	25952	23504	514	1934
24-Dec-09	79158	73273	1334	4551
25-Dec-09	12074	11158	179	737
26-Dec-09	1679	1592	21	66
27-Dec-09	1595	1409	26	160
28-Dec-09	3728	3592	55	81
29-Dec-09	883	858	13	12
30-Dec-09	112	92	6	14
31-Dec-09	1472	1402	13	57

Appendix A2 2010 Lightning Data – CONUS Sums
Color-coding indicates the relative rank of the date within the calendar year, from green (low events), through yellow and orange, to red (high events).

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
1-Jan-10	43358	40470	927	1961
2-Jan-10	1620	1467	76	77
3-Jan-10	430	372	16	42
4-Jan-10	30	29	0	1
5-Jan-10	609	481	76	52
6-Jan-10	937	841	35	61
7-Jan-10	266	244	7	15
8-Jan-10	291	267	14	10
9-Jan-10	58	53	1	4
10-Jan-10	26	20	4	2
11-Jan-10	50	39	7	4
12-Jan-10	343	283	41	19
13-Jan-10	1238	1051	93	94
14-Jan-10	2425	2107	62	256
15-Jan-10	75488	73581	622	1285
16-Jan-10	104174	100176	1169	2829
17-Jan-10	8983	7735	339	909
18-Jan-10	1406	1189	86	131
19-Jan-10	2823	1820	490	513
20-Jan-10	27201	24875	646	1680
21-Jan-10	175774	158578	4017	13179

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
22-Jan-10	44695	39966	1040	3689
23-Jan-10	12856	12209	105	542
24-Jan-10	29997	24055	1722	4220
25-Jan-10	34969	31232	879	2858
26-Jan-10	4594	4213	146	235
27-Jan-10	915	784	15	116
28-Jan-10	50287	43420	1431	5436
29-Jan-10	63223	56438	1076	5709
30-Jan-10	35845	32640	832	2373
31-Jan-10	12298	11426	228	644
1-Feb-10	15238	14795	193	250
2-Feb-10	27858	26220	387	1251
3-Feb-10	10085	9440	159	486
4-Feb-10	5061	4473	146	442
5-Feb-10	19623	16114	939	2570
6-Feb-10	5434	4864	83	487
7-Feb-10	1570	1311	89	170
8-Feb-10	7423	5758	238	1427
9-Feb-10	10954	9256	403	1295
10-Feb-10	9291	8294	263	734
11-Feb-10	2666	2196	118	352
12-Feb-10	2517	2099	228	190
13-Feb-10	8371	7992	104	275

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
14-Feb-10	230	163	28	39
15-Feb-10	2457	2101	128	228
16-Feb-10	11230	10247	415	568
17-Feb-10	302	249	31	22
18-Feb-10	18213	17217	398	598
19-Feb-10	1613	1474	54	85
20-Feb-10	2249	2077	51	121
21-Feb-10	52070	46743	993	4334
22-Feb-10	125387	116260	2239	6888
23-Feb-10	9074	8163	238	673
24-Feb-10	26706	22808	644	3254
25-Feb-10	23800	23094	262	444
26-Feb-10	3350	2756	176	418
27-Feb-10	3706	3051	267	388
28-Feb-10	5988	5320	233	435
1-Mar-10	1831	1561	86	184
2-Mar-10	19144	16125	755	2264
3-Mar-10	60988	59553	454	981
4-Mar-10	1573	1335	84	154
5-Mar-10	1904	1617	102	185
6-Mar-10	2432	2140	78	214
7-Mar-10	2846	2220	113	513
8-Mar-10	34398	27539	882	5977

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
9-Mar-10	29036	24904	680	3452
10-Mar-10	69356	58915	2622	7819
11-Mar-10	152119	129137	7317	15665
12-Mar-10	103392	84407	4450	14535
13-Mar-10	64031	59806	1224	3001
14-Mar-10	21602	19979	472	1151
15-Mar-10	9656	8500	257	899
16-Mar-10	2461	2038	116	307
17-Mar-10	1938	1752	44	142
18-Mar-10	5885	5386	189	310
19-Mar-10	10611	9778	161	672
20-Mar-10	29637	25918	888	2831
21-Mar-10	34578	28129	1350	5099
22-Mar-10	66292	60396	1044	4852
23-Mar-10	31906	28734	397	2775
24-Mar-10	9396	7660	167	1569
25-Mar-10	92906	83696	1809	7401
26-Mar-10	25740	22141	1226	2373
27-Mar-10	13299	12713	118	468
28-Mar-10	136772	124153	3419	9200
29-Mar-10	89625	78465	2178	8982
30-Mar-10	25270	24283	182	805
31-Mar-10	1200	1033	82	85

