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DEVELOPING METHODS TO NOWCAST TOTAL LIGHTNING FLASH RATES AND CONVECTIVE INITIATION USING SATELLITE INFRARED CONVECTIVE CLOUD INFORMATION

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1 INTRODUCTION

Proven 0-1 hour forecasts of convective initiation (CI) using operational GOES satellites are expanding toward predictions of lightning. For this study, CI is defined as the first occurrence of a ≥35 dBZ radar echo from convective clouds (see Roberts and Rutledge 2003). Beyond providing 0-1 hour forecasts of the first occurrences of ≥35 dBZ echoes/thunderstorms, a method that addresses first lightning initiation (LI) is under development. Monitoring the Lagrangian evolution of 1 km-resolution cumulus as they grow, glaciate, precipitate and produce lightning exemplifies the unique aspects of this research. We subsequently combine in one framework National Weather Service (NWS) WSR-88D radar, GOES 1 km visible and 4-8 km infrared data, and "total lightning" (in-cloud, cloud-to-ground, cloud-to-air) from the NASA Marshall Space Flight Center's (MSFC) North Alabama Lightning Mapping Array (LMA). [‡]

With the advent of the LMA, total lightning activity may be measured over Northern Alabama and surrounding regions. The LMA, consisting of an array of 10 ground-based detectors, is capable of mapping lightning in 3-dimensions at 1/80th second frequencies. It provides a wealth of unique information, complementing cloud-to-ground flash data gathered by the United States National Lightning Detection Network (NLDN) (see Koshak et al. 2004; Goodman et al. 2004).

To date, few studies address the real-time prediction of lightning from satellite-based instruments (e.g., Mazany et al. 2002). A number of studies, capitalizing on the Lightning Imaging Sensor (LIS) on the TRMM satellite, relate satellite-infrared and microphysical structures to lightning within convective clouds (Goodman et al. 1988; Rosenfeld and Woodley 2003). In contrast, several studies have been carried out toward correlating convective storm behavior and morphology to cloud-to-ground flashes (e.g., Livingston et al. 1996). With respect to "total lightning" however, few studies have yet been undertaken toward relating total lightning characteristics of convective storms to radar, with fewer still involving satellite information (D. Buechler, personal communications). Using remote sensing to predict first lightning (i.e. the nature of lightning events) prior to storm development has obvious benefits to many sectors of society. Farmers, pilots, utility workers, and outdoor enthusiasts stand to gain critical lead-time warnings of lightning as a result of this research. The plan is to operate a real-time CI and LI/lightning intensity nowcasting algorithm for the continental U.S. to support NWS and aviation weather forecasting.

With respect to total lightning, the relationships between lightning, radar echoes, and satellite-observed clouds are poorly understood. It is known however that charge separation is related to freezing altitude and cloud depth below 0° C. Updraft width and strength likewise affects the mass of suspended graupel and ice hydrometeors. Developing and exploiting relationships between satellite-observed cumulus growth and known lightning behavior defines this projects goals (understanding that cumulus–lightning relationships vary significantly across convective regimes, e.g., Midlatitude, tropical, mountainous).

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2 BACKGROUND & DATA

In 2002, work began toward identifying the main signals of convective initiation (*the first occurrence of a ≥ 35 dBZ radar echo*) in GOES 1 km resolution visible and 4-8 km resolution infrared data. This research has culminated in 30-60 min nowcasts of convective initiation (CI) at the GOES visible resolution, 1 km, over this satellite's footprint (Mecikalski and Bedka 2004). For GOES-12, CI nowcasts covering the Eastern U. S. are occurring now at the UAH and UW-CIMSS: CI nowcasts are now available in realtime over the southeastern U. S. (see *http://biscayne.nsstc.uah.edu/~johnm/CI_home/* for the northern U.S. and Great Lakes region, and *http://nsstc.uah.edu/johnm/ci_studies.html* for the south-central and southeastern U.S.).

