Lightning Nowcasting towards Quantified Lightning Warnings using Geostationary Satellite and NWP data

John Mecikalski[1]
Mathew Saari[1]
Lori Schultz[1]
Eugene McCaul[2]
Haig Iskendarian[3], Laura Bickmeier[3]

[1]*Atmospheric Science Department*
University of Alabama in Huntsville
Huntsville, AL

[2]*USRA/NASA Marshall Space Flight Center*
Huntsville, AL

[3]*MIT Lincoln Laboratory*
Lexington, MA

Supported by:

NASA Advance Satellite Aviation Weather Products (ASAP)
National Science Foundation
NASA SPoRT

Outline

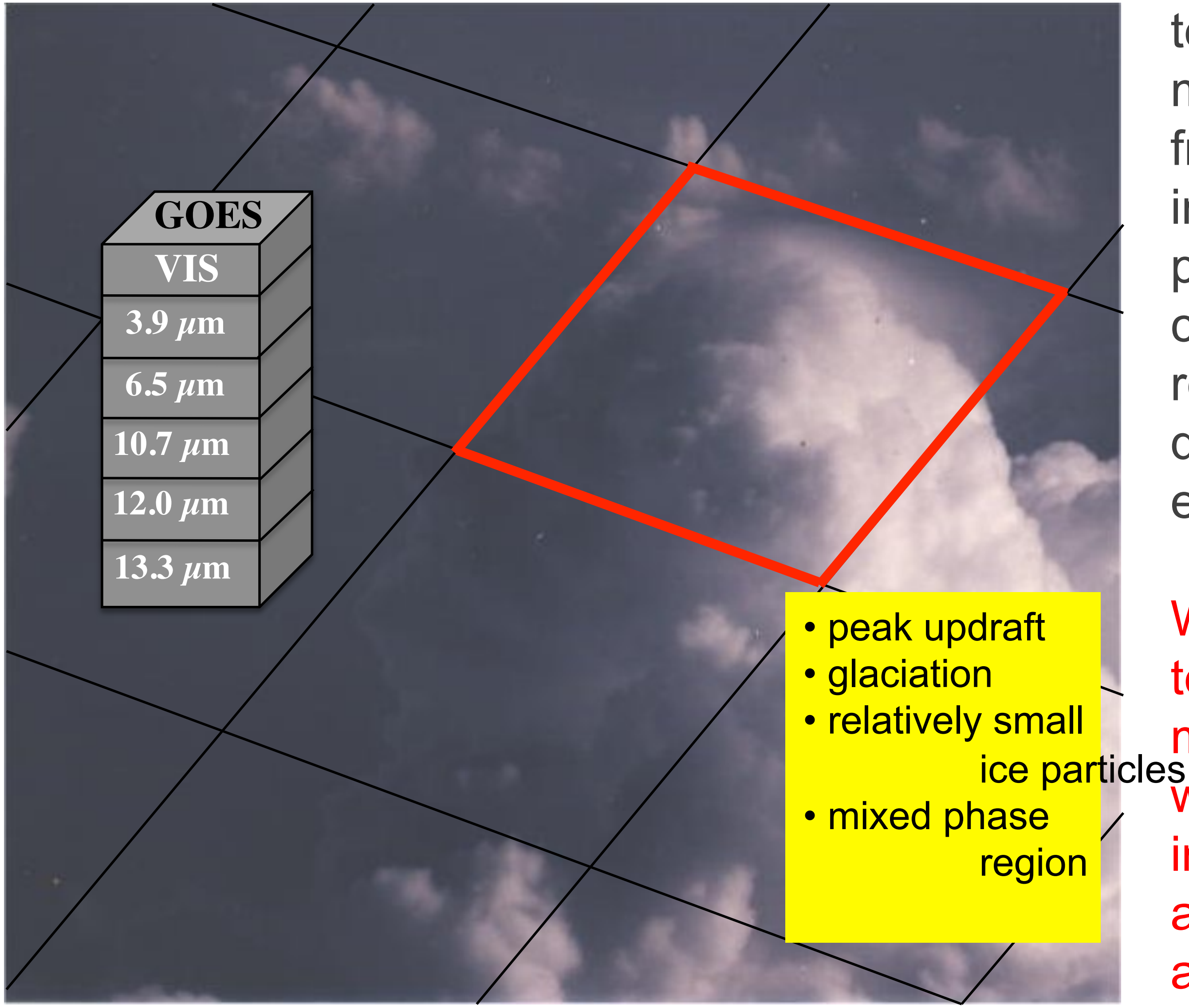
1. **Estimating first flash lightning initiation using geostationary infrared satellite data**

2. **Evaluation of GOES LI indicators in Corridor Integrated Weather System (CIWS) – some proof they work.**

3. **Linking GOES LI indicators to an lightning NWP-based "lightning potential" or "threat" product – towards quantifying how much lightning will occur once nowcasted.**

Conception & Hypothesis

Quantifying nature with pixels



How to relate infrared temperature and moisture (estimated from radiance) information to physical processes in growing cumulus, subsequently related to precipitation development and electrification?

We must infer from temperature and moisture information what we know to be important for rainfall and lightning formation and occurrence.

Background: Object Tracking Algorithm

Download latest satellite imagery

Make Cloud Mask

Produce MAMVs

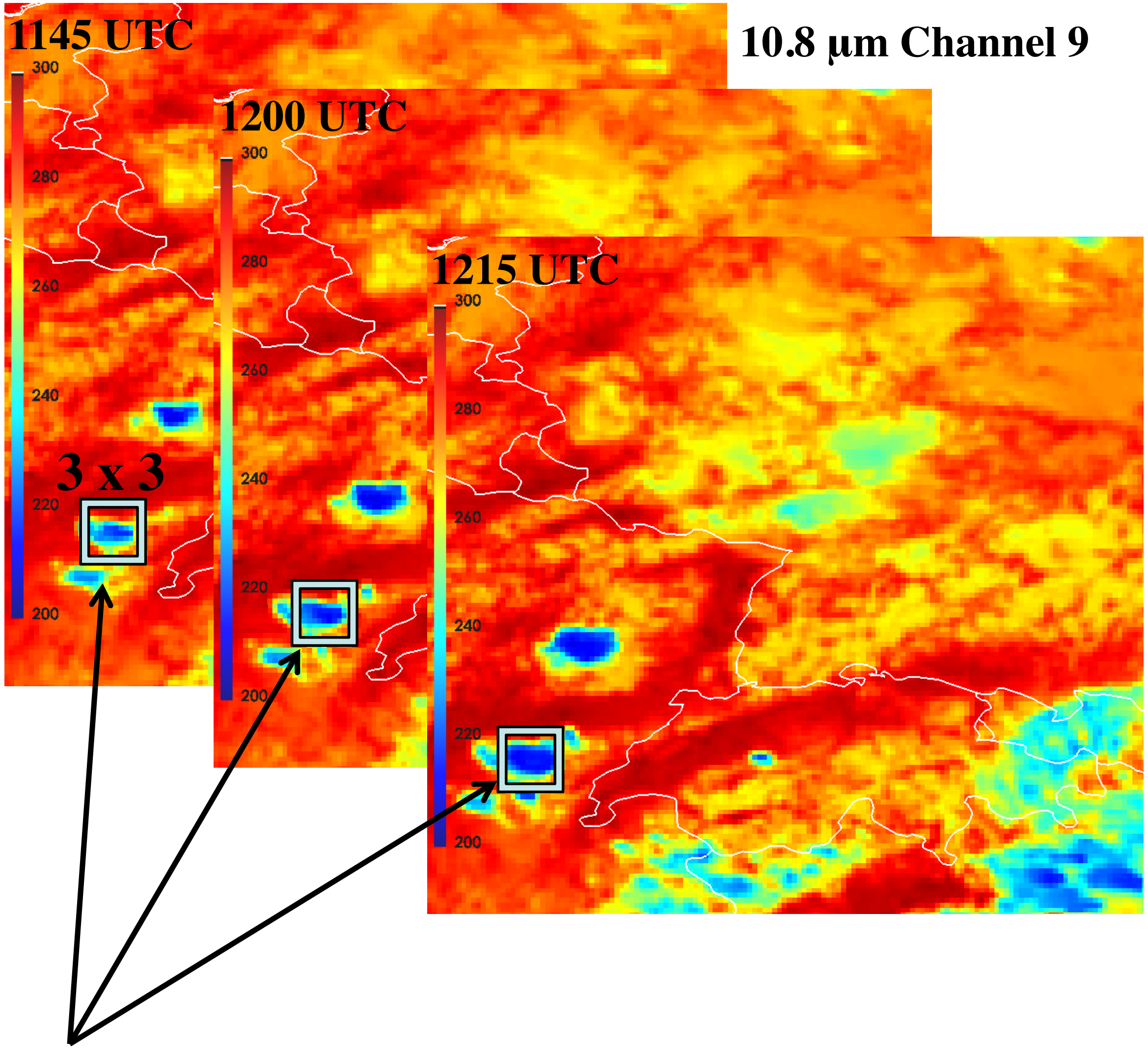
Track "Cloud Objects" from 'T1' to 'T2'