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
1-Apr-10	444	387	15	42
2-Apr-10	34869	30649	710	3510
3-Apr-10	40013	35179	926	3908
4-Apr-10	5179	4075	265	839
5-Apr-10	55957	45468	1639	8850
6-Apr-10	120393	100938	3342	16113
7-Apr-10	100402	84113	2606	13683
8-Apr-10	107456	90686	4430	12340
9-Apr-10	106744	97130	2469	7145
10-Apr-10	20517	19313	322	882
11-Apr-10	53100	45665	1504	5931
12-Apr-10	76634	66066	2041	8527
13-Apr-10	102106	82056	2862	17188
14-Apr-10	74866	63004	1771	10091
15-Apr-10	70810	59210	2562	9038
16-Apr-10	80796	75309	916	4571
17-Apr-10	83187	77456	1145	4586
18-Apr-10	45333	41687	696	2950
19-Apr-10	29750	25005	1088	3657
20-Apr-10	23741	19566	870	3305
21-Apr-10	50748	42472	1464	6812
22-Apr-10	128284	114070	2492	11722
23-Apr-10	154977	138892	2835	13250

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
24-Apr-10	279753	254296	6893	18564
25-Apr-10	175382	147550	5685	22147
26-Apr-10	271967	257287	3218	11462
27-Apr-10	104541	100123	866	3552
28-Apr-10	30890	28119	583	2188
29-Apr-10	37106	35851	256	999
30-Apr-10	157478	138582	4032	14864
1-May-10	409192	381917	7379	19896
2-May-10	189285	169222	3928	16135
3-May-10	110447	90326	3931	16190
4-May-10	30816	22432	1530	6854
5-May-10	58868	41592	4375	12901
6-May-10	104318	79210	6158	18950
7-May-10	119504	103313	3598	12593
8-May-10	132076	108200	5221	18655
9-May-10	87289	79668	2272	5349
10-May-10	128365	117043	2391	8931
11-May-10	62378	52333	2331	7714
12-May-10	339263	314232	3650	21381
13-May-10	329723	297386	4980	27357
14-May-10	308417	282704	5616	20097
15-May-10	273326	255251	3657	14418
16-May-10	312044	281811	4772	25461

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
17-May-10	194619	168915	4481	21223
18-May-10	261406	237124	3379	20903
19-May-10	202227	181956	3932	16339
20-May-10	266860	244509	4135	18216
21-May-10	182529	161213	3909	17407
22-May-10	102724	89134	3487	10103
23-May-10	167255	140781	3925	22549
24-May-10	387994	316728	14904	56362
25-May-10	548593	490150	10371	48072
26-May-10	346436	313599	5666	27171
27-May-10	288625	257440	5638	25547
28-May-10	324542	287710	6677	30155
29-May-10	368989	312850	12522	43617
30-May-10	279666	249339	7073	23254
31-May-10	445371	406050	5823	33498
1-Jun-10	305258	274321	5933	25004
2-Jun-10	490917	445257	6959	38701
3-Jun-10	496040	466387	4673	24980
4-Jun-10	361464	338119	2659	20686
5-Jun-10	420624	389157	5615	25852
6-Jun-10	291279	253062	4843	33374
7-Jun-10	355697	305396	8186	42115
8-Jun-10	434792	394367	8098	32327

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
9-Jun-10	443542	410278	4798	28466
10-Jun-10	292822	263475	5951	23396
11-Jun-10	367819	328521	8683	30615
12-Jun-10	453708	415593	8330	29785
13-Jun-10	434578	386366	6178	42034
14-Jun-10	401529	361528	5763	34238
15-Jun-10	402946	370591	4838	27517
16-Jun-10	384882	351665	5076	28141
17-Jun-10	504172	442302	13136	48734
18-Jun-10	367834	336249	5137	26448
19-Jun-10	477407	445096	5683	26628
20-Jun-10	455755	409843	6782	39130
21-Jun-10	626745	568123	9212	49410
22-Jun-10	532361	477502	9769	45090
23-Jun-10	667959	615614	8656	43689
24-Jun-10	480541	430705	7131	42705
25-Jun-10	394657	360529	6015	28113
26-Jun-10	499721	456653	8704	34364
27-Jun-10	597957	542303	11360	44294
28-Jun-10	386067	357258	4355	24454
29-Jun-10	242347	224410	2418	15519
30-Jun-10	283255	249764	4995	28496
1-Jul-10	256514	224125	4606	27783