For the Mecikalski and Bedka algorithm, several aspects of the GOES data stream are important when satellite infrared–LMA lightning relationships are to be formed. GOES-12 data used for this study consists of 15-30 minute frequency visible and infrared data. Infrared data comes in three "broad band" channels: 6.5 μm, 10.7 μm and 13.3 μm. In particular, GOES-12 provides four "interest fields" of CI that are closely related to cloud growth, growth rates and characteristics (e.g., glaciation). They are the 10.7 μm infrared cloud-top brightness temperature (T_B), the local time-trend of 10.7 μm T_B [$\partial(10.7\mu m)/\partial t$], a glaciation indicator (13.3-10.7 μm, and its time rate of change), and a cloud-growth indicator (6.5-10.7 μm, and its time rate of change). A "cumulus cloud mask" is employed (Nair et al. 1998, 1999, 2005) by the Mecikalski and Bedka algorithm to delineate growing cumulus clouds from all other cloud types within GOES imagery, such that the algorithm can process all interest fields for only the 10-30% of CI-relevant pixels in an image. Typical GOES images used in this processing consist of 10^6 or more pixels.

This satellite information, when tracked in time via the Bedka and Mecikalski (2005) wind methodology, can be used as surrogate indicators of updraft strength within developing cumulus. A breadth of research shows that charge separation is related to several aspects of convective clouds, those being the relationship between the freezing altitude and suspension of graupel and ice, the distance of the freezing level above ground, and updraft velocities (MacGorman and Rust 1998). Updraft strength is invariably related to lightning flash characteristics because it affects the suspension of hydrometeors and the depth of cloud above the freezing level. Therefore, relationships between satellite-derived cloud growth information and known lightning sources, in space and time, will be exploited using the LMA as a testbed for this research.

The North Alabama LMA network locates the sources of impulsive VHF radio signals associated with charge neutralization in a lightning channel. Each of the network's 10 stations measure the time of arrival and magnitude of the peak lightning radiation signal ("source") in successive 80 μs intervals. Reconstructing this information in time and space yields a 3-dimensional map of a lightning channel (Goodman et al. 2004). Full resolution (80 μs interval) LMA data are not available during, or immediately after an event, but decimated data (peak signal within 500 μs intervals) are made available in real-time. This data was used for the current study. From the 3-dimensional data, lightning source densities are calculated over 5 min intervals by vertically integrating source counts into 1 km^2 horizontal bins.

For the 6 July 2004 case [Fig. 1(a-h)], a day possessing CI and good LMA data over N. Alabama and S. Tennessee, archive level II radar data from WSR-88D station KHTX (Huntsville, Alabama) were used. KHTX was operating in Volume Coverage Pattern (VCP) 11, where each 5 minute volume scan is comprised of 14 sweeps at elevation angles between 0.5 and 19.5. These data were transformed from radar space to Cartesian grid space by the NCAR REORDER software package, and data from the 3 km MSL (above mean sea level) grid level were chosen. This choice was made to strike a balance between using data at a height close to where CI first occurred, and avoiding possible bright band enhancement of radar reflectivity (the estimated environmental sounding freezing level is 4.5 km MSL). Additionally, only reflectivity values >10 dBZ were examined to reduce the impact of instrument noise and the appearance of spurious echoes in our analysis.

Once the GOES and LMA data sets were prepared as described above, they were remapped to the radar projection using the University of Wisconsin McIDAS software via nearest-neighbor interpolation. The radar data was assumed to have the correct Earth-relative navigation compared to the other datasets. In this way, all three data sets were in a common spatial framework, and at the resolution of the GOES visible data (1 km). The next step, to be able to more accurately co-locate the data sets, was to correct the GOES data for parallax error due to satellite viewing angle. This was accomplished using empirical relationships to cor-