(Similar to "Cb-TRAM" Zinner et al. 2008)

Determine CI forecast for each tracked Cloud Object using 6 spectral/temporal differencing tests (aka: "Interest Fields")

Per-Object CI forecast

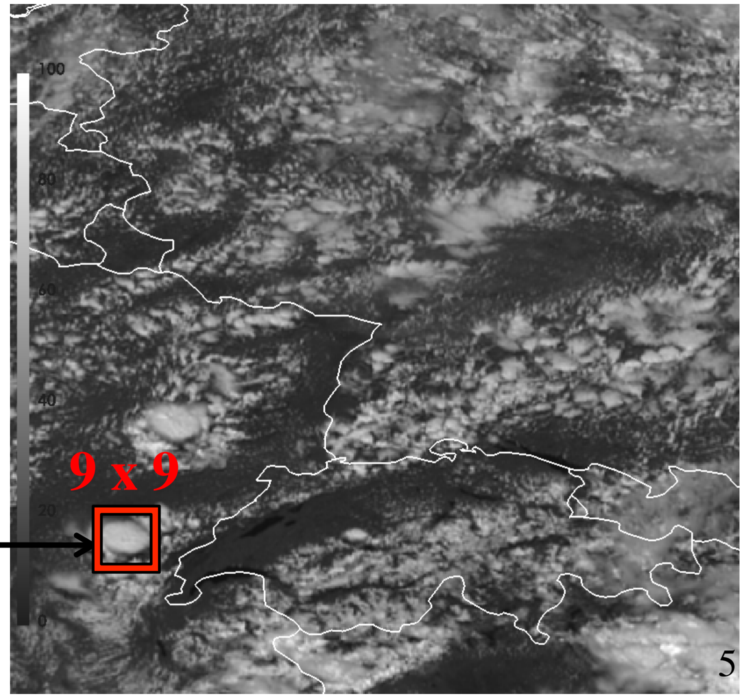
SATCAST Algorithm: COPS CI Events



10.8 µm Channel 9

A CI “object” was evaluated per CI “event” as a unique cumulus cloud was observed to develop in MSG IR and visible data and produce a >35 dBZ echo (as see in POLIDAD and other radars).

1215 UTC HRV



A “sort of” CI Event…

SATellite Convection AnalySis and Tracking (SATCAST) System

MSG IR Interest Fields per Physical Process

Cloud Depth

- 6.2-10.8 μm difference
- 6.2-7.3 μm difference
- 10.8 μm T_B
- 7.3-13.4 μm
- 6.2-9.7 μm difference
- 8.7-12.0 μm difference

Glaciation

- 15-min Trend Tri-spectral
- Tri-spectral
- 30-min Trend Tri-spectral
- 15-min 8.7-10.8 μm
- 15-min 12.0-10.8 μm Trend
- 15-min 3.9-10.8 μm Trend
- 12.0-10.8 μm difference

Updraft Strength

- 30-min 6.2-7.3 μm Trend
- 15-min 10.8 μm Trend
- 30-min 10.8 μm Trend
- 15-min 6.2-7.3 μm Trend
- 30-min 9.7-13.4 μm Trend
- 30-min 6.2-10.8 μm Trend
- 15-min 6.2-12.0 μm Trend
- 15-min 7.3-9.7 μm Trend

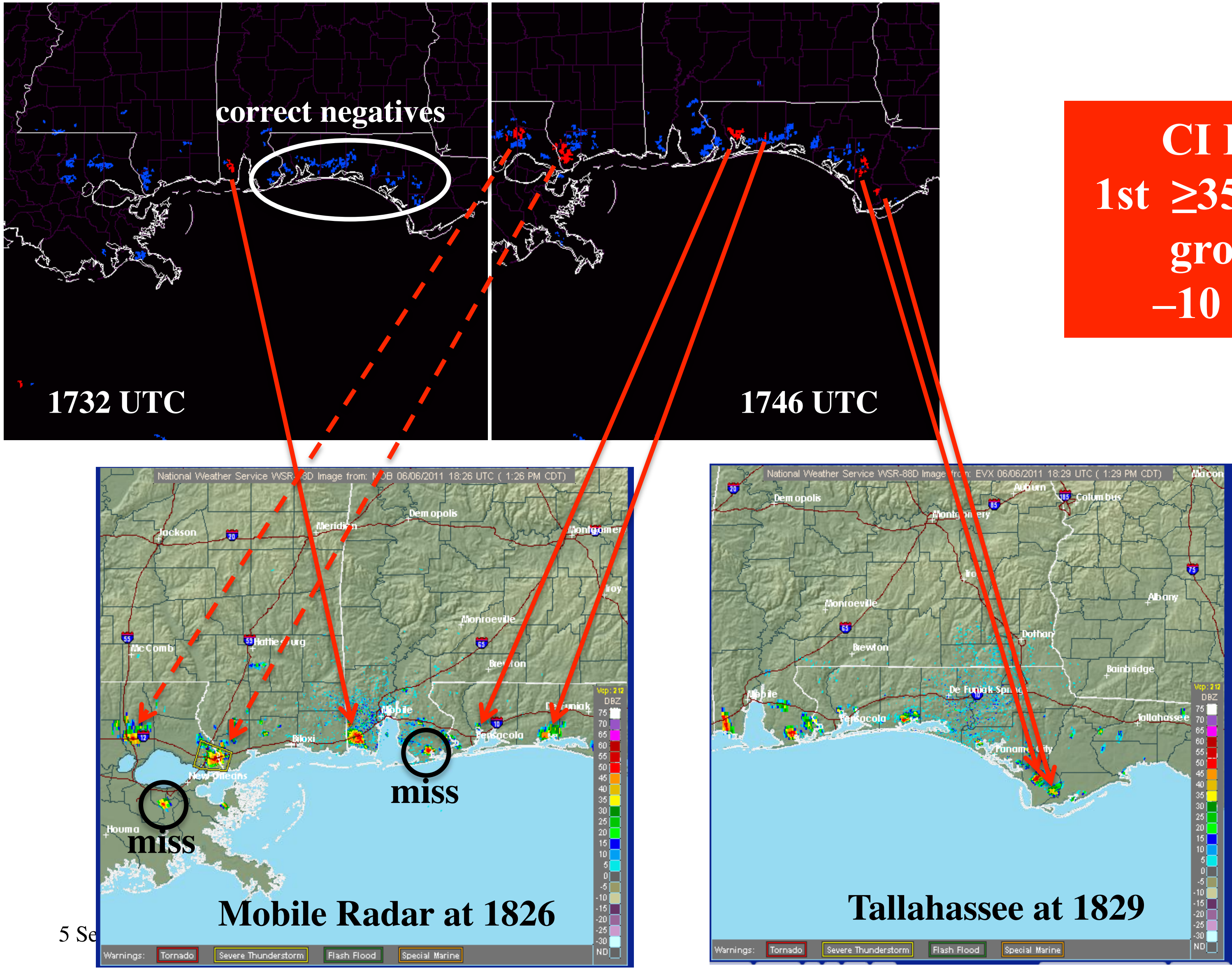
Channels related to the following were found to contain redundant information as they were highly correlated:

8.7-13.4 μm, 8.7-10.8 μm, 7.3-10.8 μm, 13.4-10.8 μm, 8.7-12.0 μm, and Time Trends of these fields.

21 IR indicators for Nowcasting CI from MSG (*GOES-R*).

Methods: Convective Nowcasts/Diagnoses

SATellite Convection AnalySis and Tracking (SATCAST) System

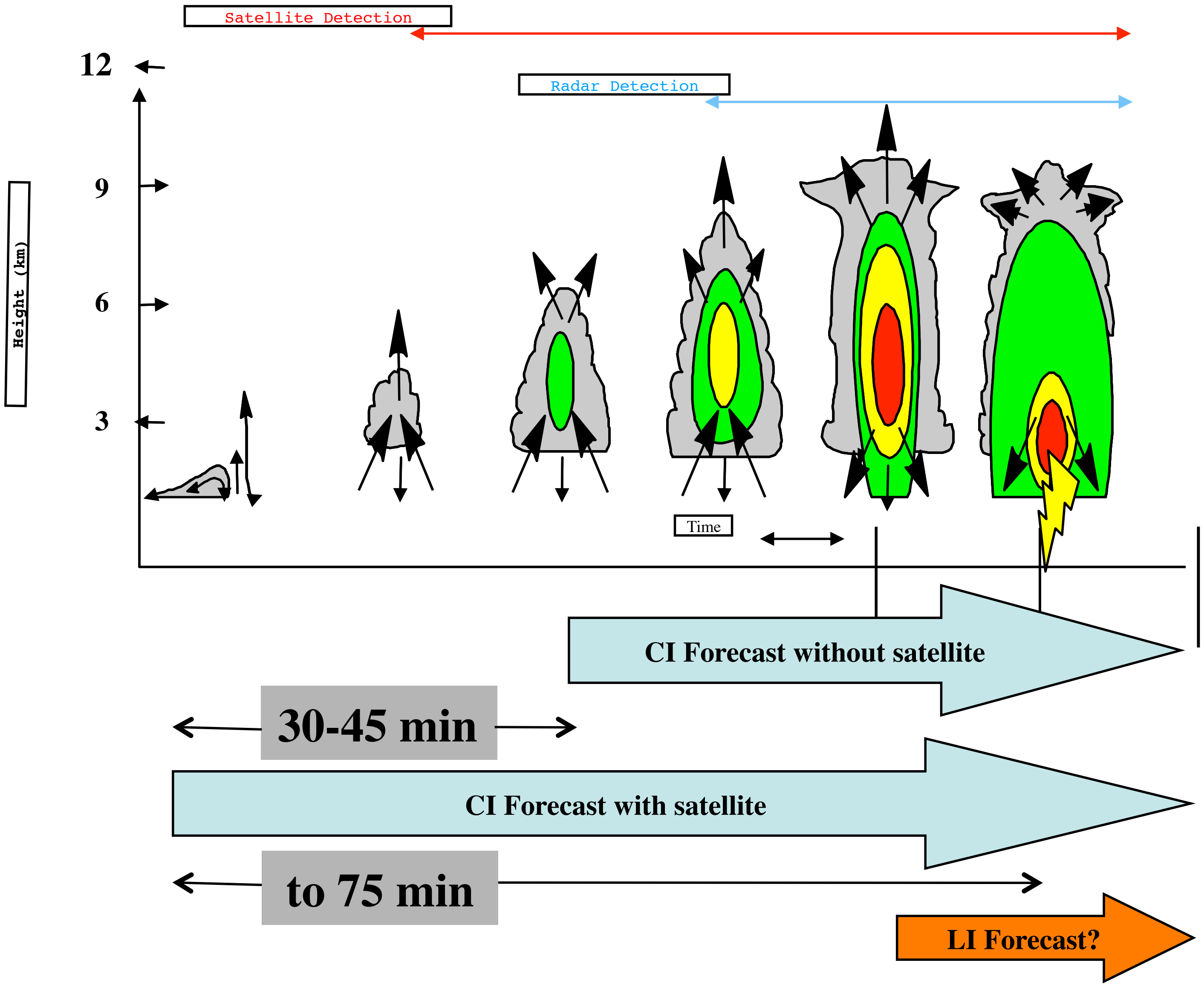


CI Definition:
1st ≥35 dBZ echo at ground, or at –10 ºC altitude

Walker et al. (2011)

Lightning Initiation: Conceptual Idea

What is the current LI forecast lead time?



Up to ~60 min added lead time for LI using GOES

Lead time increases with slower growing cumulus clouds (i.e. in lower CAPE environments)

Introduction: Lightning Primer

Ice crystal-Graupel, Precip & other collisions (particularly in updraft) displace charge

-- (+) charge carried to upper cloud

-- (-) charge settles in mixed-phase region
-- Ground under cloud switches polarity to (+)

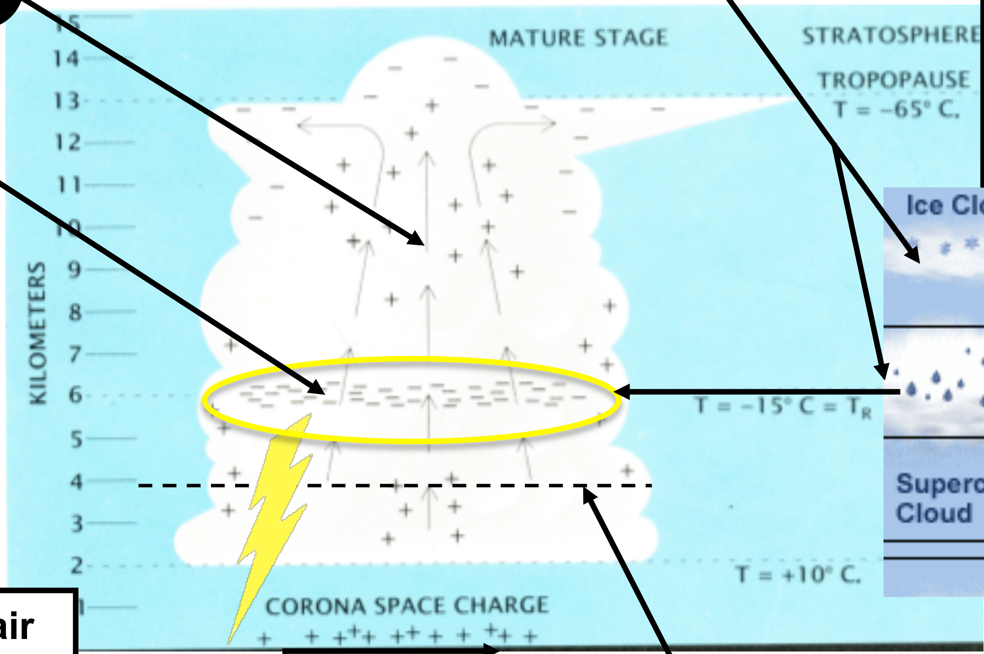
6 Electric field increases until insulating properties of air break down → Result is Lightning