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
2-Jul-10	429600	359643	8624	61333
3-Jul-10	349804	300060	8373	41371
4-Jul-10	229729	203862	4823	21044
5-Jul-10	132675	117689	2590	12396
6-Jul-10	139920	125990	2271	11659
7-Jul-10	219820	194847	4228	20745
8-Jul-10	263358	242181	3211	17966
9-Jul-10	311968	295330	3402	13236
10-Jul-10	303835	284906	3680	15249
11-Jul-10	465861	421079	6994	37788
12-Jul-10	466002	420875	7469	37658
13-Jul-10	458609	404489	7498	46622
14-Jul-10	550586	473692	13626	63268
15-Jul-10	655577	596186	7689	51702
16-Jul-10	433539	409905	4048	19586
17-Jul-10	533226	483843	8892	40491
18-Jul-10	696943	637968	9512	49463
19-Jul-10	645045	577767	9355	57923
20-Jul-10	632534	587873	7828	36833
21-Jul-10	643023	590549	8487	43987
22-Jul-10	503986	454155	8251	41580
23-Jul-10	472189	423447	7935	40807
24-Jul-10	568138	514194	9176	44768

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
25-Jul-10	403678	369708	4396	29574
26-Jul-10	461438	429056	4011	28371
27-Jul-10	625851	551585	13063	61203
28-Jul-10	463658	417757	6809	39092
29-Jul-10	491952	448753	5506	37693
30-Jul-10	482587	442369	5658	34560
31-Jul-10	415206	372153	6361	36692
1-Aug-10	481326	431434	6911	42981
2-Aug-10	448556	400332	6026	42198
3-Aug-10	538404	483411	7899	47094
4-Aug-10	667325	608002	8492	50831
5-Aug-10	733648	690514	6515	36619
6-Aug-10	389421	370857	3543	15021
7-Aug-10	389253	362672	3870	22711
8-Aug-10	408030	354923	6327	46780
9-Aug-10	565690	525885	5340	34465
10-Aug-10	496641	442470	8327	45844
11-Aug-10	454219	417735	4829	31655
12-Aug-10	483383	442255	5665	35463
13-Aug-10	462914	421796	6307	34811
14-Aug-10	355122	338014	2403	14705
15-Aug-10	413693	386953	3386	23354
16-Aug-10	443929	408436	5294	30199

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
17-Aug-10	268700	244985	3530	20185
18-Aug-10	299075	267868	3583	27624
19-Aug-10	348802	322421	3494	22887
20-Aug-10	454502	415668	5339	33495
21-Aug-10	318093	298822	2928	16343
22-Aug-10	267695	251783	1686	14226
23-Aug-10	296372	280362	2122	13888
24-Aug-10	330639	308811	2879	18949
25-Aug-10	189252	175388	1673	12191
26-Aug-10	216362	206987	1045	8330
27-Aug-10	184547	175239	1271	8037
28-Aug-10	177597	164302	1743	11552
29-Aug-10	173168	161181	1567	10420
30-Aug-10	233751	211698	3135	18918
31-Aug-10	229339	212206	2235	14898
1-Sep-10	226988	205434	3579	17975
2-Sep-10	257150	230149	3585	23416
3-Sep-10	215159	196740	2978	15441
4-Sep-10	165979	160489	770	4720
5-Sep-10	190382	179685	1817	8880
6-Sep-10	226597	211538	2615	12444
7-Sep-10	183510	168175	2501	12834
8-Sep-10	160294	142406	2963	14925

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
9-Sep-10	176527	163323	1808	11396
10-Sep-10	125371	114159	1860	9352
11-Sep-10	151859	144775	1493	5591
12-Sep-10	130234	120914	1156	8164
13-Sep-10	152115	141382	1605	9128
14-Sep-10	190690	176242	2203	12245
15-Sep-10	309200	283328	3971	21901
16-Sep-10	244010	221598	3005	19407
17-Sep-10	164202	156385	1436	6381
18-Sep-10	130713	120303	2030	8380
19-Sep-10	219891	209447	1756	8688
20-Sep-10	79139	74849	704	3586
21-Sep-10	206484	184591	4496	17397
22-Sep-10	23828	21172	322	2334
23-Sep-10	0	0	0	0
24-Sep-10	0	0	0	0
25-Sep-10	0	0	0	0
26-Sep-10	0	0	0	0
27-Sep-10	52138	48772	607	2759
28-Sep-10	140164	133200	1242	5722
29-Sep-10	32883	30088	461	2334
30-Sep-10	17513	16572	200	741
1-Oct-10	31344	30352	203	789

