Relationships between Lightning, Radar Fields, and Satellite Infrared Observations for Convective Storms

John Mecikalski[1]
Retha Matthee[1]
Xunali Li[1]
Jason Apke[1]
Shaima Nasiri[2]
Tong Ren[2]
Larry Carey[1]

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

[2]Atmospheric Science Department
Texas A & M University
College Station, TX USA

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Motivation and Project Goals

- Increase understanding of the relationships between lightning and non–lightning storms

  Time–evolution:
  - Cloud–top infrared (IR) fields
  - Ground–based dual–polarimetric radar fields
  - Lightning fields
- Describe physical attributes of growing cumulus clouds:
  - Water, precipitation and non–precipitation ice mass production
  - Updraft strength
  - Cloud depth
  - Cloud–top glaciation/phase

Main Outcomes:

(a) Enhance predictability and identification of cloud–to–ground (CG) lightning events

(b) Bridge gap between satellite–observed cloud top and in–cloud radar observed hydrometeors

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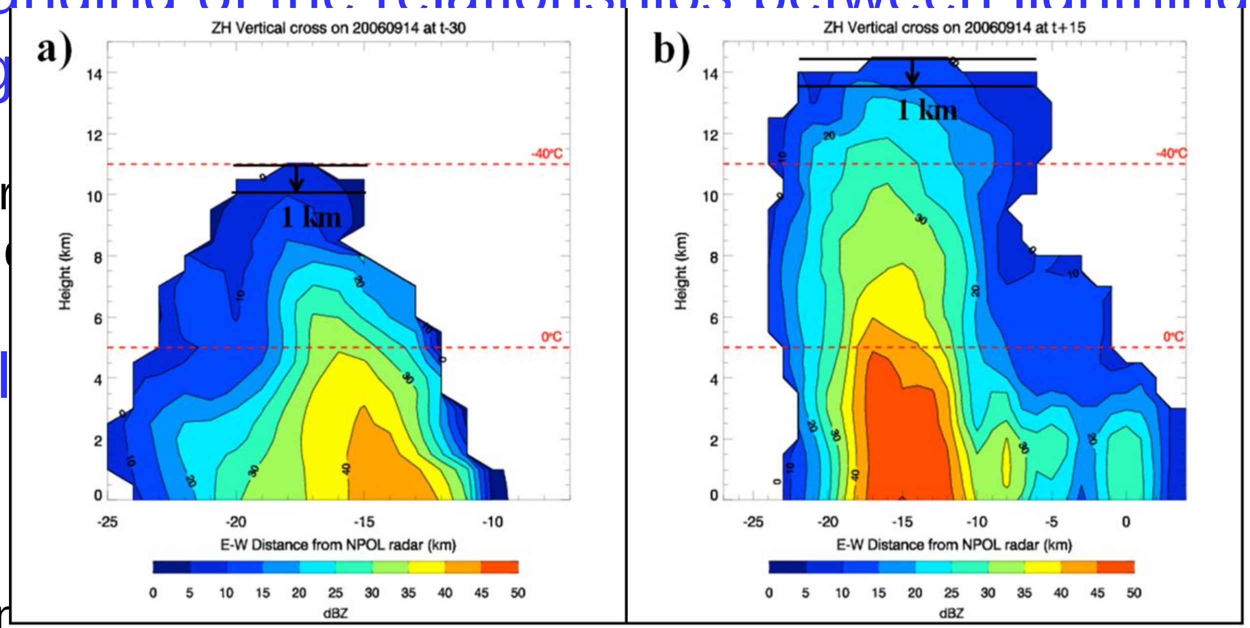

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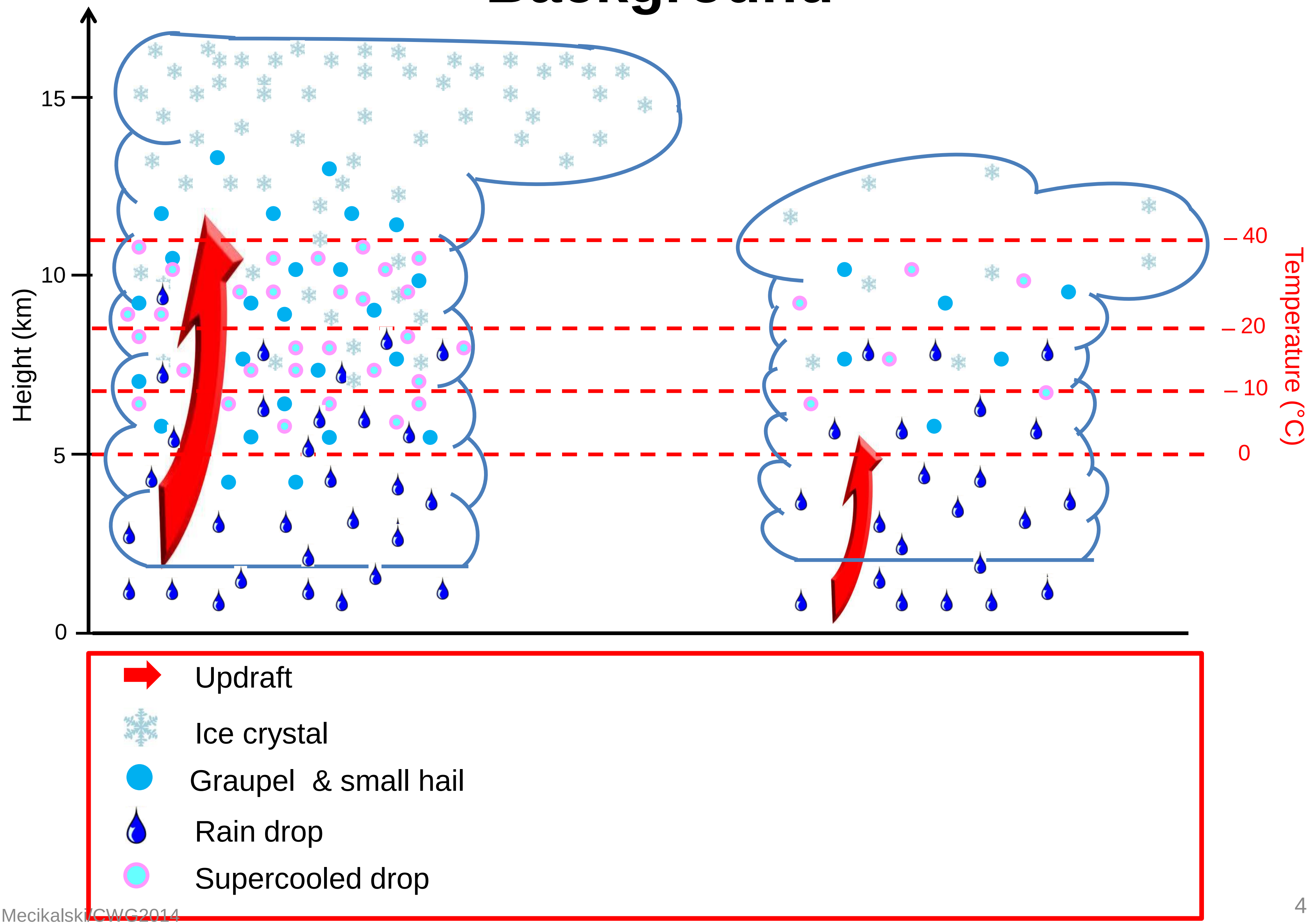
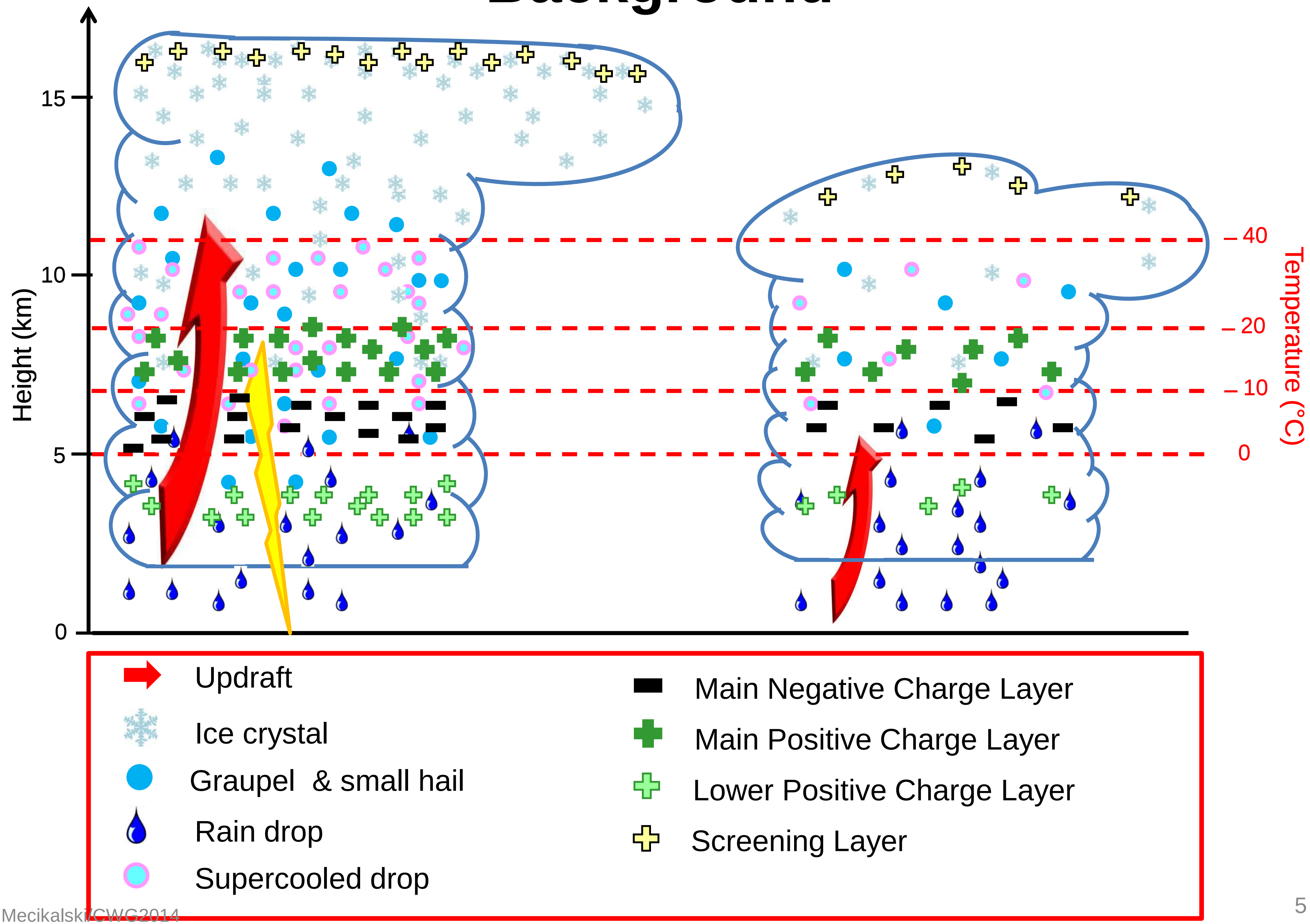
Background



15
10
5
0
Height (km)
– 40
– 20
– 10
0
Temperature (°C)
Updraft
Ice crystal
Graupel & small hail
Rain drop
Supercooled drop

Background



Height (km)
15
10
5
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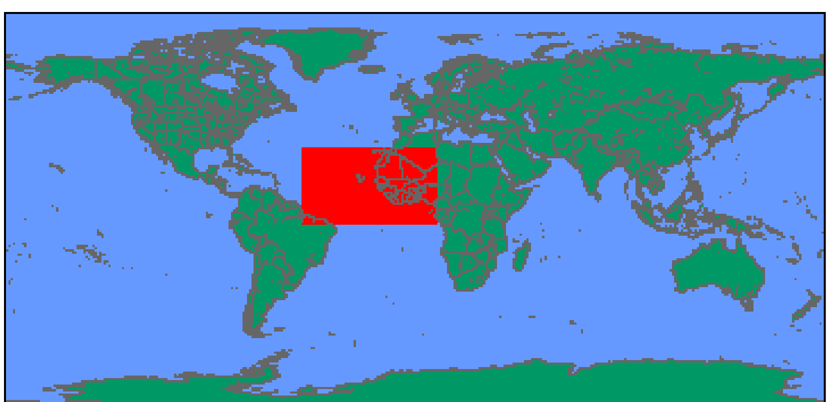
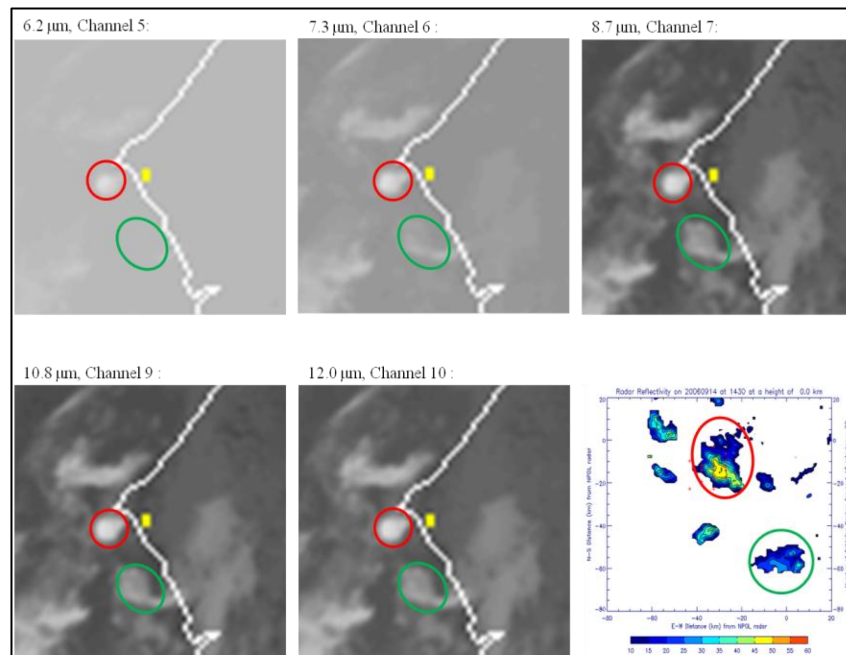
Temperature (°C)
– 40
– 20
– 10
0
Updraft
Ice crystal
Graupel & small hail
Rain drop
Supercooled drop
Main Negative Charge Layer
Main Positive Charge Layer
Lower Positive Charge Layer
Screening Layer