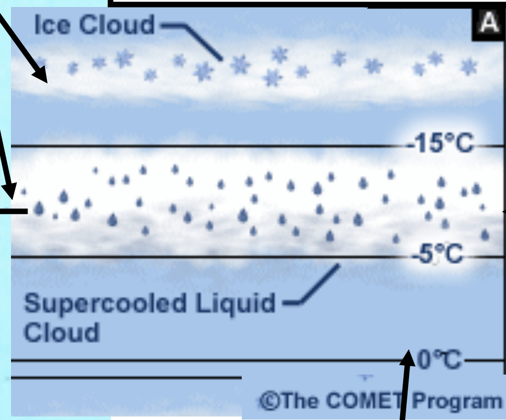
4 Cloud continues vertical ascent to heights at T< –15 to –20°C
→Ice crystal & graupel formation increase
→Some formation between –5 to –15°C as ice crystals fall into the layer (mixed-phase region)

5

Reynolds et al. (1957)
Cecil et al. (2005)
McCaul et al. (2009)

3 Cloud top ascends to heights at T = –5 to –15°C
→Supercooled droplets pool here

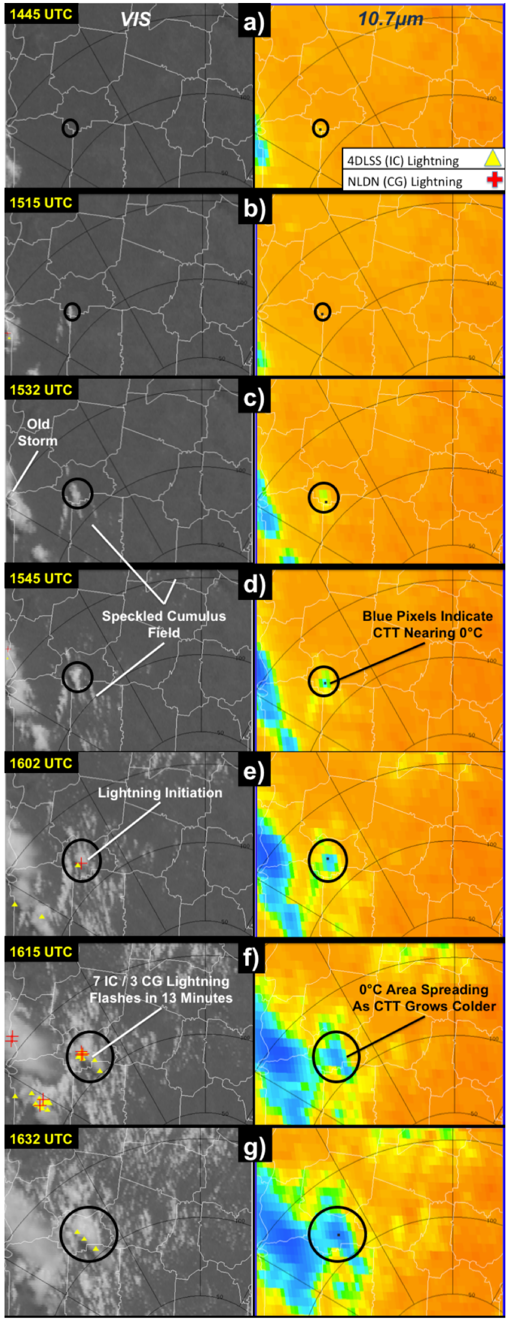




1 **Warm-moist air**
+
Instability
+
Trigger
||
Convective cloud

2 Cloud top ascends to heights at T < 0° C
→ Precipitation processes often commence
→Cloud droplets start to become supercooled

Satellite LI Indicators: Methodology



1. **Identify and track growing cumulus clouds from their first signs in visible data, until first lightning.**
2. **Analyze "total lightning" in Lightning Mapping Array (LMA) networks, not only cloud-to-ground lightning, to identify for LI.**
3. **Monitor 10 GOES reflectance and IR indicators as clouds grow, every 5- to 15-minutes.**
4. **Perform statistical tests to determine where the most useful information exists.**
5. **Set initial critical values of LI interest fields.**

Harris, R. J., J. R. Mecikalski, W. M. MacKenzie, Jr., P. A. Durkee, and K. E. Nielsen, 2010: Definition of GOES infrared fields of interest associated with lightning initiation. *J. Appl. Meteor. Climate*. **49**, 2527-2543.

Mecikalski, J. R., T. Coleman, E. McCaul, and L. Carey, 2011: Evaluating geographical variations in GOES lightning initiation interest fields. *J. Appl. Meteor. Climate*. In preparation.

Mecikalski, J. R., X. Li, and L. Carey, 2011: Comparison between GOES infrared indicators and radar reflectivity profiles for first-flash lightning initiation events. *Mon. Wea. Rev*. In preparation.

SATCAST Algorithm: *Lightning Initiation Interest Fields*

These indicators for LI are a subset of those for CI.

They identify the wider updrafts that possess stronger velocities/ mass flux (ice mass flux).

In doing so, we may highlight convective cores that loft large amounts of hydrometers across the –10 to –15 °C level, where the charging process tends to be significant.

Provides up to a 75 lead time on first-time LI.

Interest Field	MB06 Critical CI Value	Siewert LI Value	15 to 30–min Threshold (This LI Study)	Description
10.7 µm T_B	< 0°C	≤ –13°C	*< 0° C*	Cloud tops cold enough to support supercooled water and ice mass growth; cloud–top glaciation
10.7 µm T_B Time Trends[1]	< –4°C / 15 min (ΔTb / 30 min < ΔTb / 15 min)	≤ –10°C / 15 min	*< –6° C / 15 min*	Cloud growth rate (vertical)
Timing of 10.7 µm T_B drop below 0° C	Within prior 30 min	*Not used*	*Not Used*	Cloud–top glaciation
6.5–10.7 µm T_B difference	Tb Diff: –35°C to –10°C	≥ –17°C	*> –30° C*	Cloud top height relative to mid/upper troposphere
13.3–10.7 µm T_B difference	Tb Diff: –25°C to –5°C	≥ –7°C	*> –13° C*	Cloud top height relative to mid/upper troposphere; better indicator of early cumulus development but sensitive to cirrus
6.5–10.7 µm T_B Time Trend	> 3°C / 15 min	≥ 5°C / 15 min	*> 5° C / 15 min*	Cloud growth rate (vertical) toward dry air aloft
13.3–10.7 µm T_B Time Trend	> 3°C / 15 min	≥ 5°C / 15 min	*> 4° C / 15 min*	Cloud growth rate (vertical) toward dry air aloft
3.9–10.7 µm T_B Difference[3]	*Not used*	*Not used*	*> 17° C*	Cloud–top glaciation
3.9–10.7 µm T_B Time Trend[2]	*Not used*	T–T(t–1) < –5°C and T–T(t+1) < –5°C	*> 1.5° C / 15 min*	Sharp decrease, then increase indicates cloud–top glaciation
3.9 µm Fraction Reflectance[2]	*Not used*	≤ 0.05	*< 0.11*	Cloud top consists of ice (ice is poorer reflector than water at 3.9 µm)
3.9 µm Fraction Reflectance Trend[3]	*Not used*	*Not used*	*< –0.02 / 15 min*	Cloud–top glaciation rate

1 Represents two unique 10.7 µm T_B interest fields in MB06. No 30-min trends were used in Siewert (2008) or in this study.
2 Added to MB06 fields by Siewert (2008).
3 Unique to this study.