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
2-Oct-10	45108	42686	375	2047
3-Oct-10	76416	69391	1055	5970
4-Oct-10	106152	94234	2060	9858
5-Oct-10	95750	87090	1298	7362
6-Oct-10	83235	74513	1565	7157
7-Oct-10	41037	36138	932	3967
8-Oct-10	29031	26870	690	1471
9-Oct-10	12177	10554	602	1021
10-Oct-10	20076	17482	364	2230
11-Oct-10	104567	97289	1065	6213
12-Oct-10	142303	133919	1399	6985
13-Oct-10	91976	85989	1025	4962
14-Oct-10	55171	52091	514	2566
15-Oct-10	34509	33166	367	976
16-Oct-10	16442	15595	226	621
17-Oct-10	24147	22218	288	1641
18-Oct-10	31637	29373	273	1991
19-Oct-10	117257	111454	1117	4686
20-Oct-10	99595	92727	970	5898
21-Oct-10	175390	156580	2636	16174
22-Oct-10	93808	81964	1578	10266
23-Oct-10	90994	81388	1742	7864
24-Oct-10	57420	50672	1323	5425

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
25-Oct-10	181464	162561	3352	15551
26-Oct-10	81578	76267	1017	4294
27-Oct-10	31779	29335	341	2103
28-Oct-10	97607	91088	953	5566
29-Oct-10	37835	36712	255	868
30-Oct-10	4796	4624	45	127
31-Oct-10	1852	1714	35	103
1-Nov-10	14706	13969	102	635
2-Nov-10	164195	158332	1158	4705
3-Nov-10	45052	43209	332	1511
4-Nov-10	45299	42438	617	2244
5-Nov-10	9135	8876	77	182
6-Nov-10	3339	3147	92	100
7-Nov-10	1979	1892	22	65
8-Nov-10	280	169	13	98
9-Nov-10	568	518	32	18
10-Nov-10	689	572	30	87
11-Nov-10	473	307	19	147
12-Nov-10	26068	23149	711	2208
13-Nov-10	1698	1432	76	190
14-Nov-10	19	16	3	0
15-Nov-10	5339	4767	128	444
16-Nov-10	30437	28745	472	1220

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
17-Nov-10	6059	5330	174	555
18-Nov-10	7351	6946	97	308
19-Nov-10	452	417	19	16
20-Nov-10	437	358	46	33
21-Nov-10	666	420	103	143
22-Nov-10	10893	7449	507	2937
23-Nov-10	15587	12346	1030	2211
24-Nov-10	4340	3399	297	644
25-Nov-10	10735	8763	673	1299
26-Nov-10	64	47	13	4
27-Nov-10	192	178	3	11
28-Nov-10	36	32	2	2
29-Nov-10	6851	5955	282	614
30-Nov-10	31707	29614	575	1518
1-Dec-10	1412	1253	34	125
2-Dec-10	86	80	2	4
3-Dec-10	1205	1178	6	21
4-Dec-10	3606	3465	51	90
5-Dec-10	10679	10391	96	192
6-Dec-10	676	615	25	36
7-Dec-10	2036	1881	69	86
8-Dec-10	4372	3551	262	559
9-Dec-10	1226	1101	51	74

Dates	Total Strokes	Negative	Positive	Cloud-to-cloud
10-Dec-10	618	556	17	45
11-Dec-10	1924	1588	146	190
12-Dec-10	4528	4015	246	267
13-Dec-10	22821	21768	521	532
14-Dec-10	2920	2529	243	148
15-Dec-10	164	125	9	30
16-Dec-10	183	165	7	11
17-Dec-10	88	78	4	6
18-Dec-10	5240	4851	174	215
19-Dec-10	5317	5048	125	144
20-Dec-10	4300	3978	165	157
21-Dec-10	1316	969	195	152
22-Dec-10	130	97	17	16
23-Dec-10	300	232	10	58
24-Dec-10	7438	5478	397	1563
25-Dec-10	4990	4550	98	342
26-Dec-10	2990	2552	171	267
27-Dec-10	523	441	39	43
28-Dec-10	224	218	3	3
29-Dec-10	8542	7331	218	993
30-Dec-10	22830	21722	246	862
31-Dec-10	51326	47455	1022	2849

Appendix A3 2011 Lightning Data – CONUS Sums
Color-coding indicates the relative rank of the date within the calendar year, from green (low events), through yellow and orange, to red (high events).