Location of Research

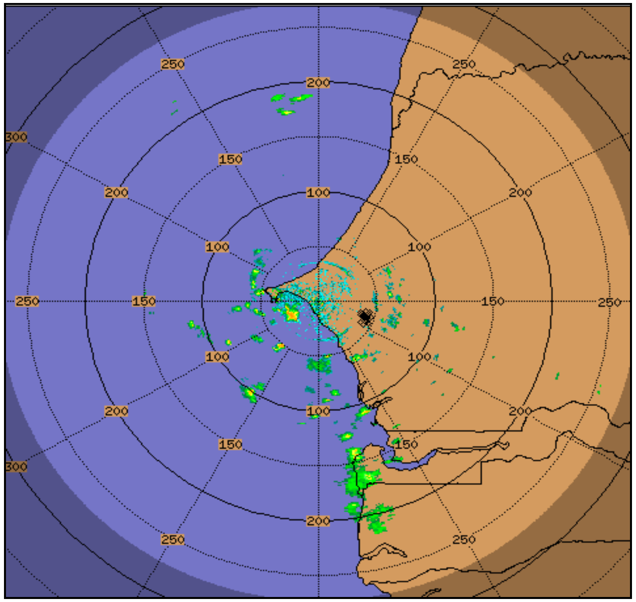
- NASA African Monsoon Multidisciplinary Analyses (NAMMA) campaign
- Research focus:
  - 13° to 16° North and 15.5° to 18.5° West
- Dates: 19 August 2006 to 30 September 2006
- 33 lightning and 30 non–lightning storms

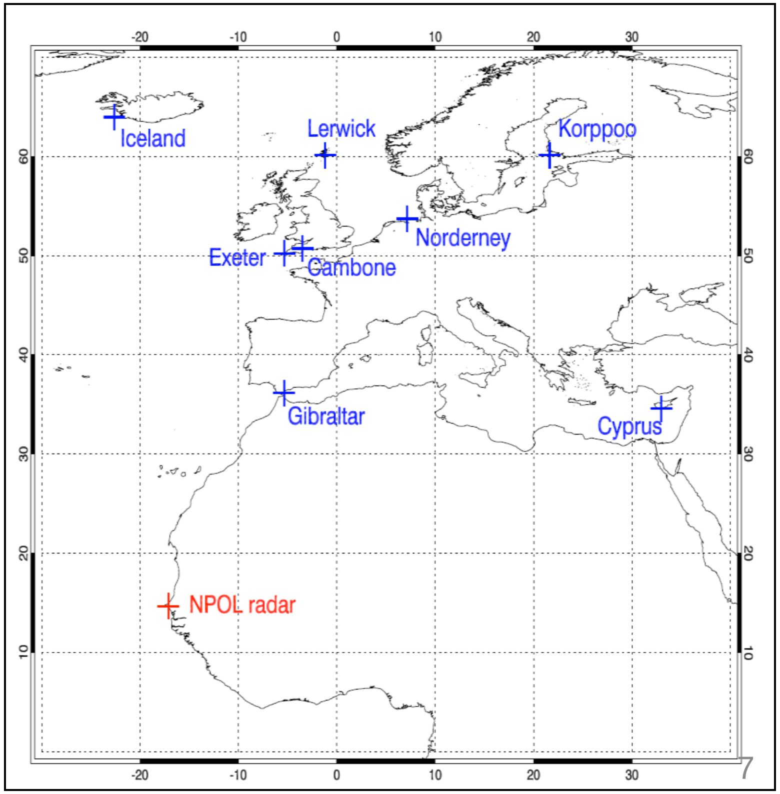




Data

- Radar:
  - NASA Polarimetric Doppler Weather Radar (NPOL)
  - S–band
- Lightning:
  - Very Low Frequency (VLF) Arrival Time Difference (ATD) lightning data
  - Detects return strokes from CG flashes





Matthee and Mecikalski (2013)

Channel differencing and time trends	Category	Critical value for CG lightning to occur
6.2 μm – 7.3 μm	Cloud depth	≥ –5 °C
6.2 μm – 10.8 μm	Cloud depth	≥ –5 °C
15 minute 6.2 μm – 7.3 μm	Updraft strength	Positive trends for ≥ 30 minutes with ≥ 2 °C increase during this time
30 minute 6.2 μm – 7.3 μm	Updraft strength	Positive trends for ≥ 30 minutes with ≥ 4 °C increase during this time
15 minute 10.8 μm	Updraft strength	≤ –10 °C
30 minute 10.8 μm	Updraft strength	≤ –20 °C
8.7 μm –10.8 μm	Cloud–top glaciation	≥ –5 °C
(8.7 μm – 10.8 μm) – (10.8 μm – 12.0 μm)	Cloud–top glaciation	≥ 0.5 °C

Matthee and Mecikalski (2013)

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		≤ –20 °C
		≥ –5 °C
		≥ 0.5 °C

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Geostationary infrared methods for detecting lightning-producing cumulonimbus clouds

Retha Matthee[1] and John R. Mecikalski[1]

Received 10 October 2012; revised 7 May 2013; accepted 9 May 2013.

[1] This study documents the behavior of cloud top infrared (IR) fields known to describe physical processes associated with growing convective clouds, for 30 nonlightning and 33 cloud-to-ground (CG) lightning-producing convective storms. The goal is to define “critical” threshold values for up to 10 IR fields that delineate lightning from nonlightning convective storms. *Meteosat* Second Generation and United Kingdom Meteorological Office very low frequency arrival time difference satellite and lightning data, respectively, were used in this study. These were collected during the National Aeronautics and Space Administration (NASA) African Monsoon Multidisciplinary Analyses (NAMMA) field campaign in August–September 2006 in Equatorial Africa. The main conclusions show that eight of 10 IR fields that describe updraft strength, cloud depth, and glaciation (or ice at cloud top) are significantly different between the nonlightning and lightning-producing convective clouds. The lack of notch overlap in “box and whiskers” plots confirms a 95% confidence that the two data sets are different. Nonlightning-producing clouds are far less vertically developed and possess >50% weaker updrafts (as estimated from satellite trends), as well as little to no evidence of ice or glaciation at cloud top. Results from this study therefore can be used to nowcast and identify with high confidence convective clouds that are producing or are going to produce CG lightning using *Meteosat* data, assuming appropriate tracking of growing cumulus clouds is performed.

Citation: Matthee, R., and J. R. Mecikalski (2013), Geostationary infrared methods for detecting lightning-producing cumulonimbus clouds, *J. Geophys. Res. Atmos.*, *118*, doi:10.1002/jgrd.50485.

Matthee and Mecikalski (2013)

Channel differencing and time trends	Categ
6.2 µm – 7.3 µm	Cloud d
6.2 µm – 10.8 µm	Cloud d
15 minute	

DECEMBER 2010 HARRIS ET AL. 2527

The Definition of GOES Infrared Lightning Initiation Interest Fields

RYAN J. HARRIS

Department of Meteorology and Space Systems Academic Group, Graduate School of Engineering and Applied Sciences, Naval Postgraduate School, Monterey, California

JOHN R. MECIKALSKI

Atmospheric Science Department, University of Alabama in Huntsville, Huntsville, Alabama

WAYNE M. MACKENZIE JR.

Earth Systems Science Center, National Space Science and Technology Center, University of Alabama in Huntsville, Huntsville, Alabama

PHILIP A. DURKEE AND KURT E. NIELSEN

Department of Meteorology and Space Systems Academic Group, Graduate School of Engineering and Applied Sciences, Naval Postgraduate School, Monterey, California

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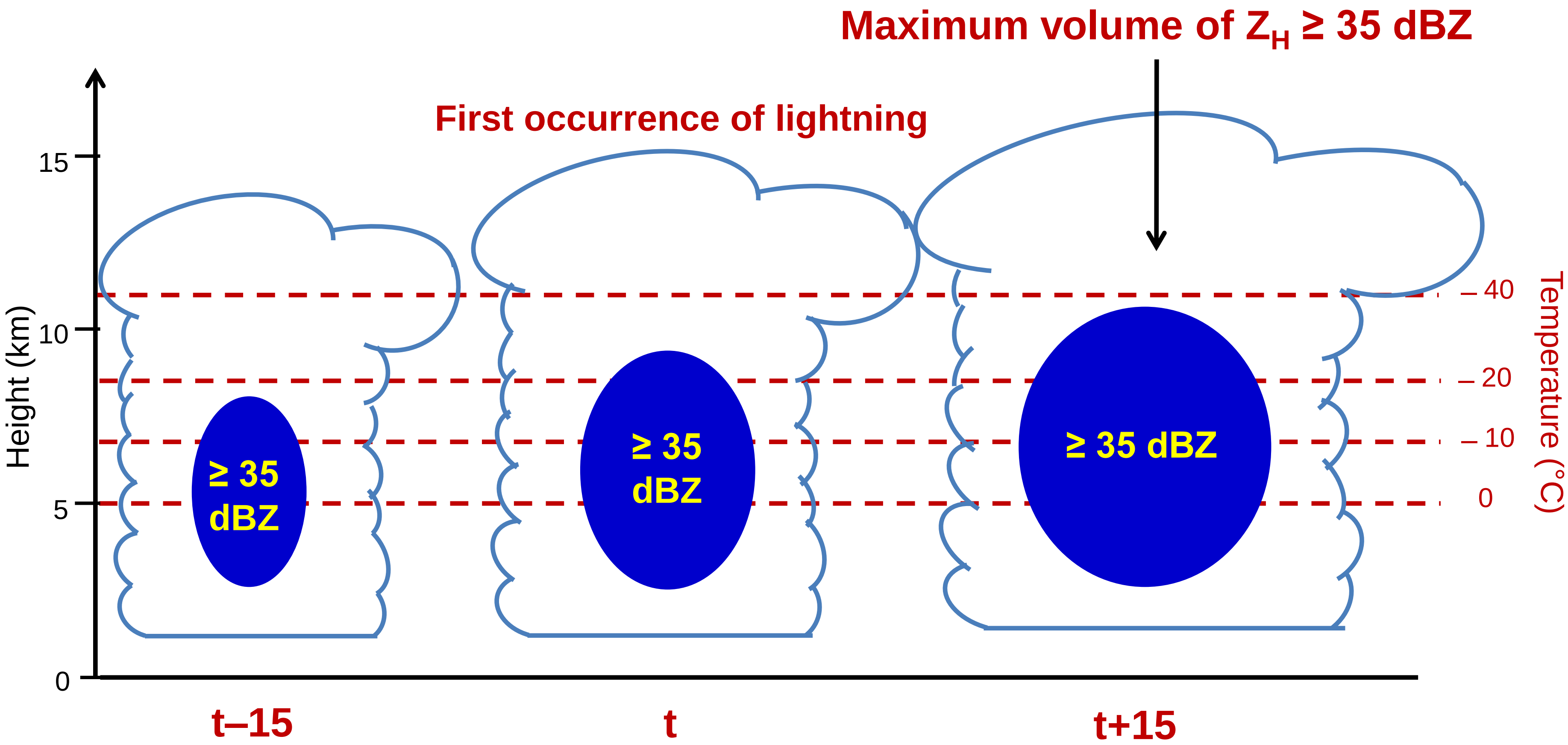
2 °C increase during this time
Positive trends for ≥ 30 minutes with ≥ 4 °C increase during this time
≤ –10 °C
≤ –20 °C
≥ –5 °C
≥ 0.5 °C

Methodology

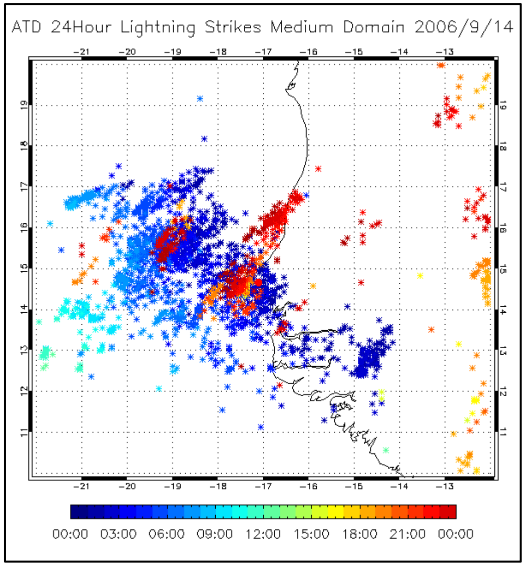
- "t" times:

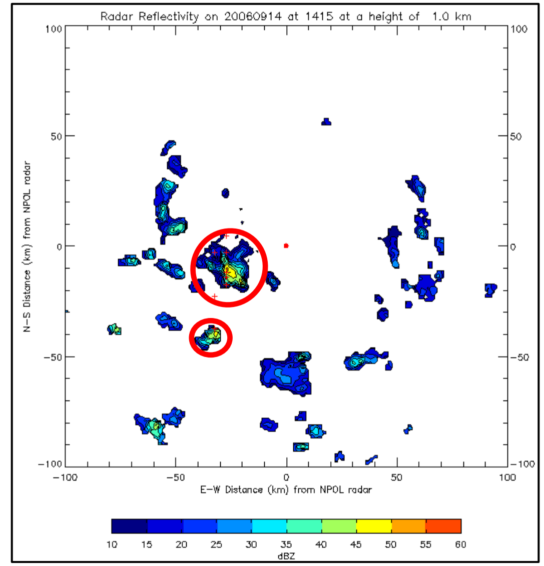


Time frames: t–45 through t+30 (Radar and Satellite)

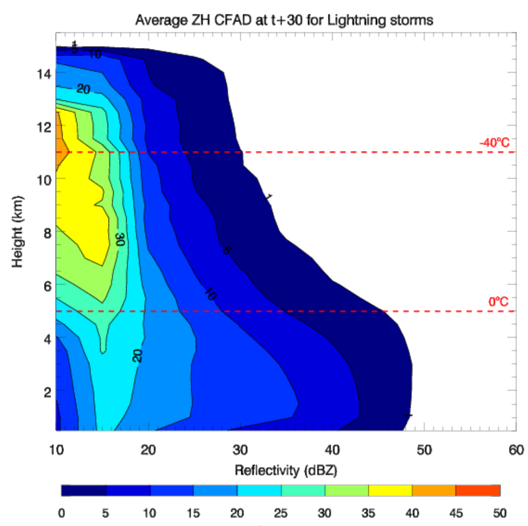
Methodology (Cont.)