Satellite Indicators of Lightning

Focus on 5 Lightning Initiation interest field to start…

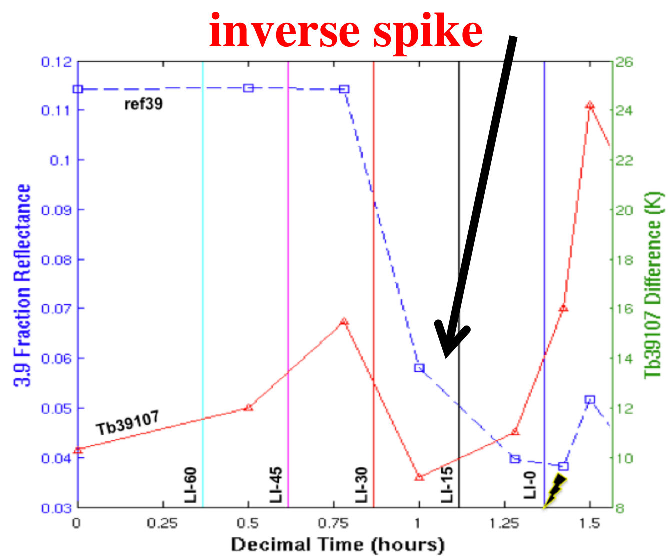
(1) 3.9 µm reflectance: Monitor clouds where the cloud-top reflectance consistently falls from >10% to near or below 5%. The rate found is ~2-4%/15-min.

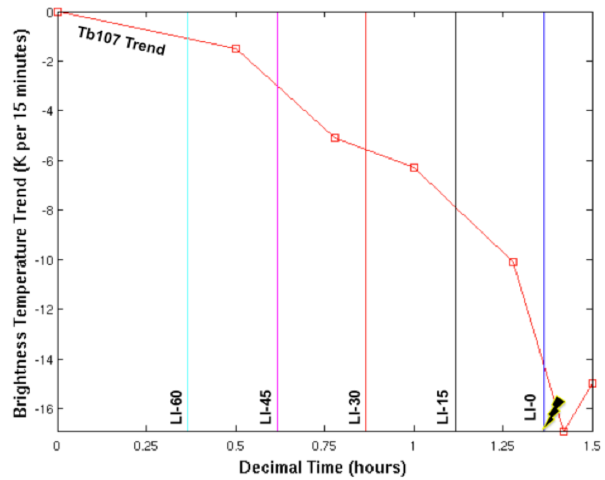
(2) For clouds with 10.7 µm T_B< 0°C and >–18°C (255 K), use the 3.9–10.7 µm difference fields, with a threshold at >17°C degrees.

(3) Trends in the 3.9–10.7 µm difference should be >1.5 °C/15-min. For ideal cases, the trend in 3.9–10.7 µm will reverse directions, falling by up to 5°C/15-min, then rising (by up to 5°C/15-min). This down-up "*inverse spike*" is the result of cloud-top glaciation, but as it only seems to occur for the "better" LI events, it may lead to lower detection probabilities in less prolific lightning-producing clouds.

(4) The 15-min trend in 6.5–10.7 µm difference of >5°C. This is a good indicator of a strong updraft.

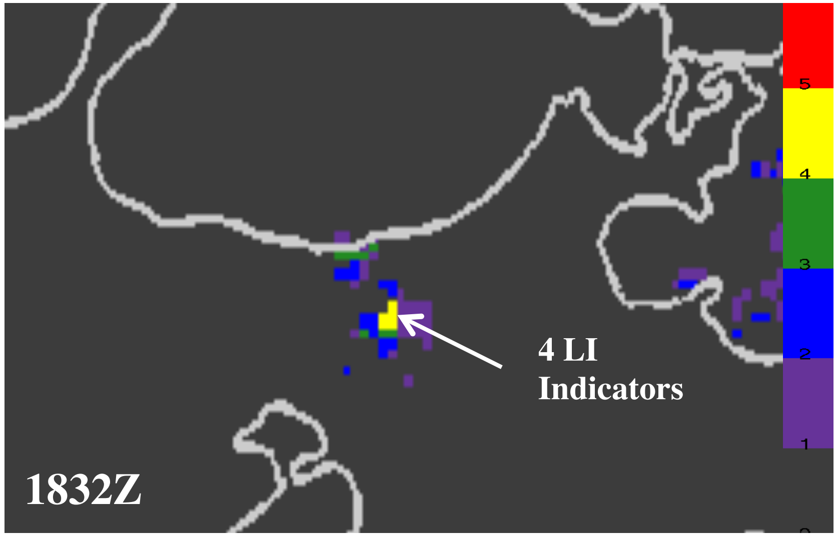
(5) The 15-min 10.7 μm Trend – Updraft strength indicator.



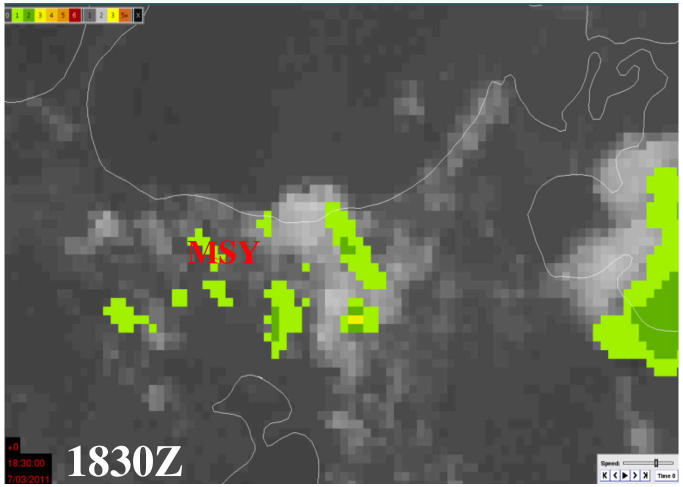


Use of Lightning Initiation Indicators

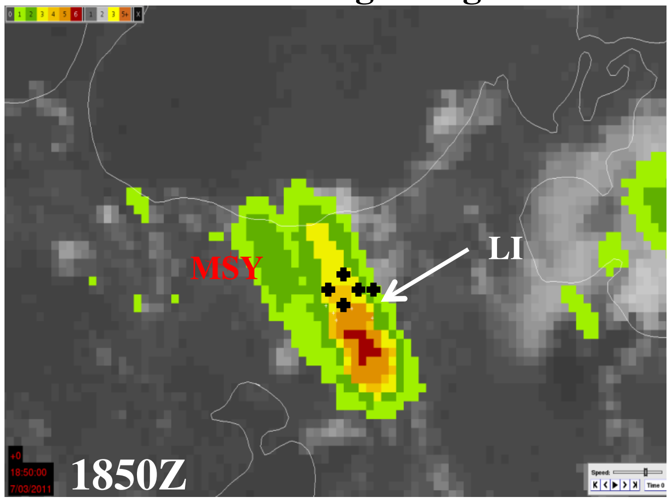
Number of LI Indicators



Visible Satellite, Radar Precipitation, and CG Lightning



Visible Satellite, Radar Precipitation, and CG Lightning



3 July 2011

Five lightning Indicators (LI) are added cumulatively on a pixel by pixel basis:

LI1: –18˚C < 10.7 μm channel < 0 ˚ C AND
3.9–10.7 μm diff>17 ˚C
LI2: 6.7–10.7 μm 15 min trend > 5 ˚C
LI3: 3.9 μm reflectivity < 0.11 AND
3.9 μm reflectivity 15 min trend < –0.02
LI4: 3.9–10.7 μm 15 min trend > 1.5 ˚C
LI5: 10.7 μm 15 min trend < –6 ˚C

Goal: Couple to Lightning Potential algorithm

Satellite LI Nowcast & Flash Potential Forecast

Goals:

- Forecast time of initiation, location, and density of lightning event.
- Bridge gap between lightning initiation and threat.
- Compile a list of ~200 lightning cases within Lightning Mapping Arrays (LMA) in North Alabama and Eastern Florida.
- Analyze SATCAST Lightning Initiation fields for each case to find where cumuli, that would later be capable of producing lightning, were detected. Analyze LMA data to determine where lightning initiation (LI) occurred.
- Create a storm motion vector between the SATCAST detection and LI, and find the change in time between the two.
- Analyze results to find a correlation between storm motion from SATCAST point, forecasted LI time and location, and actual LI.

WRF Lightning Threat Forecasts

Methodology:

1. Create WRF 2-km resolution forecasts of LTG threat using proxy fields from explicitly simulated convection:
   (a) graupel flux at –15 ºC
   (b) vertically integrated ice (VII)

2. Calibrate WRF LTG proxies using peak total LTG flash rate densities from HSV LMA; relationships look linear, with regression line passing through origin satisfactory.

3. Also evaluate threats for areal coverage, time variability

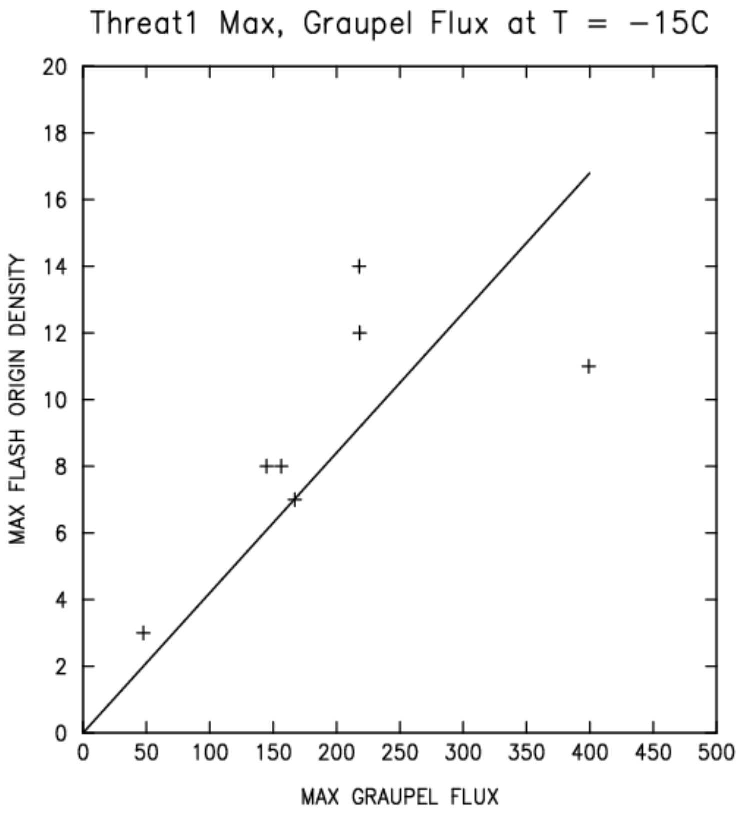
4. Truncate low threat values to make threat areal coverage match LMA flash extent density observations

5. Blend proxies to achieve optimal performance for LTG peaks and areal coverages.

Cecil et al. (2005)
McCaul et al. (2009)

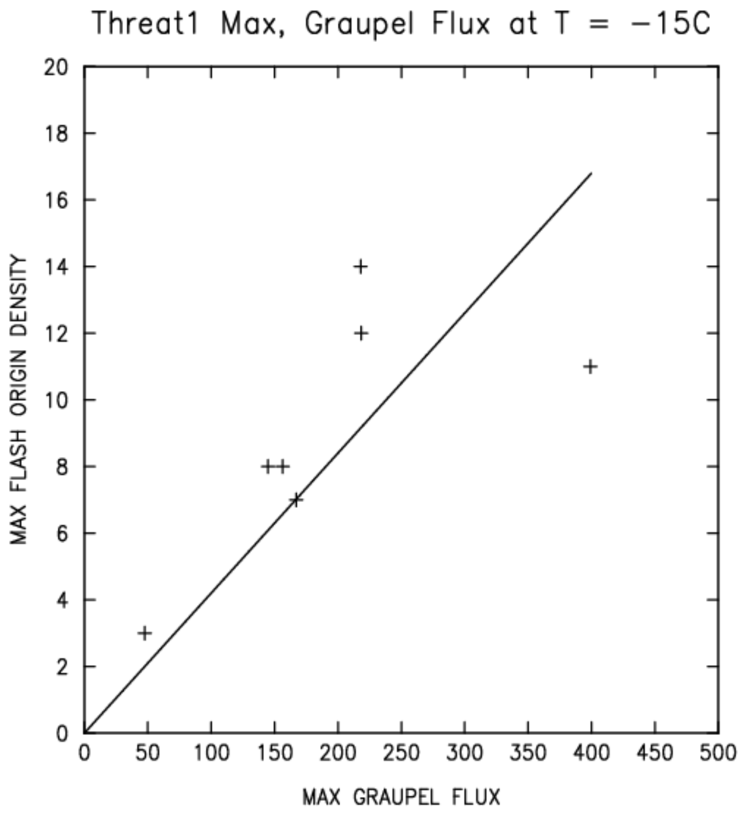
WRF Lightning Threat Forecasts

Calibration Curve Threat 1 (graupel flux)



$F_1 = 0.042$ FLX

Calibration Curve Threat 2 (vertically integrated ice)