Date	Total	Negative	Positive	Cloud-to-cloud
1-Jan-11	0	0	0	0
2-Jan-11	0	0	0	0
3-Jan-11	0	0	0	0
4-Jan-11	0	0	0	0
5-Jan-11	0	0	0	0
6-Jan-11	12464	12062	166	236
7-Jan-11	50310	49433	293	584
8-Jan-11	1847	1536	134	177
9-Jan-11	39077	33921	1223	3933
10-Jan-11	14969	13511	381	1077
11-Jan-11	8179	8033	53	93
12-Jan-11	7089	6863	85	141
13-Jan-11	216	161	32	23
14-Jan-11	416	412	1	3
15-Jan-11	151	147	2	2
16-Jan-11	2477	1908	142	427
17-Jan-11	35849	32146	1424	2279
18-Jan-11	18171	17471	264	436
19-Jan-11	7745	7493	104	148
20-Jan-11	3613	3376	111	126
21-Jan-11	43098	39331	1510	2257

Date	Total	Negative	Positive	Cloud-to-cloud
22-Jan-11	3395	3198	102	95
23-Jan-11	9983	9808	103	72
24-Jan-11	2031	1709	53	269
25-Jan-11	109673	104076	2084	3513
26-Jan-11	54312	50401	1671	2240
27-Jan-11	19406	18627	457	322
28-Jan-11	5052	4954	62	36
29-Jan-11	3659	3453	106	100
30-Jan-11	6900	5800	223	877
31-Jan-11	14781	13775	220	786
1-Feb-11	42271	36238	1541	4492
2-Feb-11	44903	39916	1141	3846
3-Feb-11	14320	11828	508	1984
4-Feb-11	5529	4823	249	457
5-Feb-11	1680	1429	79	172
6-Feb-11	5867	5202	229	436
7-Feb-11	11736	10376	399	961
8-Feb-11	898	817	43	38
9-Feb-11	3	3	0	0
10-Feb-11	10586	9780	202	604
11-Feb-11	656	624	15	17
12-Feb-11	476	448	17	11
13-Feb-11	110	101	0	9

Date	Total	Negative	Positive	Cloud-to-cloud
14-Feb-11	143	107	20	16
15-Feb-11	1189	940	123	126
16-Feb-11	352	272	19	61
17-Feb-11	1033	742	75	216
18-Feb-11	198	136	42	20
19-Feb-11	3388	2878	185	325
20-Feb-11	28649	25068	942	2639
21-Feb-11	965	672	36	257
22-Feb-11	51	47	0	4
23-Feb-11	718	519	20	179
24-Feb-11	43241	36863	1840	4538
25-Feb-11	14819	12869	767	1183
26-Feb-11	3848	3628	108	112
27-Feb-11	12958	10003	476	2479
28-Feb-11	156920	132143	5759	19018
1-Mar-11	41872	37828	1080	2964
2-Mar-11	1889	1825	29	35
3-Mar-11	3018	2647	85	286
4-Mar-11	12945	11437	438	1070
5-Mar-11	175347	163798	2654	8895
6-Mar-11	35506	31968	932	2606
7-Mar-11	29465	27109	569	1787
8-Mar-11	34543	31436	723	2384

Date	Total	Negative	Positive	Cloud-to-cloud
9-Mar-11	235981	218762	3852	13367
10-Mar-11	169111	159000	3136	6975
11-Mar-11	2565	2293	129	143
12-Mar-11	43	26	12	5
13-Mar-11	3179	2709	220	250
14-Mar-11	71673	64757	1723	5193
15-Mar-11	11324	9999	434	891
16-Mar-11	12993	12022	287	684
17-Mar-11	45945	43302	697	1946
18-Mar-11	6124	5037	312	775
19-Mar-11	55440	50360	1025	4055
20-Mar-11	45570	37695	1637	6238
21-Mar-11	44440	36104	1435	6901
22-Mar-11	63422	54132	1793	7497
23-Mar-11	48707	37759	1811	9137
24-Mar-11	40413	37022	897	2494
25-Mar-11	8529	7684	233	612
26-Mar-11	0	0	0	0
27-Mar-11	0	0	0	0
28-Mar-11	37873	34046	682	3145
29-Mar-11	58654	51067	862	6725
30-Mar-11	320875	301365	5115	14395
31-Mar-11	174132	159307	3490	11335