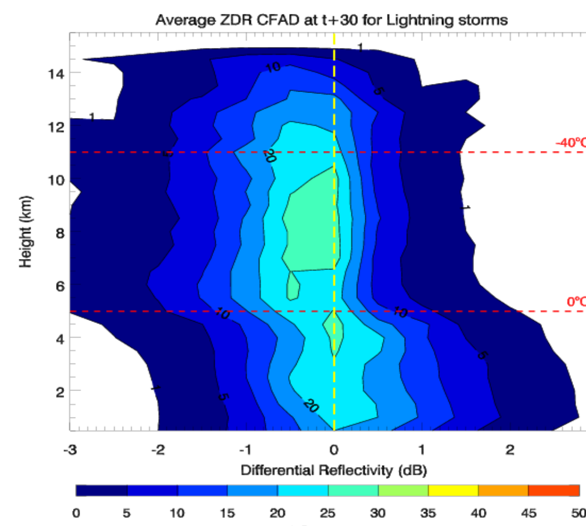
- ATD lightning field:





- Radar Variables:
  - Un–normalized CFADs:
    - Z_H (dBZ) → 5 dBZ bin
    - Z_{DR} (dB) → 0.5 dB bin





Yuter & Houze, 1995; Zeng *et al*., 2001; Lang *et al*., 2003; Cifelli *et al*., 2004; Wang & Carey, 2005; Rogers *et al*., 2007; Cecil, 2011

Methodology (Cont.)

- Radar Variables (Continued):
  - Rain line:
    - Calculated using $Z_{DP} = 10\log_{10}(Z_H - Z_V)$ with Z_H > 35 dBZ and $Z_H > Z_V$
    - Z_V obtained from Z_{DR}:

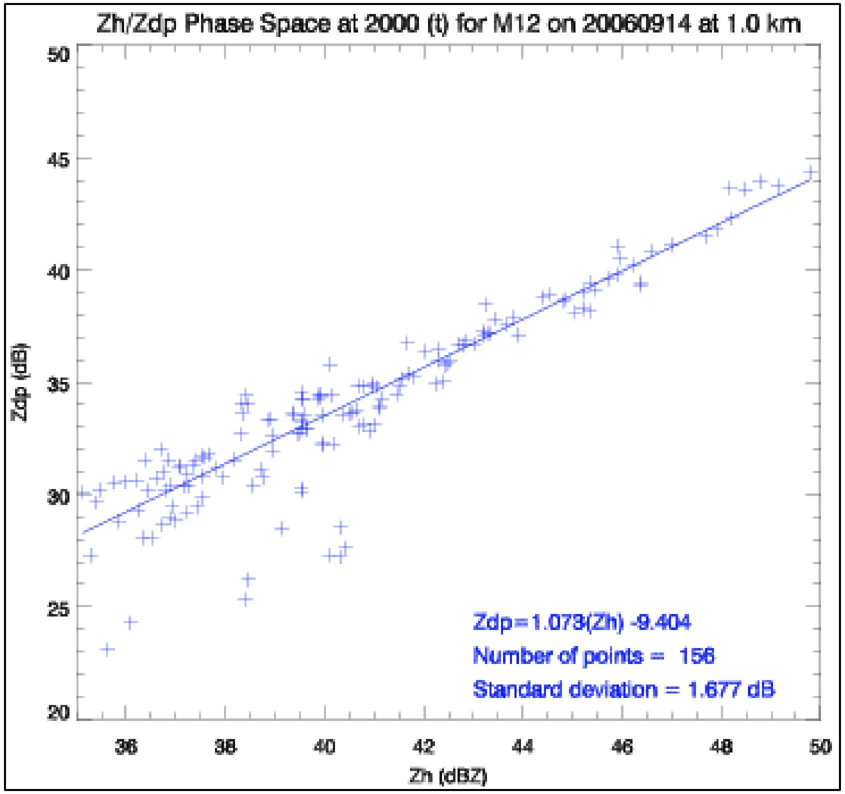
$$Z_{DR} = 10\log_{10}\left(\frac{Z_H}{Z_V}\right)$$

  - Calculate water and ice fractions to get masses

$$f_R = \frac{Z_{HR}}{Z_H} \longrightarrow f_I = 1 - f_R$$

$$M_w = 3.44x10^{-3}(Z_{HR})^{(4/7)}\ (gm^{-3})$$

$$M_i = 1000\pi\rho_i N_0^{\frac{3}{7}}\left(5.28x10^{-18}\frac{Z_{HI}}{720}\right)^{(4/7)}\ (gm^{-3})$$



* Meischner *et al*., 1991; Aydin & Giridhar, 1992; Doviak & Zrnić, 1993; Carey & Rutledge, 1996; Tong *et al*., 1998; Carey & Rutledge, 2000; Cifelli *et al*. 2002; Wang *et al*., 2007

Methodology (Cont.)

- MSG Satellite Interest Fields: **— Cloud**

10.8 µm, Channel 9 :

288	284	279	275	269	266	270	278	281
283	276	267	260	258	261	264	273	279
274	253	233	230	234	241	242	253	274
263	226	200	206	211	222	224	249	280
255	212	201	202	209	222	244	274	288
260	217	200	208	213	228	264	285	286
268	243	221	220	225	248	273	287	284
272	269	259	257	264	273	286	288	285
280	280	278	277	279	283	288	288	286

6.2 µm, Channel 5:

235	234	235	235	235	235	236	236	236
234	234	233	233	234	234	234	234	235
234	228	218	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
232	215	200	202	209	218	220	225	233
228	205	199	202	207	216	225	233	236
229	209	199	206	211	216	229	235	235
233	223	211	212	217	225	233	236	235
235	233	230	229	231	233	235	236	235
235	235	235	235	235	235	235	235	236

Main updraft

7.3 µm, Channel 6 :

256	255	255	255	254	254	254	256	256
255	252	249	247	248	250	250	253	255
251	237	225	226	231	235	233	241	252
246	217	199	203	212	221	221	236	253
239	206	202	203	211	221	236	251	256
237	204	200	206	210	228	250	257	256
249	232	216	219	223	240	254	256	256
254	251	244	244	247	253	256	256	256
255	255	255	255	256	256	256	256	256

27 km

8.7 µm, Channel 7:

287	282	277	273	269	265	269	276	280
282	274	266	260	259	260	264	272	279
273	254	236	233	236	241	243	256	276
262	227	201	207	213	225	229	253	281
254	214	204	204	213	224	248	275	286
261	215	200	208	213	233	266	284	284
269	245	221	224	231	252	278	285	282
271	270	261	259	265	272	284	286	282
279	279	278	276	278	283	287	286	284

12.0 µm, Channel 10 :

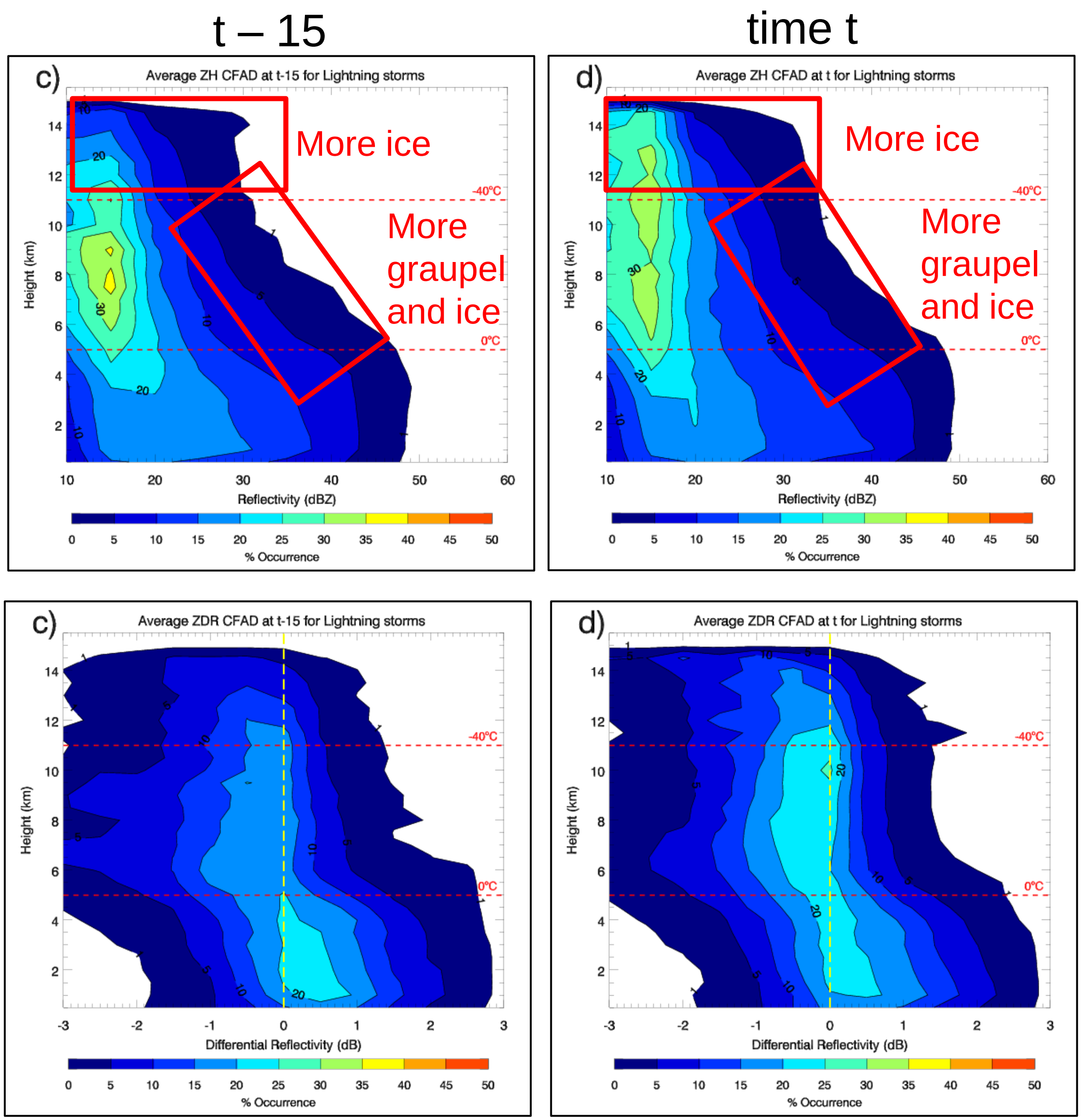
284	282	277	274	268	266	269	277	280
280	274	265	259	257	260	263	272	278
271	251	230	229	234	240	241	252	273
260	223	201	205	212	222	226	248	278
251	211	202	203	211	223	242	272	285
256	215	201	208	213	228	262	283	284
265	241	220	220	227	249	277	285	283
269	266	257	255	262	273	283	285	283
277	278	276	275	277	281	286	285	284

Did the same for the OCA fields:

- Cloud Phase
- Cloud–Top Pressure
- Cloud Effective Radius

Strabala *et al*., 1994; Ackerman, 1996; Schmetz *et al*., 1997; Setvák *et al*., 2003; Mecikalski & Bedka, 2006; Mecikalski *et al*., 2008; Rosenfeld *et al*., 2008; Harris *et al*., 2010; Mecikalski *et al*., 2010a,b