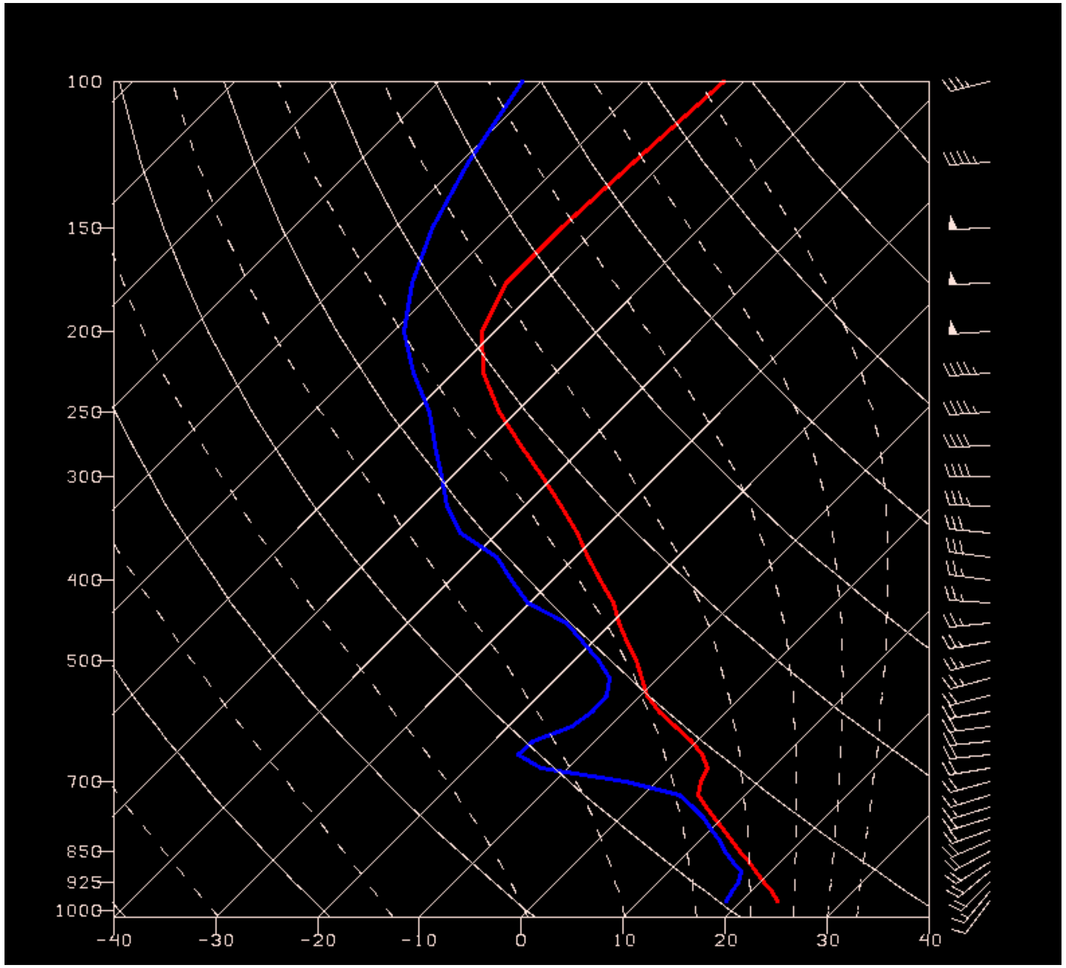
$F_2 = 0.2$ VII

Courtesy: Dr. Eugene McCaul

WRF Lightning Threat Forecasts

Case Study: 30 March 2002

Squall Line plus Isolated Supercell

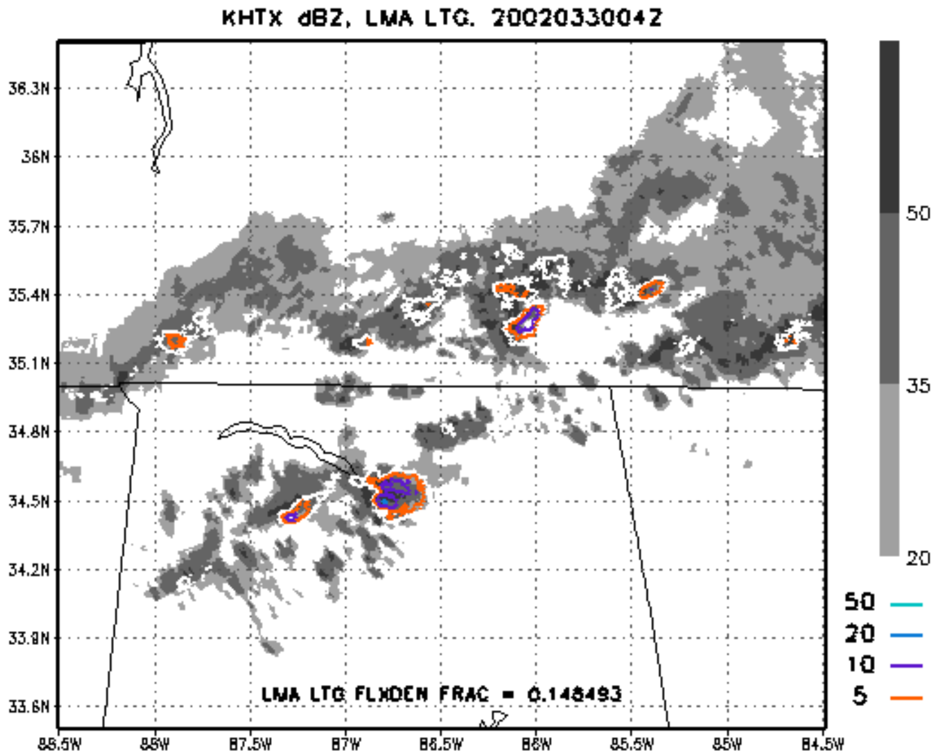


WRF Sounding
2002 30 March 0300 UTC

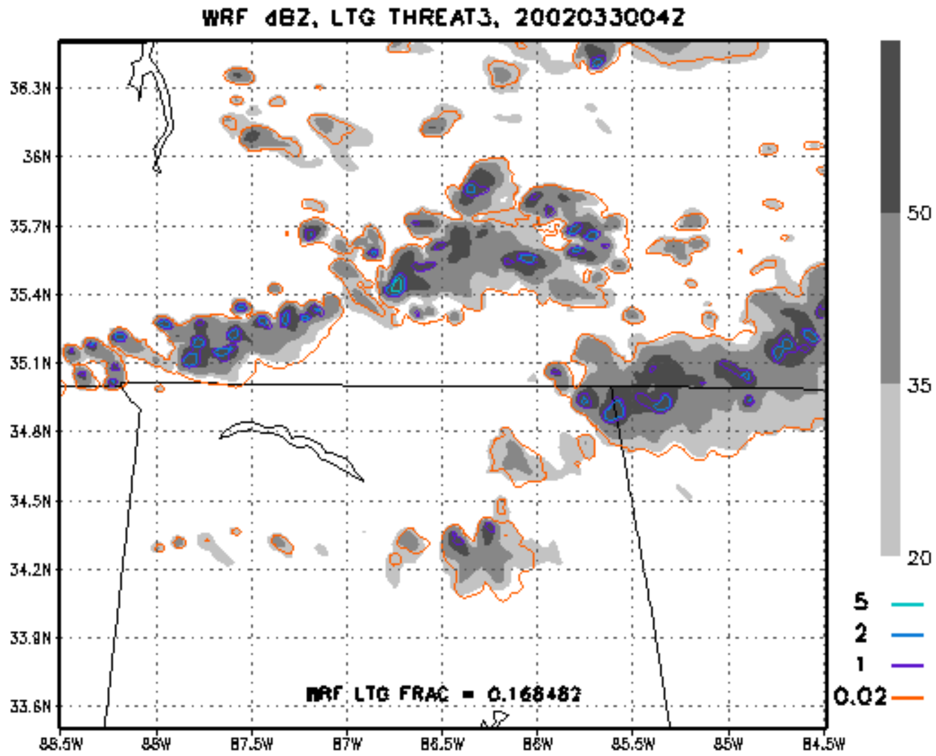
Lat = 34.4 ºN
Lon = –88.1 ºW
CAPE ~2800

WRF Lightning Threat Forecasts

<u>Ground truth</u>
LTG flash extent density (dBZ)
30 March 2002, 0400 UTC



Blended Threat3 (dBZ)
30 March 2002, 0400 UTC



McCaul et al. (2009)