Date	Total	Negative	Positive	Cloud-to-cloud
1-Apr-11	52367	48756	1161	2450
2-Apr-11	20218	19252	398	568
3-Apr-11	21997	19537	553	1907
4-Apr-11	267229	234552	6624	26053
5-Apr-11	264818	253843	2893	8082
6-Apr-11	12418	11752	275	391
7-Apr-11	3779	3164	121	494
8-Apr-11	14656	12620	482	1554
9-Apr-11	212872	192435	4176	16261
10-Apr-11	151342	117173	5816	28353
11-Apr-11	184961	154929	5820	24212
12-Apr-11	33637	30059	694	2884
13-Apr-11	76706	71688	1221	3797
14-Apr-11	21030	17046	981	3003
15-Apr-11	202522	186856	2990	12676
16-Apr-11	98175	84464	1555	12156
17-Apr-11	103074	99182	796	3096
18-Apr-11	50796	49527	324	945
19-Apr-11	126765	105127	3464	18174
20-Apr-11	264783	233703	4616	26464
21-Apr-11	213806	194834	2980	15992
22-Apr-11	146431	125282	3625	17524
23-Apr-11	225020	202131	5289	17600

Date	Total	Negative	Positive	Cloud-to-cloud
24-Apr-11	217197	190144	3863	23190
25-Apr-11	264050	241770	3589	18691
26-Apr-11	330913	302608	4939	23366
27-Apr-11	377272	352163	5251	19858
28-Apr-11	295401	267801	5501	22099
29-Apr-11	199193	190379	2692	6122
30-Apr-11	34149	30520	974	2655
1-May-11	221695	200497	2389	18809
2-May-11	75219	64461	1616	9142
3-May-11	23186	21312	442	1432
4-May-11	39333	36448	549	2336
5-May-11	15006	13783	279	944
6-May-11	18543	13388	1143	4012
7-May-11	69456	63533	1612	4311
8-May-11	30198	26869	789	2540
9-May-11	117855	100569	4816	12470
10-May-11	143063	114417	3316	25330
11-May-11	390715	327377	10175	53163
12-May-11	284053	227127	6863	50063
13-May-11	242481	214549	5816	22116
14-May-11	247400	222397	5303	19700
15-May-11	146125	127607	5515	13003
16-May-11	119990	116386	1186	2418

Date	Total	Negative	Positive	Cloud-to-cloud
17-May-11	185677	181132	1108	3437
18-May-11	180511	170115	2047	8349
19-May-11	135515	119288	3251	12976
20-May-11	359834	327205	6456	26173
21-May-11	195561	180914	3169	11478
22-May-11	195852	163922	5668	26262
23-May-11	285233	251205	6353	27675
24-May-11	241074	210506	6448	24120
25-May-11	337540	304994	5370	27176
26-May-11	300218	266287	4702	29229
27-May-11	213341	190092	5168	18081
28-May-11	159884	139969	3489	16426
29-May-11	170506	146060	2783	21663
30-May-11	198910	170896	5866	22148
31-May-11	181845	153296	6599	21950
1-Jun-11	310401	260345	7211	42845
2-Jun-11	313025	266704	8428	37893
3-Jun-11	174006	146659	6167	21180
4-Jun-11	204872	161518	6830	36524
5-Jun-11	254192	220178	3653	30361
6-Jun-11	177532	163208	2311	12013
7-Jun-11	340436	279290	8378	52768
8-Jun-11	252440	216375	6077	29988

Date	Total	Negative	Positive	Cloud-to-cloud
9-Jun-11	373190	323733	7958	41499
10-Jun-11	234433	214788	2949	16696
11-Jun-11	265894	241936	3901	20057
12-Jun-11	224543	202801	4140	17602
13-Jun-11	237259	212372	5073	19814
14-Jun-11	306799	268593	5121	33085
15-Jun-11	346737	318745	4520	23472
16-Jun-11	335085	307615	4966	22504
17-Jun-11	380233	353724	6881	19628
18-Jun-11	404801	370931	5947	27923
19-Jun-11	423404	392583	4022	26799
20-Jun-11	409527	367271	6117	36139
21-Jun-11	461682	409498	6713	45471
22-Jun-11	446383	404176	6414	35793
23-Jun-11	295267	265724	5130	24413
24-Jun-11	424443	392676	5810	25957
25-Jun-11	474095	436442	8229	29424
26-Jun-11	500255	455927	8284	36044
27-Jun-11	447195	419489	4746	22960
28-Jun-11	374219	344344	4354	25521
29-Jun-11	265908	236414	5023	24471
30-Jun-11	118139	93670	1908	22561
1-Jul-11	290671	257358	5919	27394