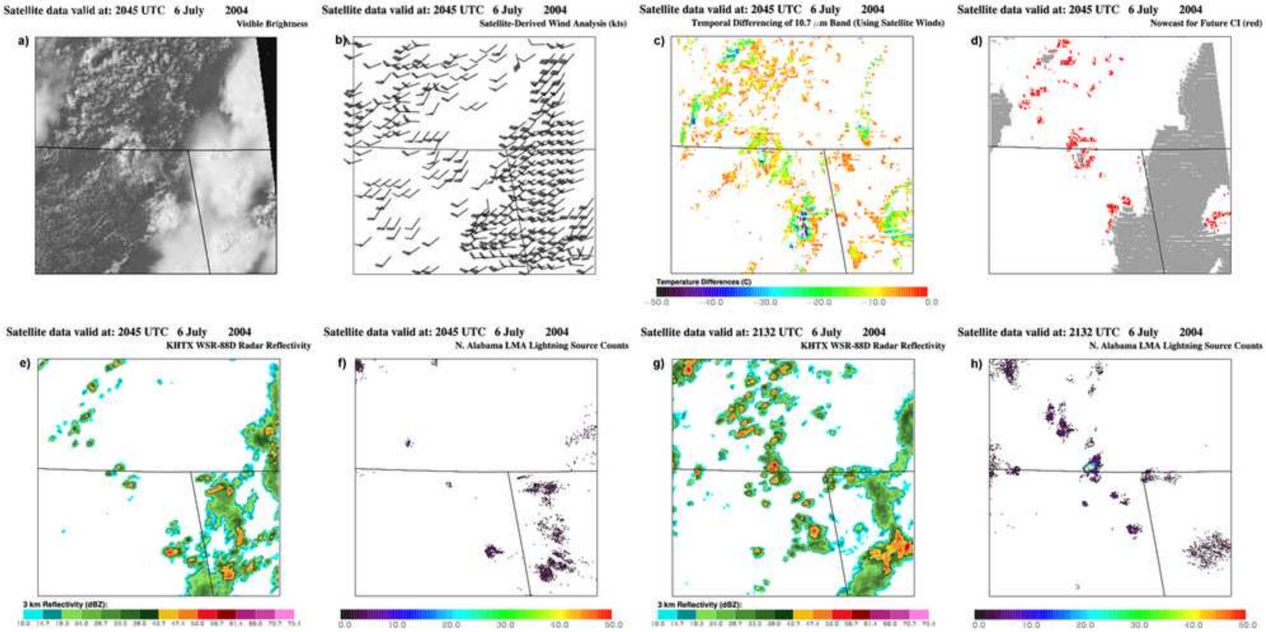

Figure 1: GOES visible imagery on 6 July 2004 (1a), cloud-motion tracking vectors (1b), infrared cloud-top cooling rates [$\partial(10.7\ \mu\text{m TB})/\partial t$] (1c), and a CI forecast made at 2045 UTC valid at ~2130 UTC (1d). Figures 1(e and g) and 1(f and h) show thunderstorm development ($\geq$35 dBZ echoes; 1e and 1g) and 5-minute lightning source density at 2045 UTC and the 2132 UTC valid time (1f and 1h). Compare Figs. 1d, 1g and h to assess current algorithm skill.

rect for view angle given the satellite's nadir longitude over the Equator. Without this common framework, there is no meaningful way of developing statistical correlations between radar echoes throughout a nearly vertical cumulonimbus, satellite infrared cloud-top observations, and lightning.

3 METHODOLOGY

Those aspects of the GOES data stream used to form satellite infrared–CI prediction are also applied toward forming satellite infrared–lightning relationships. Figure 1(a-h) demonstrates the CI–LI nowcasting methodology through coincident viewing of visible imagery (1a), cloud-motion tracking vectors (1b), cloud-top cooling rates $\partial(10.7\ \mu\mathrm{m})/\partial t$ (1c), and a CI forecast made at 2045 UTC valid at ~2130 UTC (1d). Figures 1(e and g) and 1(f and h) show thunderstorm development ($\geq$35 dBZ echoes) and 5-minute lightning source density numbers at 2045 UTC and the 2132 UTC valid time, demonstrating the algorithms initial capability.

The eventuality of this research at the UAH and UW-CIMSS, as depicted in Fig. 1, is toward *forecast first lightning* and *lightning intensity* in the 0-2 h timeframe. With all three datasets now in one coordinate system we can correlate GOES infrared signatures from the CI algorithm to radar reflectivity and co-located lighting information from the LMA (lightning source locations, source rates, lightning types), so that first lightning forecast may be made *based only on infrared cloud information.*

Figure 2 demonstrates, via a correlation plot between cloud-top cooling rates and lightning source density rates, the main satellite signal our lightning forecasting will based upon. The information used to create Fig. 2 is taken from those in Fig. 1. It is seen that robust cloud-top cooling rates [-10 C (30 min)$^{-1}$, found by monitoring $\partial(10.7\ \mu\mathrm{m}\ \mathrm{T}_B)/\partial t$], are correlated with large lightning increases. This research rests on the assumption that inferred satellite-cloud growth rates are related to parameters like updraft strength (in light of freezing level height) as found to be important for dictating lightning flash frequencies (see e.g., Stolzenburg 1996).