WRF Lightning Threat Forecasts

Implications of results:

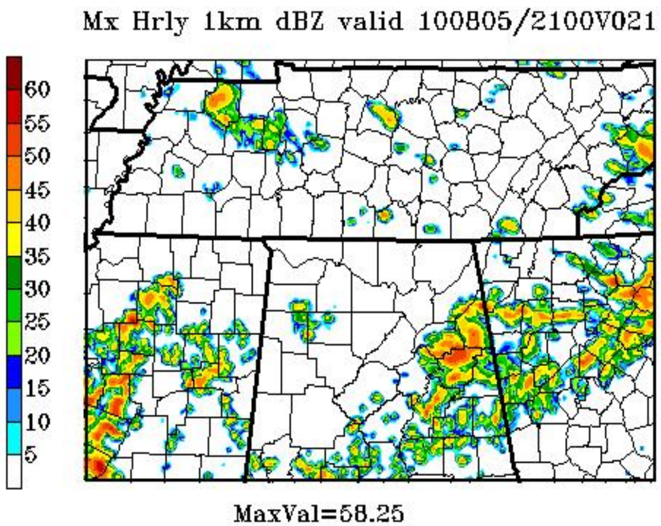
1. WRF LTG threat 1 coverage too small: updrafts only
2. WRF LTG threat 1 peak values have adequate t variability
3. WRF LTG threat 2 peak values have insufficient t variability because of smoothing effect of z integration
4. WRF LTG threat 2 coverage is good: anvil ice included
5. WRF LTG threat mean biases can exist because our method of calibrating was designed to capture *peak* flash rates correctly, not *mean* flash rates
6. Blend of WRF LTG threats 1 and 2 should offer good time variability, good areal coverage

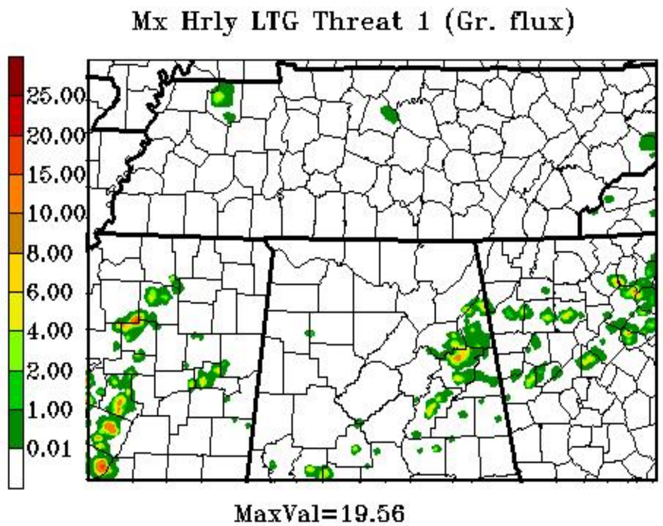
Construction of blended threat:

1. Threat 1 and 2 are both calibrated to yield correct peak flash densities
2. The peaks of threats 1 and 2 tend to be coincident in all simulated storms, but threat 2 covers more area
3. Thus, weighted linear combinations of the 2 threats will also yield the correct peak flash densities
4. To preserve most of time variability in threat 1, use large weight
5. To ensure areal coverage from threat 2, avoid very small weight
6. Tests using 0.95 for threat 1 weight, 0.05 for threat 2, yield satisfactory results

Lightning Threat Forecast

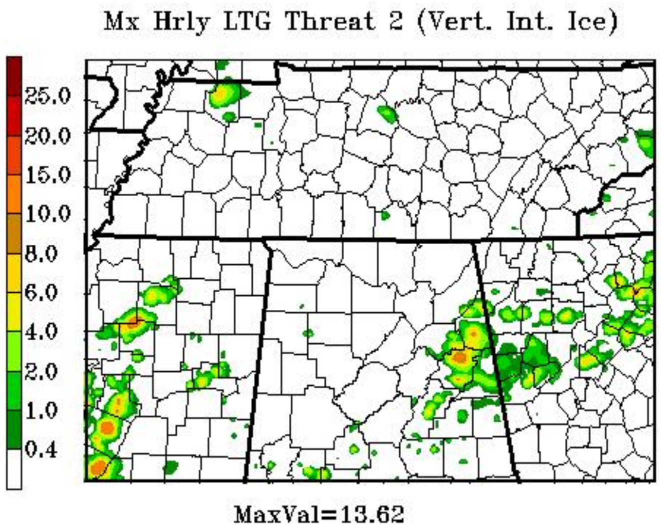
Forecast Reflectivity

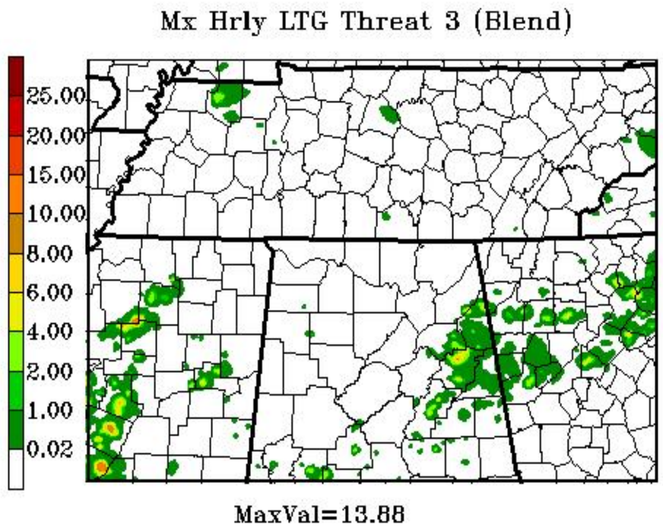




Forecast Lightning Density (Graupel Flux)

Forecast Lightning Density (Vertically Integrated Ice)





Forecast Lightning Density (Algorithm Blend)

Lightning Density in flashes per km^2 per 5 min.

Lightning Threat Forecast

1. Both LTG threats yield proper peak flash rate densities.

2. LTG threats provide more realistic spatial coverage of LTG; better than coverage of CAPE>0, which over–predicts threat, especially in summer.

3. Graupel flux LTG threat 1 is confined to updrafts, and thus underestimates LTG areal coverage; threat 2 includes anvil ice, gives better areal coverage.

4. Graupel flux LTG threat 1 shows large time rms, like observations; VII threat 2 has small time rms.

5. New blended threat yields proper peak flash rate densities, because constituents are calibrated and coincident.

6. New blended threat retains temporal variability of LTG threat 1, but offers proper areal coverage, thanks to threat 2

Courtesy: Dr. Eugene McCaul

Combined Lightning Initiation & Threat Forecast

- Created an algorithms that links 0-1 hour lightning initiation to forecast of a short-term lightning threat (density), or potential.
- Explore distance-weighted method to account for expected differences in lightning/storm initiation location and WRF-based lightning threat forecasted storms.
- Validate using LMA for truth flash density.
- Refine GOES lightning initiation method.