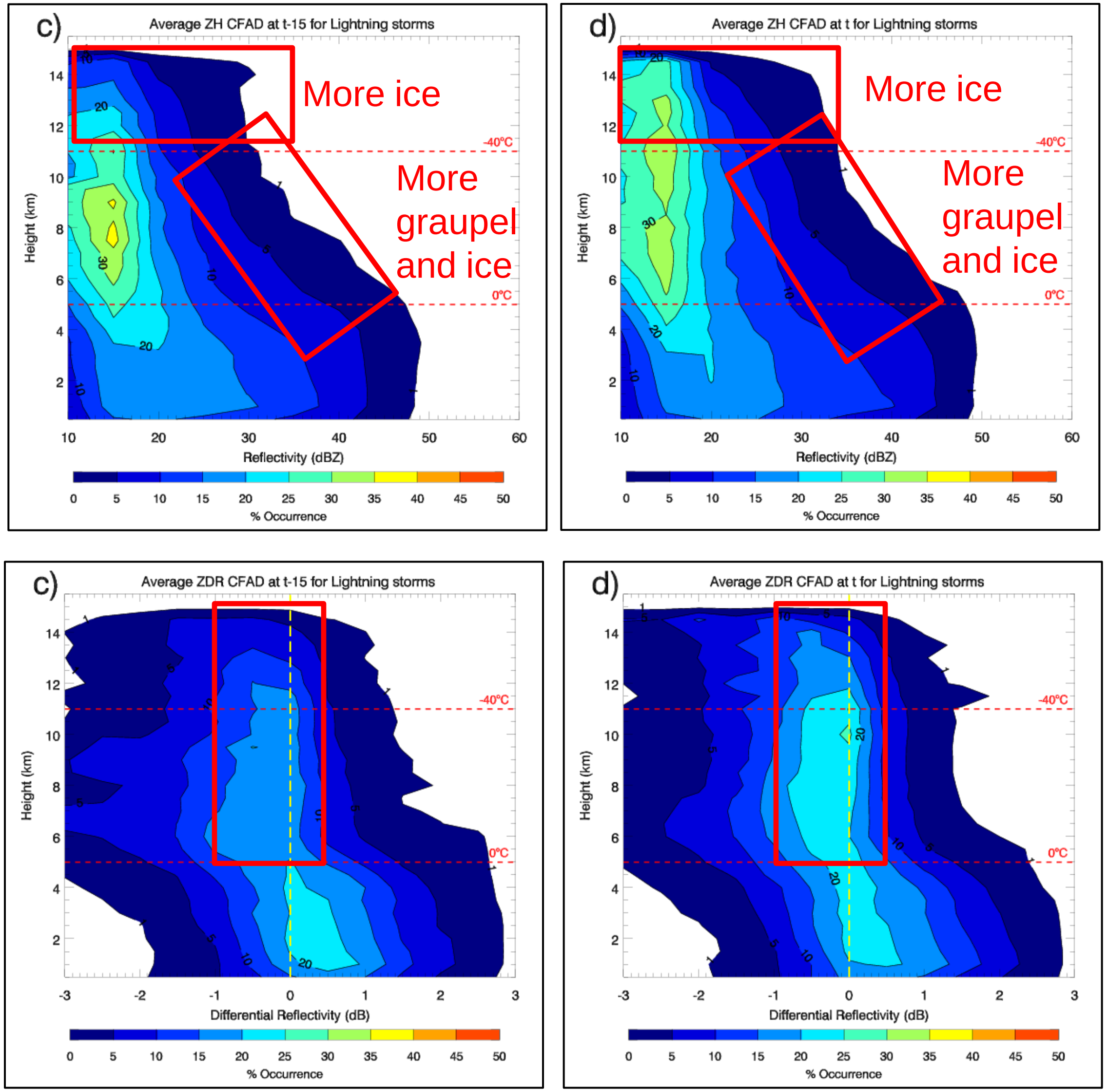
Z_H and Z_{DR} – Lightning Storms



- During the time just prior to the first CG lightning, storms show significant volumes of hydrometeors within the mixed-phased layer (0 to –40 °C), which is where charging will occur.
- Differential reflectivity (Z_{DR}) confirms the (high likelihood) presence of graupel and large ice hydrometeors within this same region.
- Cloud tops are comprised of snow and eventually ice crystals.
- Clouds reach >15 km.

Z_H and Z_{DR} – Lightning Storms

t – 15 | time t



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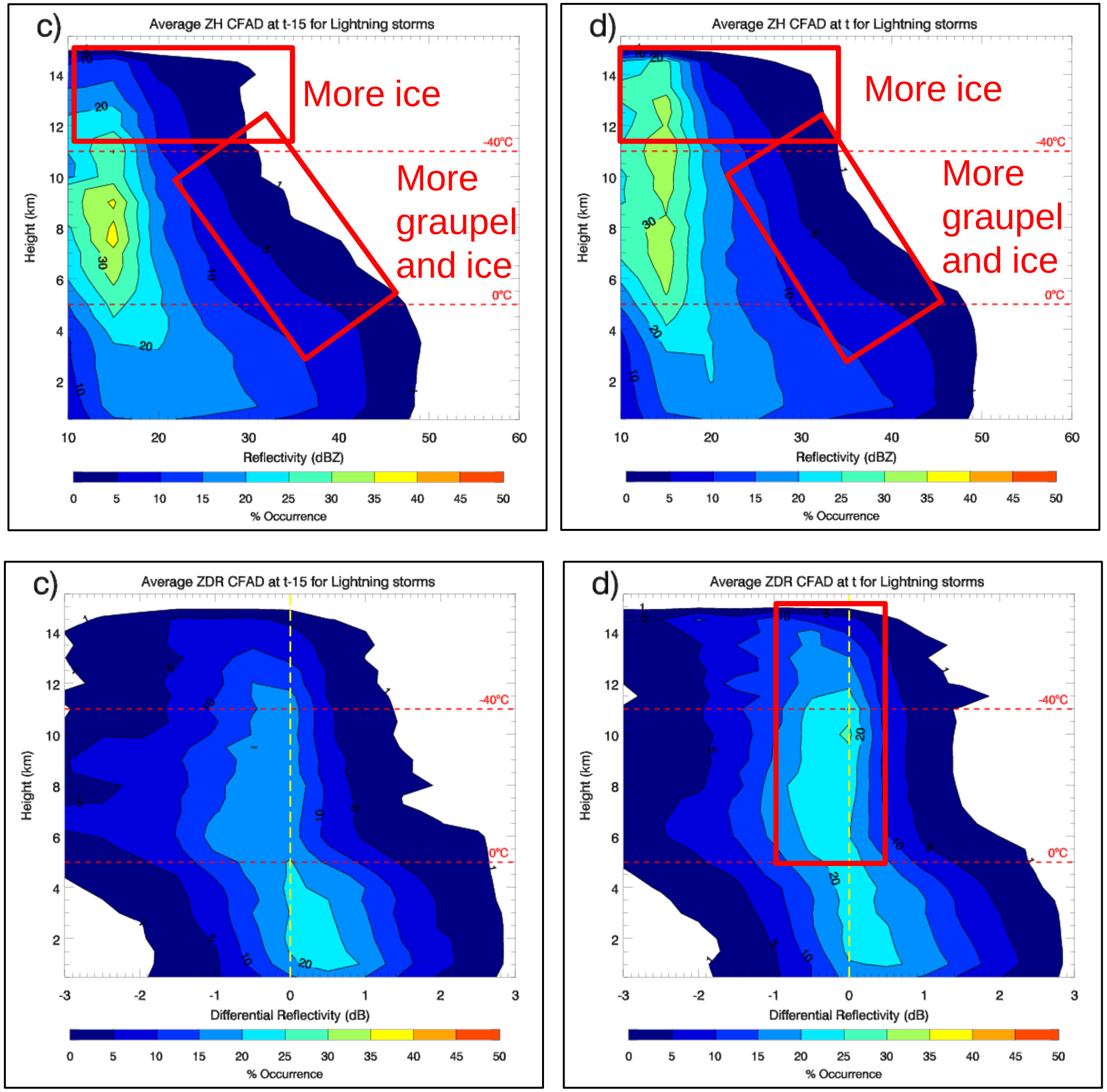
Z_H and Z_{DR} – Lightning Storms

t – 15 time t



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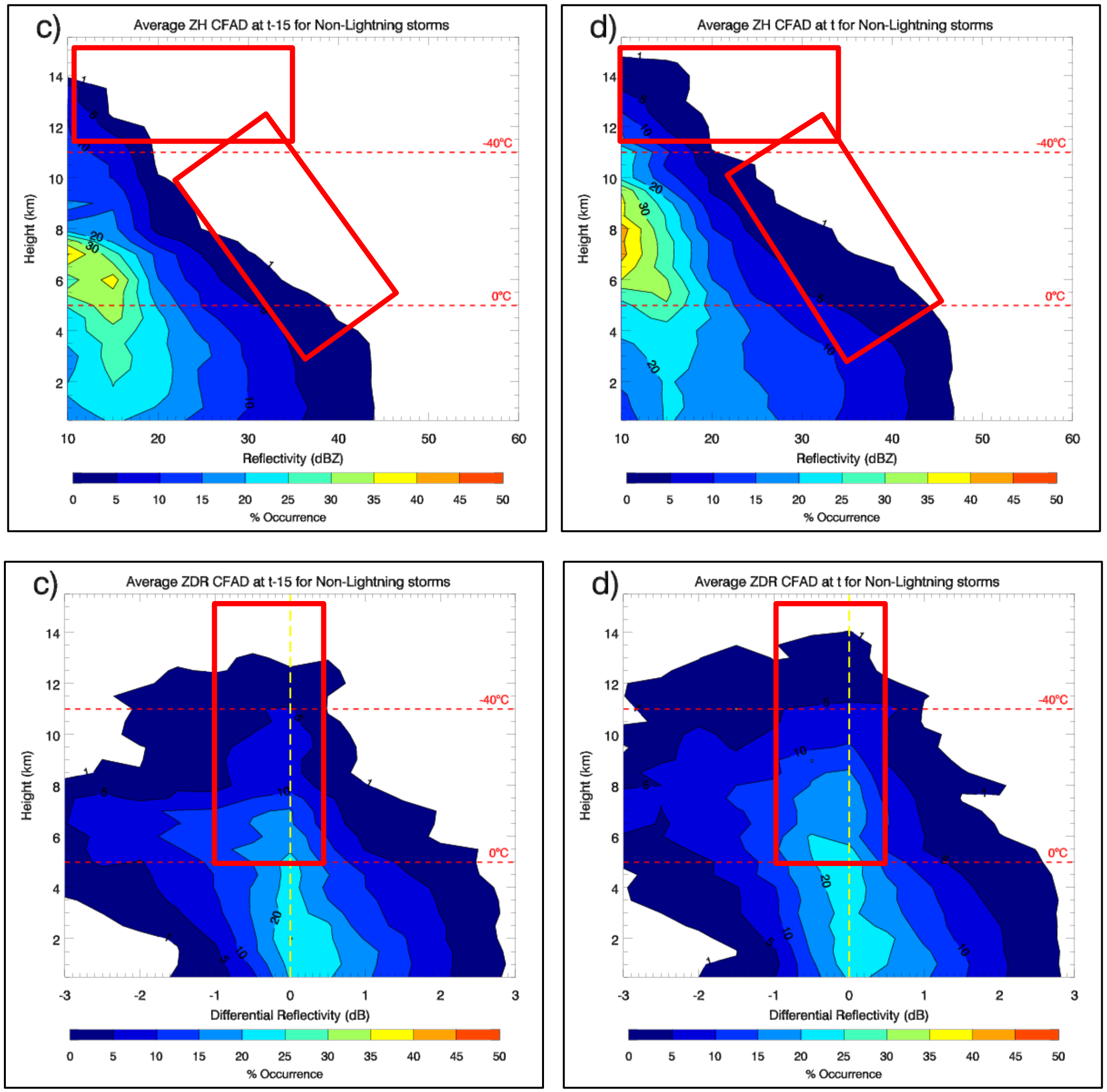
- Differential reflectivity (Z_{DR}) confirms the (high likelihood) presence of graupel and large ice hydrometeors within this same region.
- Cloud tops are comprised of snow and eventually ice crystals.
- Clouds reach >15 km.