4 ONGOING RESEARCH

Extending the relationships seen preliminarily in Fig. 2, the plan is to develop LI and lightning event forecasts as 0-2 hour probability of occurrence maps. Henceforth, the main goals of this project over the coming 2-3 years are:

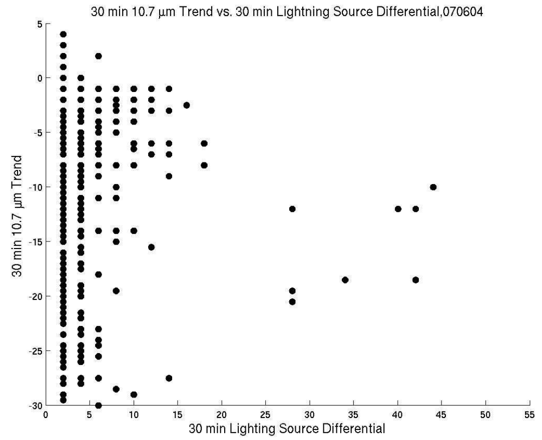

Figure 2: The relationship between past 30 min cooling rates and measured 30 min lightning source density enhancement. This figure shows that robust cloud-top cooling rates (i.e. -10 C (30 min)$^{-1}$ or greater as found by monitoring the 10.7 μm T_B) are correlated with large lightning increases.

1. Exploit the radar–CI–lightning software infrastructure to perform correlation analysis of CI (i.e. the first occurrence of a $\geq$35 dBZ radar echo) with respect to satellite infrared and total lightning information. This will be done, in particular, to assess the accuracy and confidence of the Mecikalski and Bedka (2005) algorithm and data processing methods;
2. Develop relationships between growing cumulus and eventual lightning from cumulus in a variety of atmospheric environments (Midlatitudes and Tropics);
3. Develop these relationships for lightning of different types (in-cloud and cloud-to-ground), and lightning flash rates, expanding this methodology to over ocean domains where geostationary satellite is a surrogate for radar.

With issues of GOES parallax nearly addressed, the use of multiple regression techniques are facilitated as a means of determining the relative importance of each infrared field for CI and lightning prediction from GOES, as well as to evaluate methodology skill. To begin, GOES-11 data from IHOP_2002 together with WSR-88D data over western Texas and Oklahoma are being processed so to develop such a regression relationship between CI and various Lagrangian-monitored infrared cloud properties. Using GOES-12 (Fig. 1) over North Alabama will allow us to consider development of regression relationships for both CI and lightning, incorporating the LMA information.

This statistical regression research is being done specifically to: 1) improve the level of understanding of forecast accuracy ("probability of detection" and "false alarm rates") within our current CI algorithm, 2) determine the relative importance of each GOES infrared field to CI, and 3) begin assessing our skill at LI forecasting. Flash (i.e. source density) rate predictions, and/or forecasts of significant lightning events, will follow. Interactions with the NWS Huntsville, Alabama Forecast Office, will assess how useful these CI and LI forecasts are to the NWS in general. We will seek their input toward improving the presentation and quality of this research. Another form of validation, toward gaining an improved physical understanding of how lightning initiation and trends change within clouds as measure by satellite, will involve collaboration with NASA MSFC scientists to use a lightning parameterization within a cloud-resolving model.

In addition to GOES cloud-top cooling rates $[\partial(10\mu\mathrm{m}\ \mathrm{T}_B)/\partial t]$ and glaciation information, we will begin looking at the value that data from the MODerate resolution Infrared Spectrometer (MODIS) instruments on Aqua and Terra may provide the CI and lightning research. For example, the 8.5 μm MODIS channel may have value-added information to what GOES provides for assessing cloud-top glaciation. In addition, the 1.6 μm reflectance values provides a direct indicator of cloud-top microphysics (during the daytime). The motivation to test with MODIS fields is that, once tested over the continental U.S. (over a variety of atmospheric conditions), we will extend the lightning predictions to other regions that the CI algorithm can be operated. These include areas covered by GOES (GOES-9–GOES-12; 100° E eastward to 30° W) and, in particular, the MeteoSat Next Generation (MSG) satellite over Europe. The MSG (a 12-channel 4 km-resolution geostationary instrument) possess a subset of channels as carried on MODIS (i.e. a pre-step to GOES-R in 2009).

A partial-global (~45° N–45° S) 0-1 h CI and 0-2 h lightning forecast procedure is the vision, especially as computational capabilities improve. Each step of this development will involve UAH Graduate students connecting to various end users who will benefit from this new research (e.g., the NWS, the aviation community). We expect to report on some of this CI validation and LI/lightning trend research via peer-reviewed publication shortly.

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