Date	Total	Negative	Positive	Cloud-to-cloud
2-Jul-11	285876	245678	7469	32729
3-Jul-11	467138	415686	7584	43868
4-Jul-11	492461	437332	8374	46755
5-Jul-11	426713	387382	9891	29440
6-Jul-11	442436	405862	6046	30528
7-Jul-11	335271	309454	4072	21745
8-Jul-11	358450	330951	4921	22578
9-Jul-11	290318	266777	4174	19367
10-Jul-11	324060	294299	5910	23851
11-Jul-11	549893	502804	7320	39769
12-Jul-11	492524	448176	7270	37078
13-Jul-11	471567	425750	5663	40154
14-Jul-11	491022	445633	5611	39778
15-Jul-11	464174	398692	13231	52251
16-Jul-11	290815	264642	5136	21037
17-Jul-11	415485	359749	11480	44256
18-Jul-11	495473	436874	9511	49088
19-Jul-11	360837	314249	6378	40210
20-Jul-11	533940	443256	11535	79149
21-Jul-11	323040	299706	3874	19460
22-Jul-11	527983	469078	11141	47764
23-Jul-11	563429	509025	11204	43200
24-Jul-11	456504	419102	5495	31907

Date	Total	Negative	Positive	Cloud-to-cloud
25-Jul-11	459707	424061	6111	29535
26-Jul-11	473062	425713	9008	38341
27-Jul-11	372023	341926	5311	24786
28-Jul-11	457659	417605	5888	34166
29-Jul-11	474905	435264	5036	34605
30-Jul-11	426937	385462	7394	34081
31-Jul-11	420070	386546	9096	24428
1-Aug-11	640343	544509	18239	77595
2-Aug-11	456798	406413	9507	40878
3-Aug-11	470470	430426	5421	34623
4-Aug-11	570976	539066	5560	26350
5-Aug-11	571437	533123	5461	32853
6-Aug-11	405482	372216	4873	28393
7-Aug-11	472032	432239	5781	34012
8-Aug-11	522768	486788	6409	29571
9-Aug-11	421867	391338	4247	26282
10-Aug-11	415330	380548	4985	29797
11-Aug-11	484248	441046	7009	36193
12-Aug-11	448264	406074	9187	33003
13-Aug-11	455953	427254	5574	23125
14-Aug-11	350295	324156	4657	21482
15-Aug-11	339637	305028	6795	27814
16-Aug-11	365064	329143	7343	28578

Date	Total	Negative	Positive	Cloud-to-cloud
17-Aug-11	289224	269976	4610	14638
18-Aug-11	428672	398324	5022	25326
19-Aug-11	543752	504171	8647	30934
20-Aug-11	427311	394413	8144	24754
21-Aug-11	443638	415173	4844	23621
22-Aug-11	413707	389700	4371	19636
23-Aug-11	512848	471764	9761	31323
24-Aug-11	478124	444024	4760	29340
25-Aug-11	496114	458679	4493	32942
26-Aug-11	230152	218321	2588	9243
27-Aug-11	267257	245461	5871	15925
28-Aug-11	318261	289018	7019	22224
29-Aug-11	328768	302752	6874	19142
30-Aug-11	340754	316498	4420	19836
31-Aug-11	183600	167717	2233	13650
1-Sep-11	374287	331611	9596	33080
2-Sep-11	334841	314288	4774	15779
3-Sep-11	375454	345242	3617	26595
4-Sep-11	421010	390640	4180	26190
5-Sep-11	181674	169834	1493	10347
6-Sep-11	147331	141418	801	5112
7-Sep-11	163820	157327	882	5611
8-Sep-11	72834	68188	801	3845

Date	Total	Negative	Positive	Cloud-to-cloud
9-Sep-11	144829	138698	818	5313
10-Sep-11	152305	145484	991	5830
11-Sep-11	189381	175950	1577	11854
12-Sep-11	196459	184250	1692	10517
13-Sep-11	182661	165530	2289	14842
14-Sep-11	219039	197457	3345	18237
15-Sep-11	209638	194105	2212	13321
16-Sep-11	177911	167751	2084	8076
17-Sep-11	248627	232058	2528	14041
18-Sep-11	227477	204586	2798	20093
19-Sep-11	185683	174207	1962	9514
20-Sep-11	114292	109507	892	3893
21-Sep-11	171562	161596	1249	8717
22-Sep-11	231858	217336	2015	12507
23-Sep-11	82413	78199	841	3373
24-Sep-11	87895	85577	571	1747
25-Sep-11	133051	125950	1423	5678
26-Sep-11	203727	187672	2014	14041
27-Sep-11	193089	181135	1744	10210
28-Sep-11	230077	219488	1442	9147
29-Sep-11	271209	257241	1924	12044
30-Sep-11	178703	172764	1151	4788
1-Oct-11	116036	111694	1065	3277