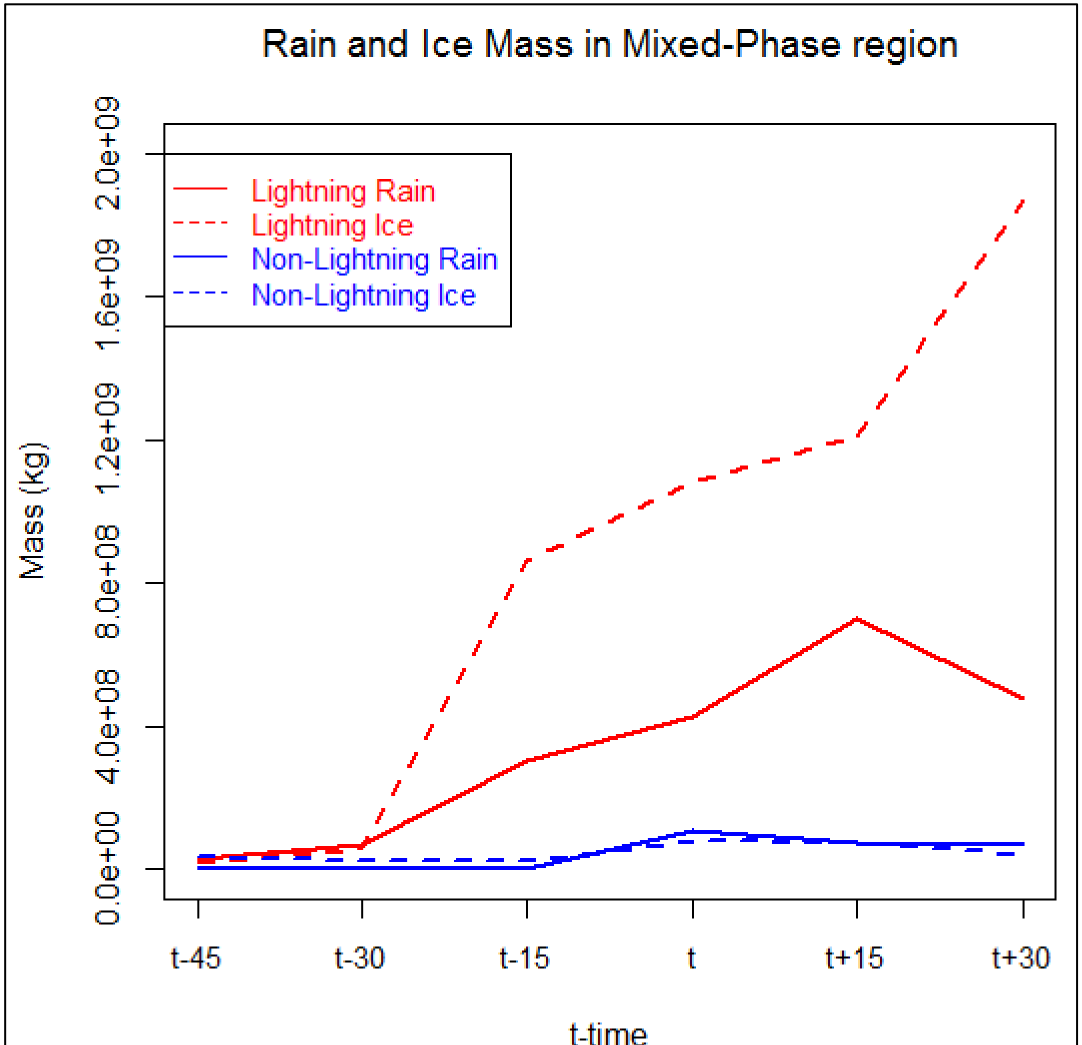
Z_H and Z_{DR} – Non-Lightning Storms

t – 15 | time t



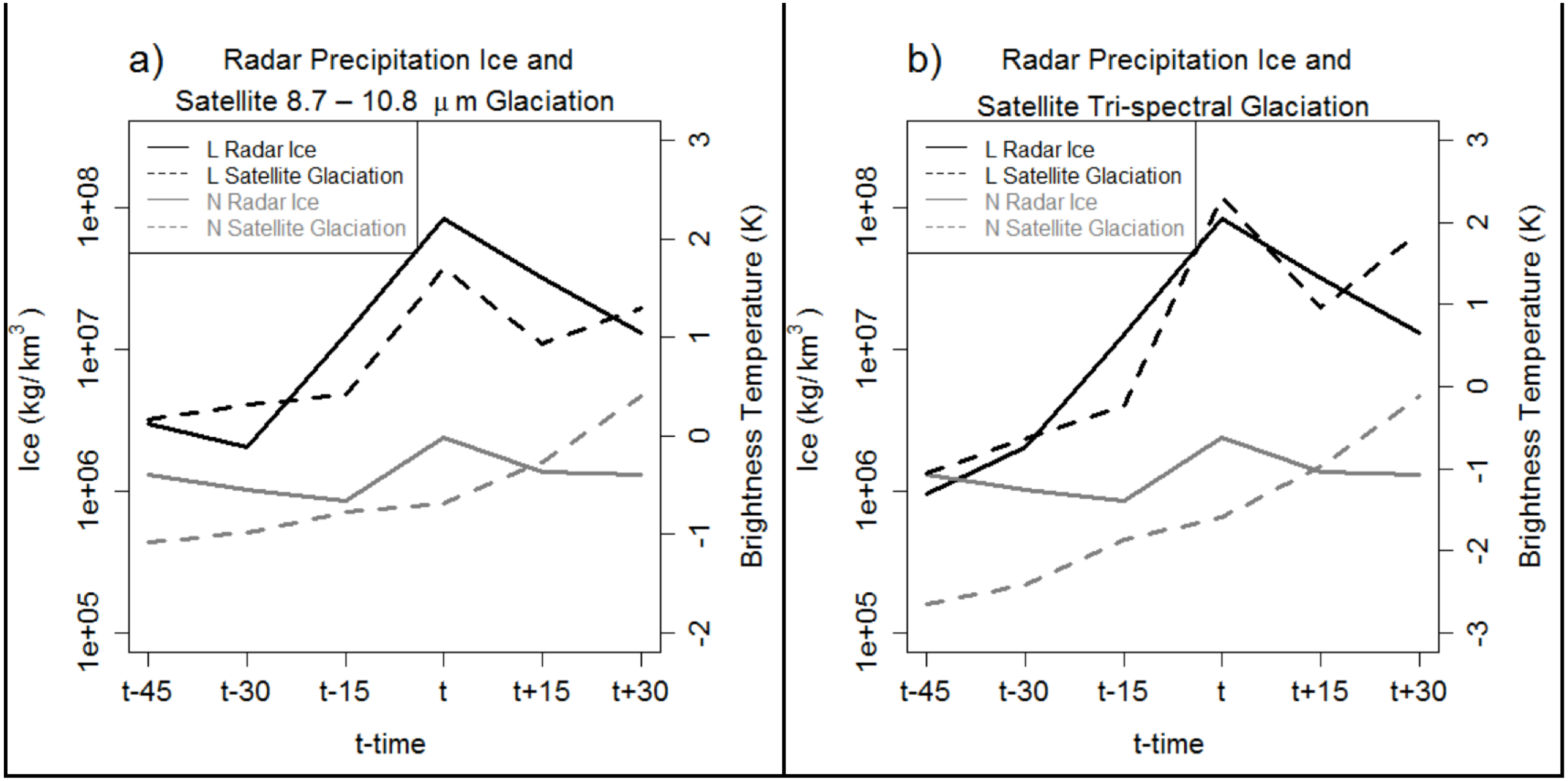
- During the time just prior to the maximum volume of ≥35 dBZ echoes (as lightning was not observed), storms show increasing hydrometeors within the mixed-phased layer (0 to –40 °C).
- However, differential reflectivity shows a lack of graupel and large ice hydrometeors within this same region.
- Cloud tops are lower, and there is no indication that updrafts extend above ~12 km.

0 °C to –40 °C Rain and Ice Masses



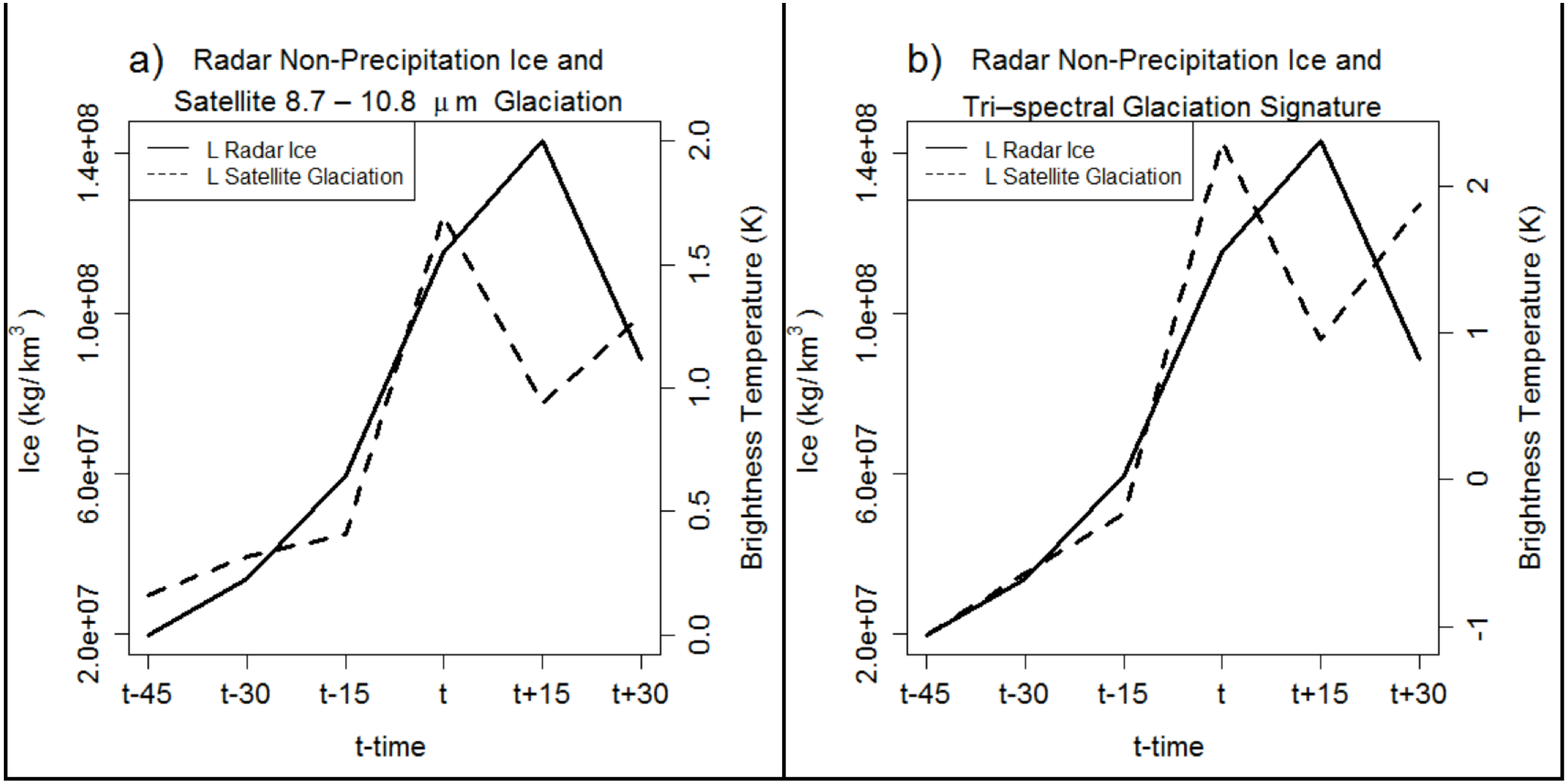
- Lightning storms have more ice than water in the mixed-phase region
- Lightning storms have much more ice AND water than non-lightning storms in the mixed–phase region
- Non–lightning storms have more water than ice between t-15 and t+15

Precipitation Ice Masses



All lightning storms are seen in black and the non–lightning storms are in grey. For both images, the radar precipitation field is a solid line and the satellite interest field is a dashed line.

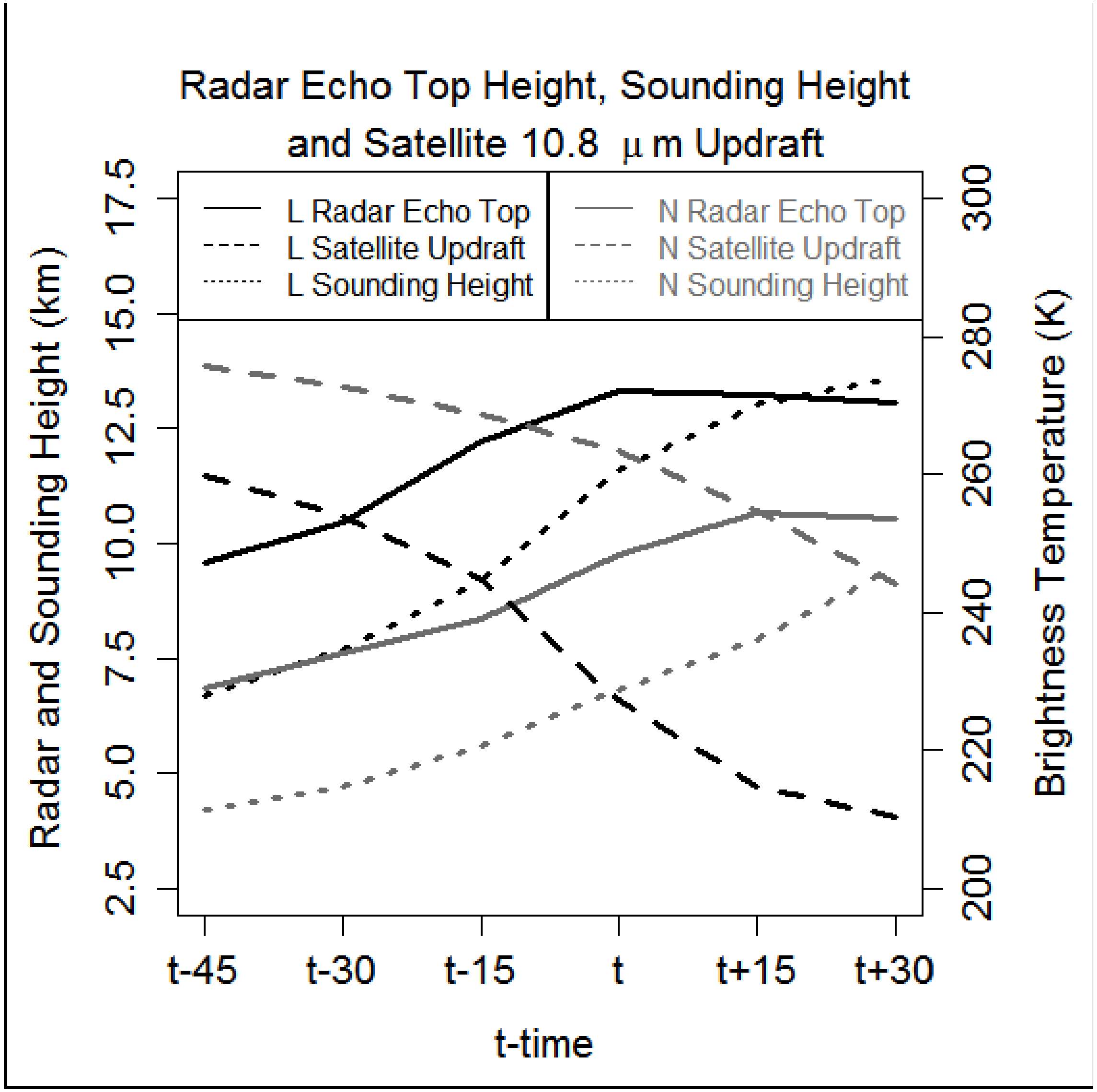
Non-Precipitation Ice Masses



Non−precipitating ice mass for **the top 1 km of the cloud** (black solid line) for the lightning storms compared to the satellite tri−spectral glaciation field (a) and the 8.7 – 10.8 μm glaciation field (b), both in dashed lines.

Cloud & Echo Top Heights

Lightning-producing convection is deeper, with a more pronounced updraft.