Date	Total	Negative	Positive	Cloud-to-cloud
2-Oct-11	106968	102952	1058	2958
3-Oct-11	74293	70423	644	3226
4-Oct-11	83463	77614	835	5014
5-Oct-11	69905	63520	922	5463
6-Oct-11	25780	23082	366	2332
7-Oct-11	77881	69414	1174	7293
8-Oct-11	164950	147819	3740	13391
9-Oct-11	129409	113509	2662	13238
10-Oct-11	42213	40344	458	1411
11-Oct-11	31738	30327	382	1029
12-Oct-11	121451	106457	2936	12058
13-Oct-11	93654	86854	1187	5613
14-Oct-11	44117	41338	875	1904
15-Oct-11	13231	12501	350	380
16-Oct-11	15184	13872	387	925
17-Oct-11	17651	16568	296	787
18-Oct-11	119216	111232	2016	5968
19-Oct-11	87449	81202	1642	4605
20-Oct-11	24325	21793	552	1980
21-Oct-11	7491	7210	160	121
22-Oct-11	31323	30281	221	821
23-Oct-11	117198	109490	1996	5712
24-Oct-11	30310	27541	734	2035

Date	Total	Negative	Positive	Cloud-to-cloud
25-Oct-11	18668	17058	338	1272
26-Oct-11	31847	27010	732	4105
27-Oct-11	16035	13610	451	1974
28-Oct-11	43430	42187	483	760
29-Oct-11	30602	29643	539	420
30-Oct-11	15860	15473	290	97
31-Oct-11	33464	32625	558	281
1-Nov-11	17488	17112	258	118
2-Nov-11	8289	7441	143	705
3-Nov-11	3258	3080	98	80
4-Nov-11	3254	2958	80	216
5-Nov-11	16907	15478	461	968
6-Nov-11	1495	1431	20	44
7-Nov-11	86893	75090	1594	10209
8-Nov-11	213254	186657	3893	22704
9-Nov-11	81586	76308	1354	3924
10-Nov-11	5674	5393	111	170
11-Nov-11	3041	2896	70	75
12-Nov-11	474	467	2	5
13-Nov-11	1239	1069	6	164
14-Nov-11	27395	19505	610	7280
15-Nov-11	102983	88284	1396	13303
16-Nov-11	80654	73012	1331	6311

Date	Total	Negative	Positive	Cloud-to-cloud
17-Nov-11	101090	93509	2391	5190
18-Nov-11	2325	2057	87	181
19-Nov-11	2054	1906	106	42
20-Nov-11	7687	7067	171	449
21-Nov-11	147704	131755	2625	13324
22-Nov-11	116818	105831	2057	8930
23-Nov-11	26146	23938	674	1534
24-Nov-11	7711	7322	166	223
25-Nov-11	4740	4210	76	454
26-Nov-11	6804	5977	81	746
27-Nov-11	6536	5976	249	311
28-Nov-11	97	87	7	3
29-Nov-11	85	78	1	6
30-Nov-11	269	235	20	14
1-Dec-11	106	72	1	33
2-Dec-11	346	330	1	15
3-Dec-11	17211	14496	579	2136
4-Dec-11	5471	4117	123	1231
5-Dec-11	17573	14261	436	2876
6-Dec-11	690	602	13	75
7-Dec-11	58	53	2	3
8-Dec-11	266	265	1	0
9-Dec-11	157	154	1	2

Date	Total	Negative	Positive	Cloud-to-cloud
10-Dec-11	794	712	37	45
11-Dec-11	610	514	45	51
12-Dec-11	2522	2175	118	229
13-Dec-11	6498	6286	66	146
14-Dec-11	18341	16345	221	1775
15-Dec-11	27000	24331	483	2186
16-Dec-11	6150	5495	176	479
17-Dec-11	1604	1509	19	76
18-Dec-11	2712	2452	24	236
19-Dec-11	12110	10030	273	1807
20-Dec-11	26848	23922	426	2500
21-Dec-11	23914	22267	394	1253
22-Dec-11	48530	43600	964	3966
23-Dec-11	5652	5201	124	327
24-Dec-11	1289	1223	23	43
25-Dec-11	2084	1911	43	130
26-Dec-11	4409	3780	190	439
27-Dec-11	7960	7350	212	398
28-Dec-11	14962	13874	645	443
29-Dec-11	631	523	8	100
30-Dec-11	2231	2051	74	106
31-Dec-11	4940	4468	221	251