2012-2015 NSF Project – Science Hypotheses

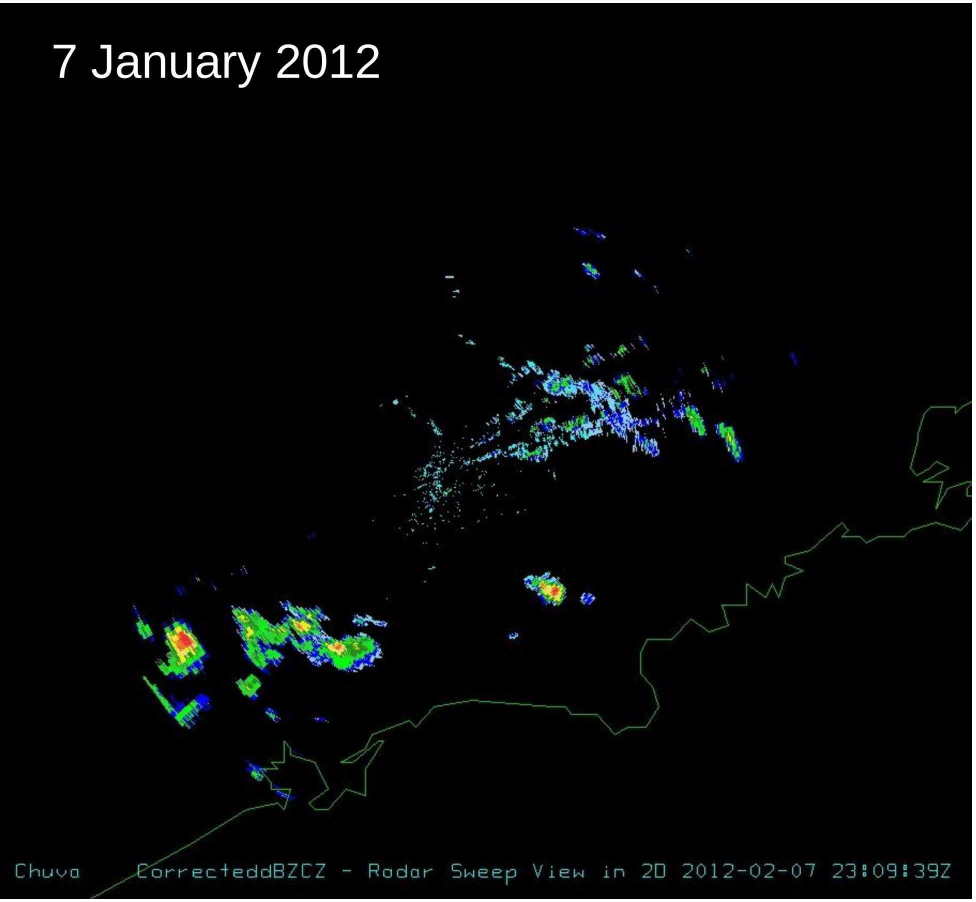
1. The kinematic and microphysical processes related to **lightning development and evolution** can be better understood through the *combined use of* satellite IR and retrieved cloud properties (e.g., cloud optical depth, particle effective radius, ice-water path), dual-pol radar observation, NWP (i.e. WRF LFA), and lightning fields (from LMA). Observed lightning will be a function of environmental factors.

2. The physical processes related to total lightning amount (flash density rates) in convective storms can be understood through analysis of GOES/MSG IR imagery, satellite-derived quantities, C-/S-/X-band dual-pol radar, and unique field observations from *CHUVA*.

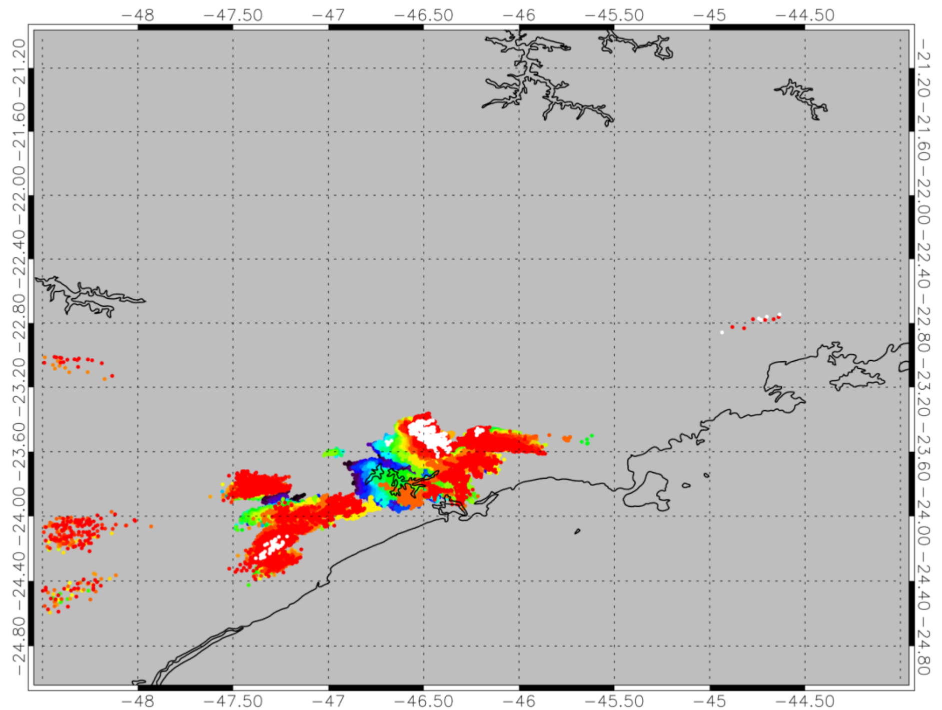
3. Developing accurate, short-term *quantitative predictions* of initial lightning occurrence, lightning rates, and total lightning activity can be obtained with combined use of dual-pol radar observations, satellite fields, and NWP model data.

4. *Aerosol-lightning relationships* that enhance predictability of lightning amounts can be established by incorporating readily available aerosol retrievals.

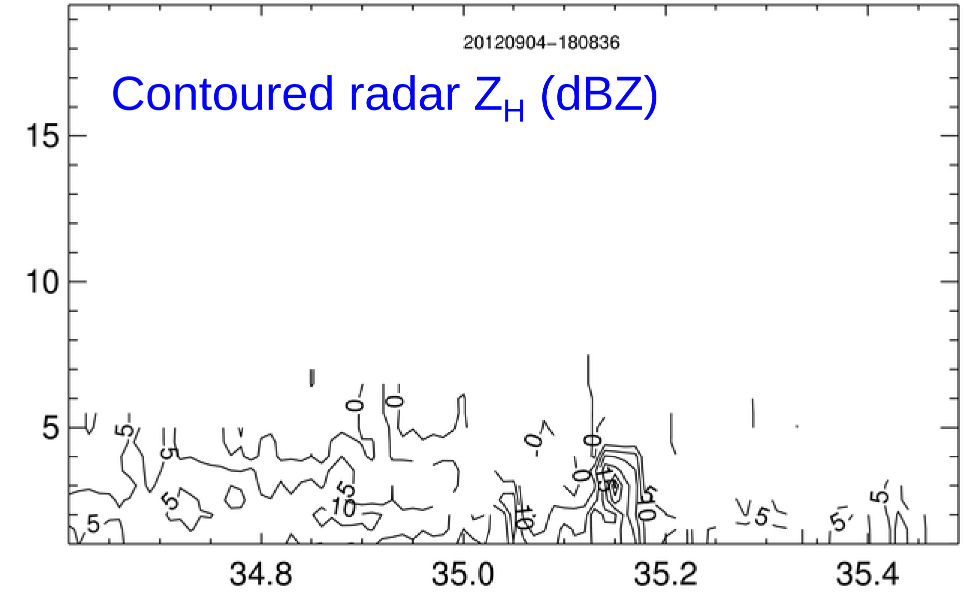
Objectives 1 & 2 – Basic Understanding

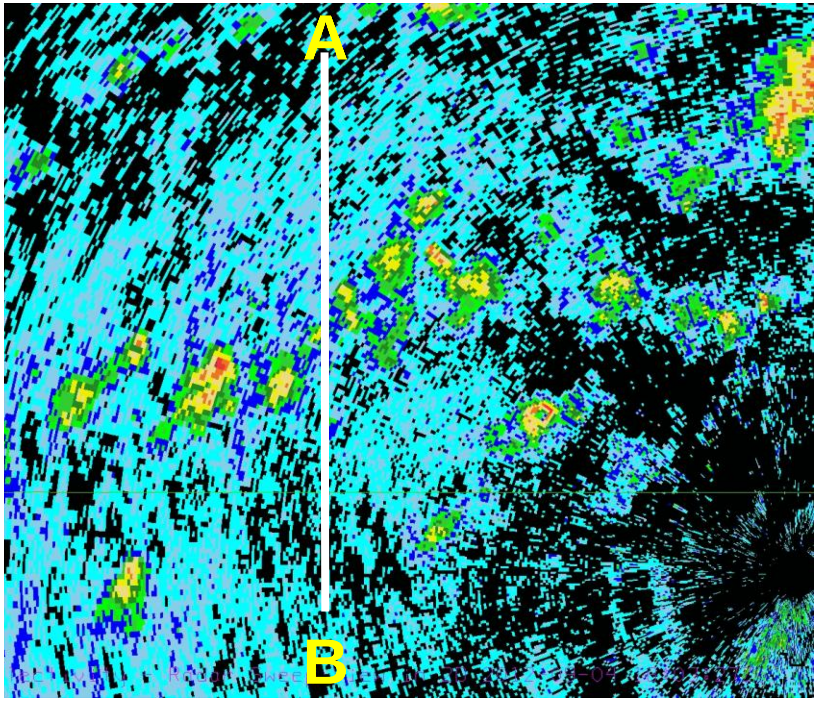


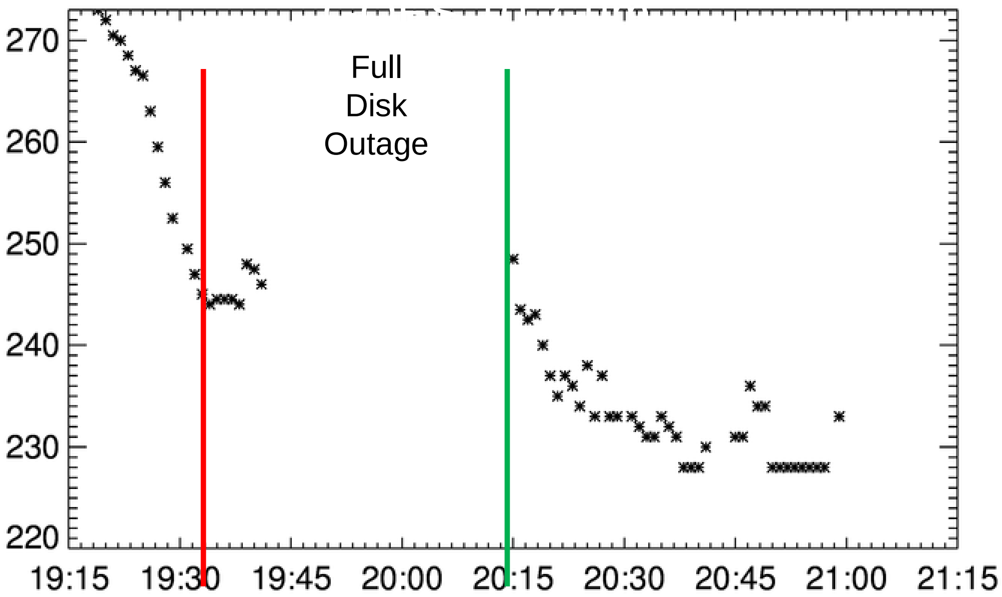
Jason Apke



Example of CHUVA X-band radar data (*left*) with lightning data colored by time (*right*). These data are soon to be combined with 15 minute temporal resolution MSG data, covering 12 spectral channels.







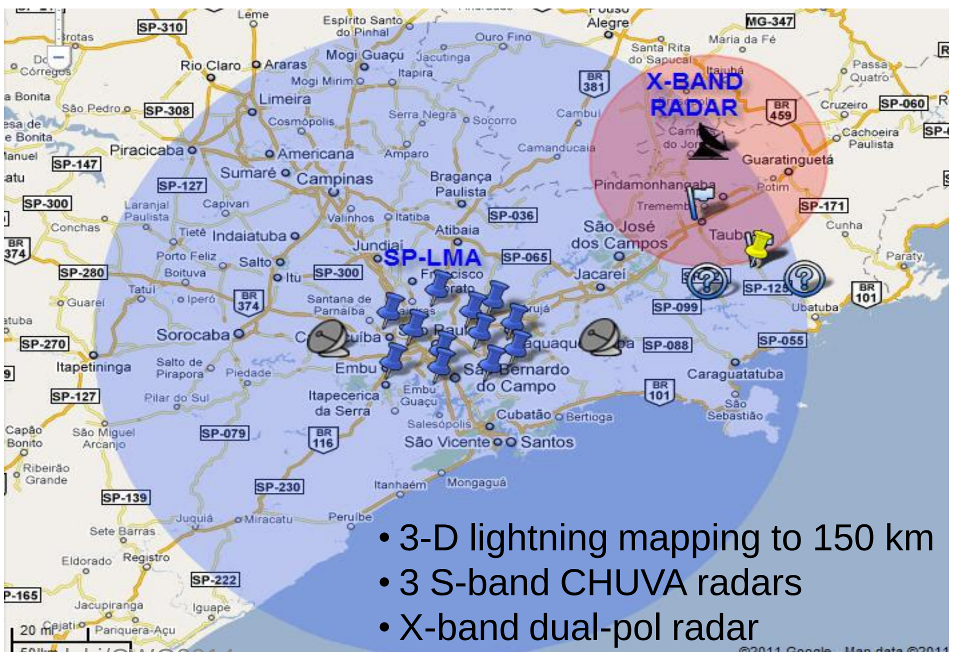
4 September 2012 Reflectivity cross section with North Alabama LMA resolved VHF radiation sources shown with stars (*top left*), reflectivity PPI at the same time (*top right*) and GOES SRSO 10.7-µm T_B coldest pixel (found in a cluster identified with WDSS-II K-means and watershed clustering) with first bubble lightning initiation (LI) shown with a **red** line and second bubble LI shown with a **green** line (*bottom left*).

Jason Apke

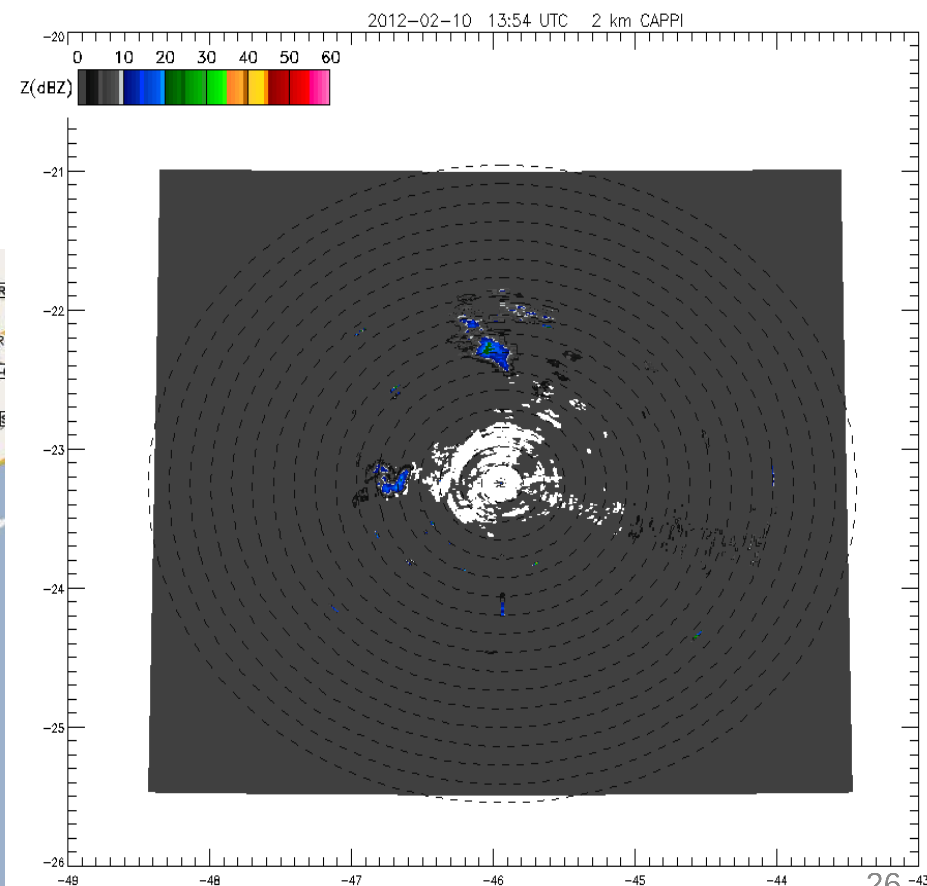
Objectives 1, 2 & 3: *CHUVA GLM–Vale do Paraiba Campaign* (2011 November – 2012 April)

- Analyze radar data for in-cloud processes, satellite data for cloud top properties, and lightning data – lighting activity behavior to form relationships between lightning, in-cloud processes and satellite-observed fields.
- Generate 3-D view from bottom to top imaging processes related to the change in lightning activity – examine cloud top properties before and after LI, quantify with respect to lightning source amounts; determine precursors in satellite data for prediction of total lightning amount.

- Level-2 reflectivity at 2 km altitude from S-band radar IACIT (close to X-pol site) every 30 min on 10 February 2012

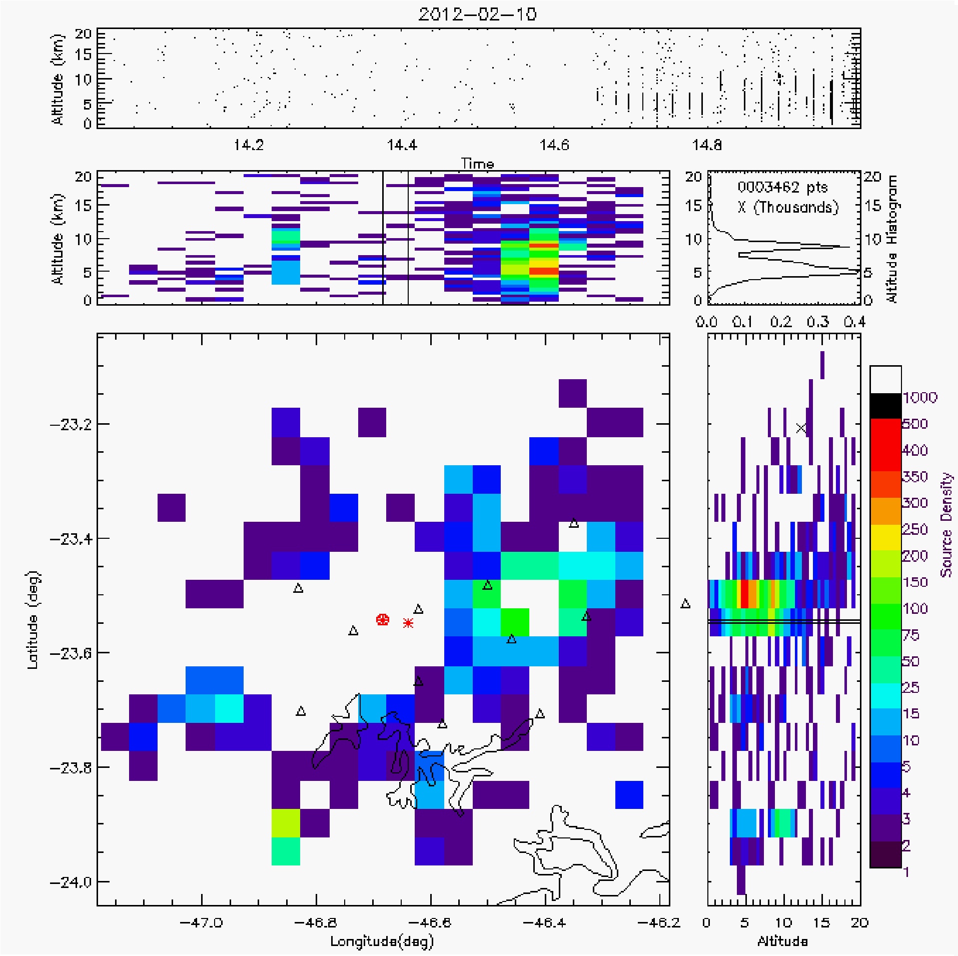


- 3-D lightning mapping to 150 km
- 3 S-band CHUVA radars
- X-band dual-pol radar

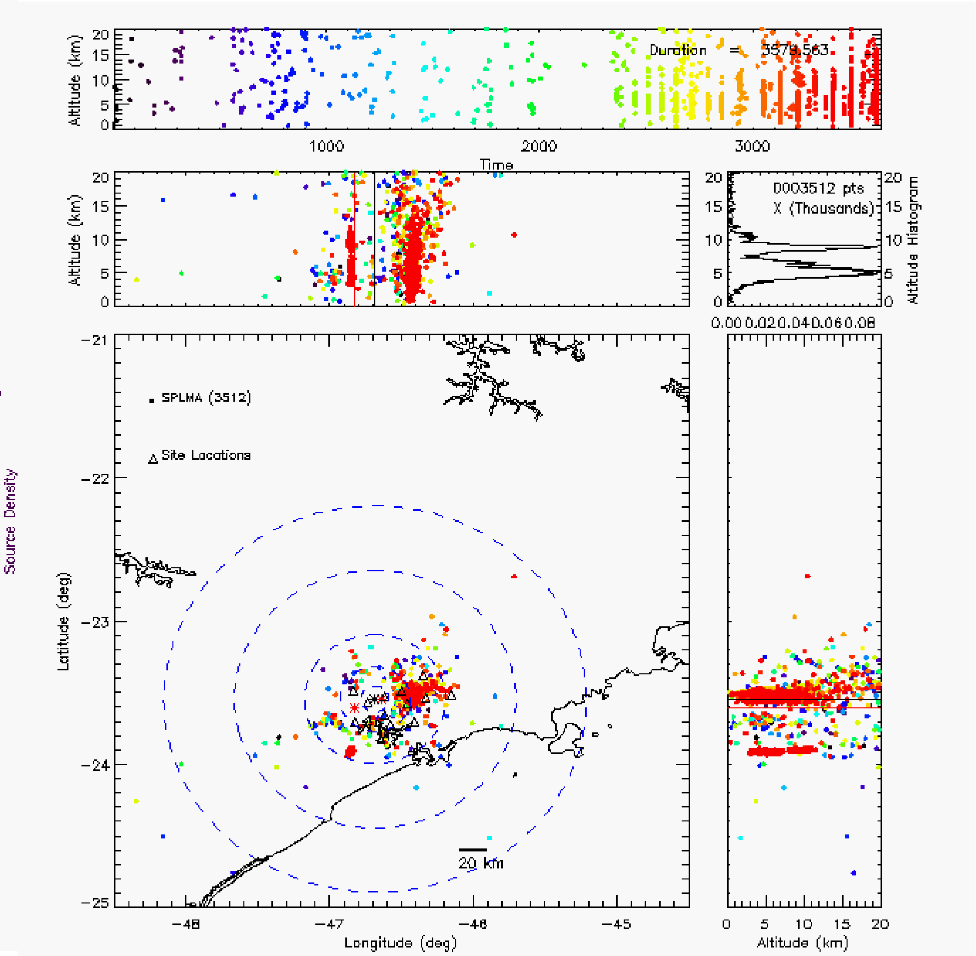


LMA data – Vale do Paraiba campaign

1400–1500 UTC 2012-02-10

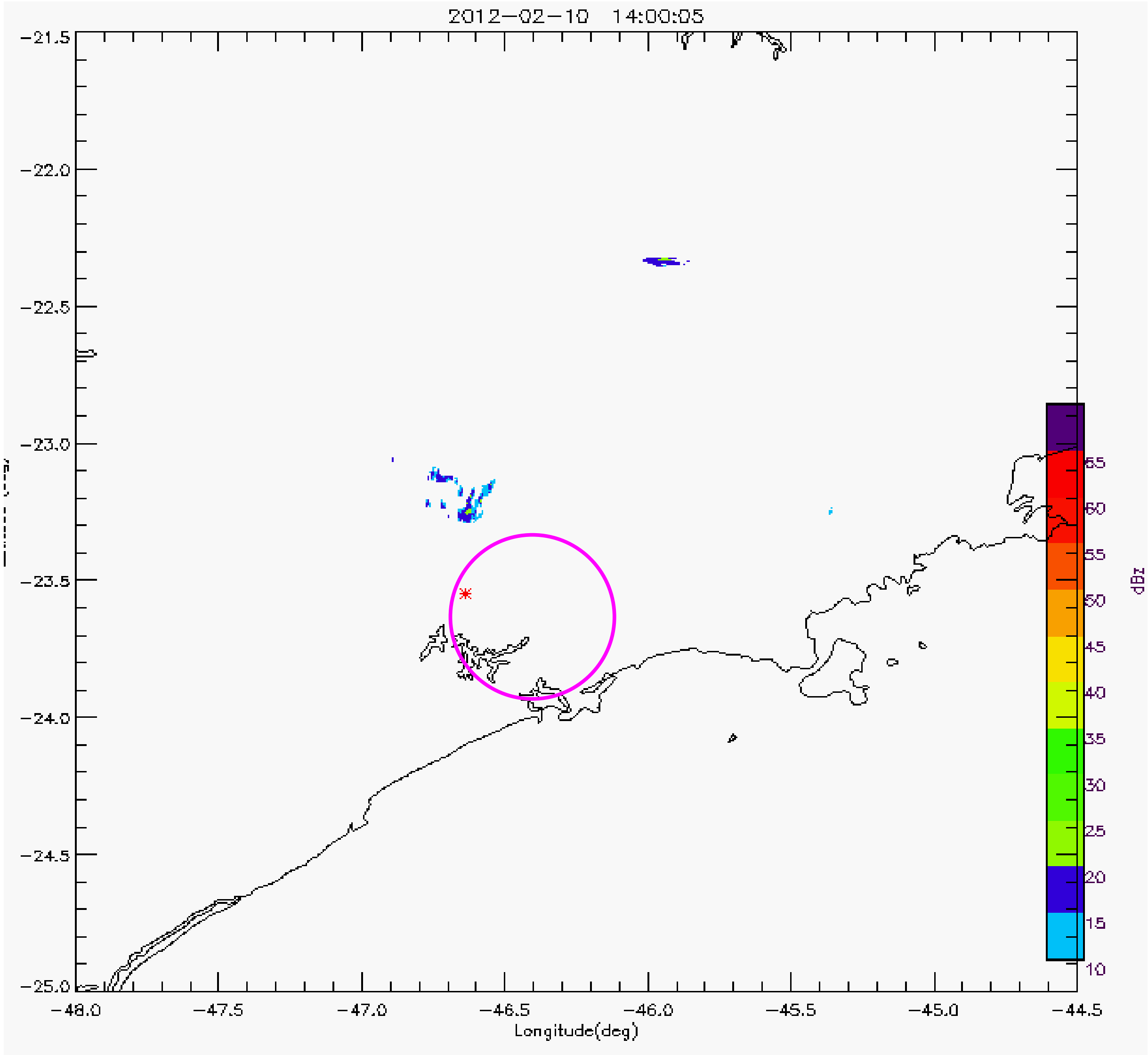


Source Density

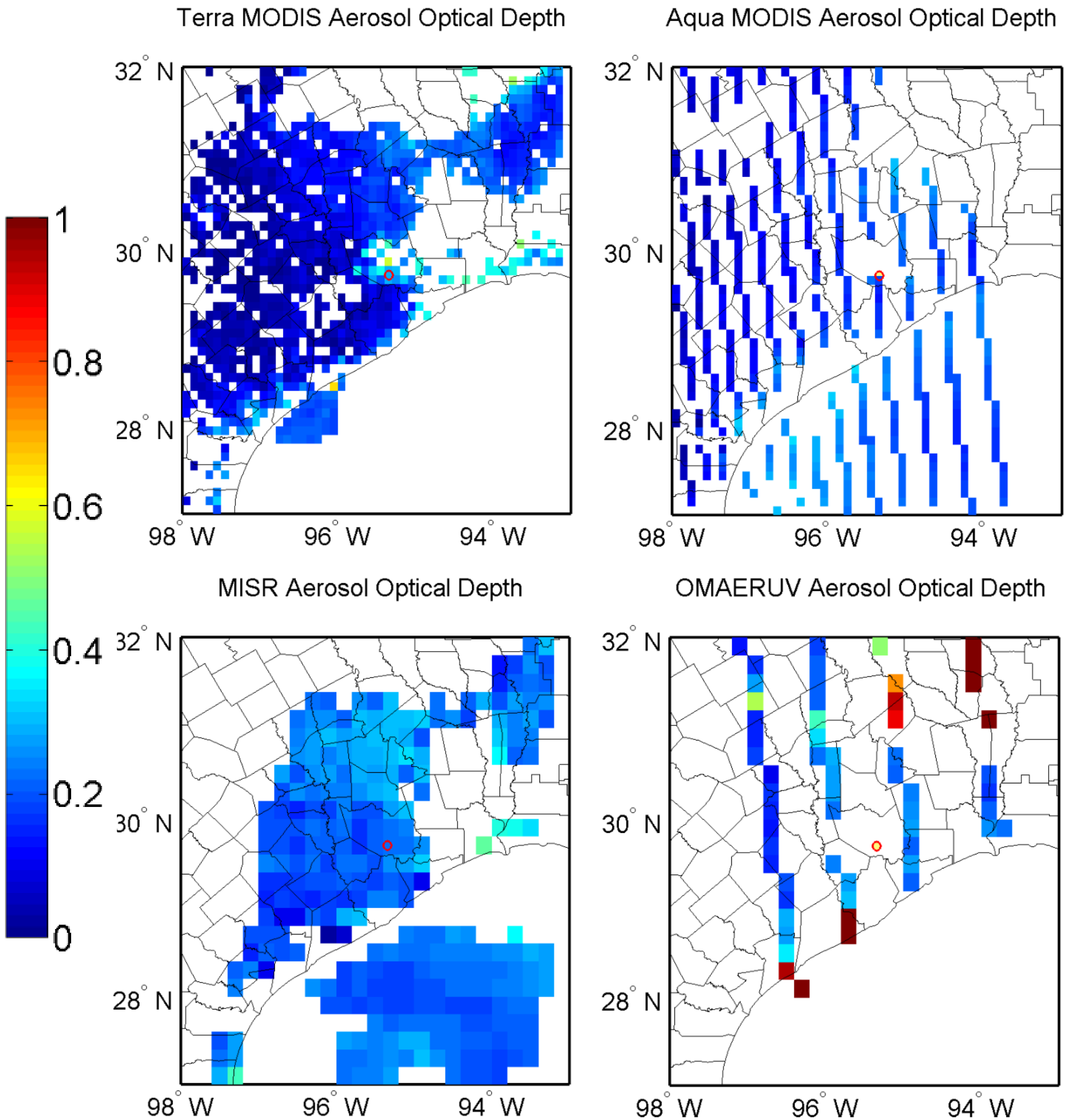


Sources

X-Band Reflectivity 1400 – 1500 UTC on 2012-02-10



Objective 4

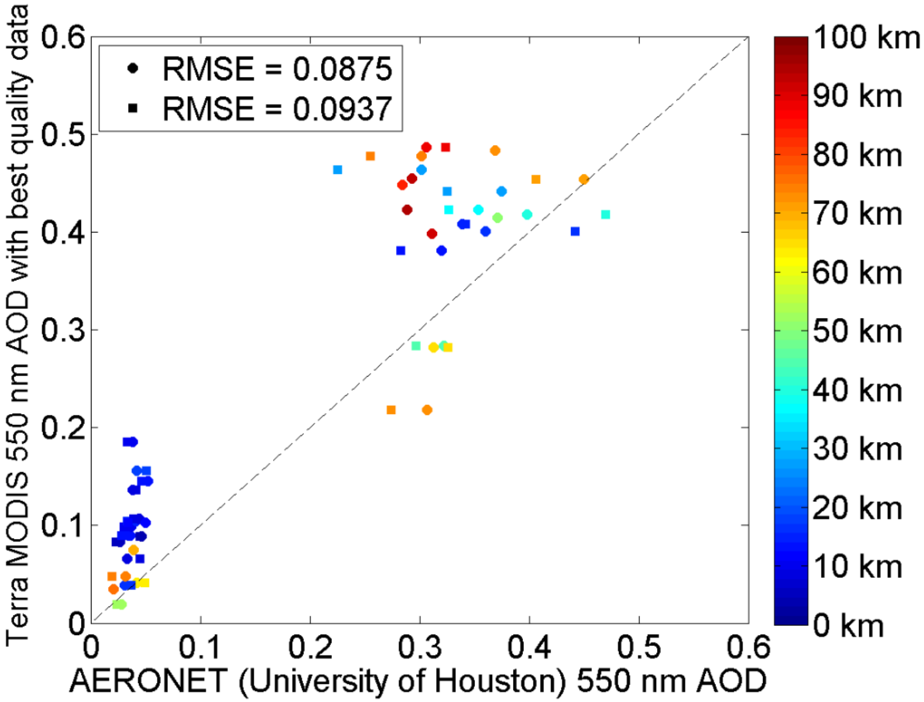


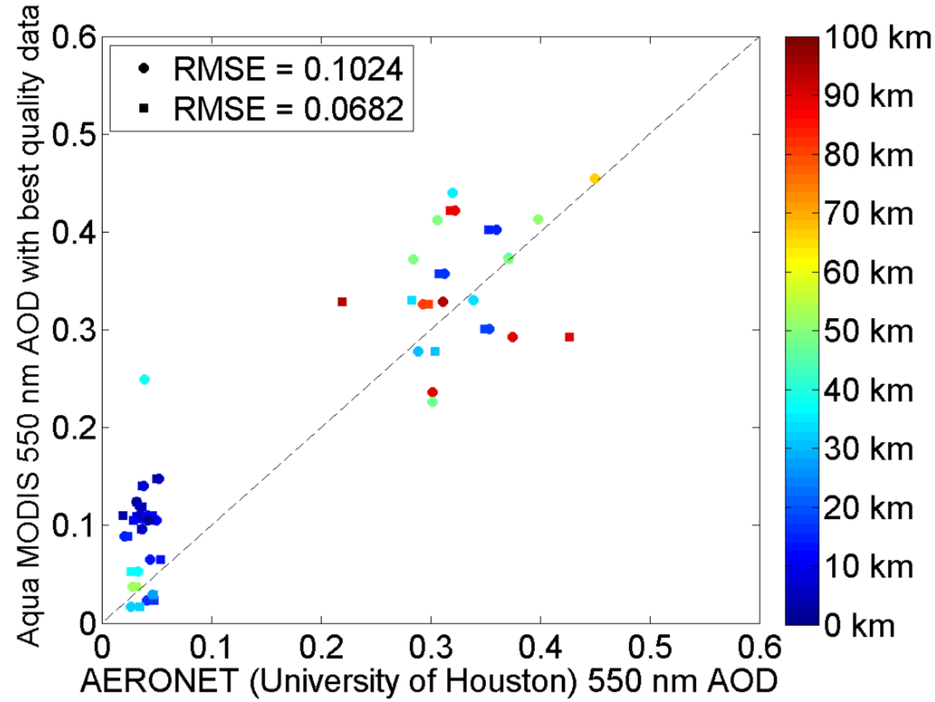
Examples of 4 satellite-based optical depth retrievals around the greater Houston area on 18 March 2013.

Univ. of Houston AERONET site

- Terra and Aqua MODIS have most days with retrievals during early 2013.
- MISR: fewer days with retrievals
- OMI: high uncertainty, poor comparisons with AERONET

Comparing MODIS and AERONET for the 20 most pristine and polluted days in 2013





- Daily averaged AERONET
- AERONET average ±1 hour around overpass

MODIS aerosol products will be used for helping understand/improve lightning prediction because they have good availability and relatively small uncertainties.

Total lightning from Houston LMA

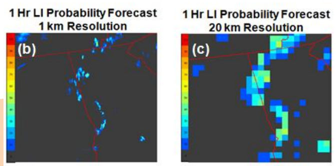
<u>Also… New in 2014</u>: Putting the satellite, radar, NWP (WRF model) diagnostics and LMA/pseudo-GLM fields together into one "lightning threat" nowcasting system

(a) GOES-R CI cloud object tracking
(b) WDSS-II object tracking with projected lightning threat (location, amount) areas
(c) Real-time monitoring of lightning on a per-cell basis, on to cessation

Multi-Source Lightning Prediction Algorithm (MSLPA)

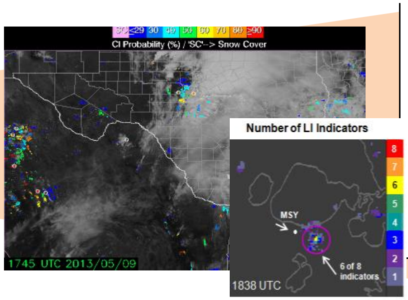
A complete picture of lightning potential from initiation through cessation.

Iskenderian et al. (2013)



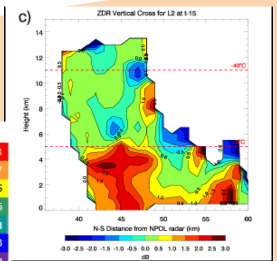
GLM

Mecikalski et al. (2008)
Harris et al. (2010)
Walker et al. (2012)



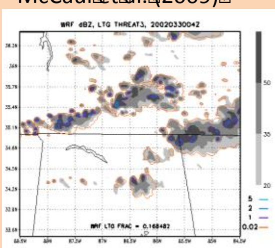
GOES-R CI/LI

e.g.,
Buechler & Goodman (1990)
Vincent et al. (2004)
Mosier et al. (2011)
Woodard et al. (2012)

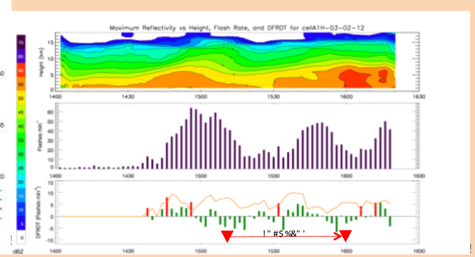


Radar/Dual-Pol

McCaul et al. (2009)



WRF LFA



LMA & Proxy GLM data

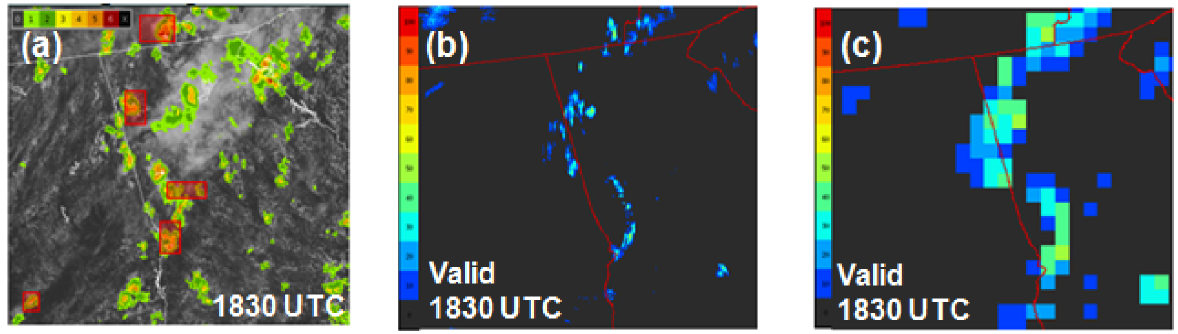
Low Probability Initiation (~30-40 min lead times) → High Prob. Initiation (~10-20 min lead times) → Prob. Continuation → Prob. Cessation (~10-20 min lead times)
→ Max. Flash Rates (~10-20 min lead times)

NOAA/NWS → Real-time Probability Displays

Private Sector Companies → Probability-based Customer Alerts

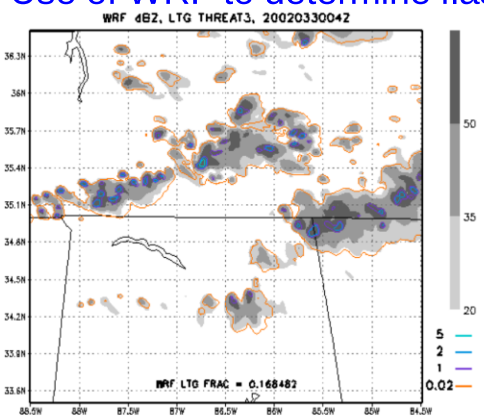
Lightning Threat Product (Iskenderian et al. (2014)

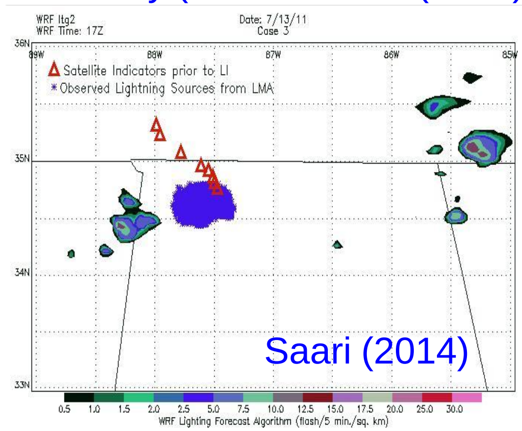
Radar, Visible Satellite, & CG Lightning Initiation Regions | **1 Hr LI Probability Forecast 1 km Resolution** | **1 Hr LI Probability Forecast 20 km Resolution**



Working in collaboration with NASA SPoRT, development of training and transition materials.

Use of WRF to determine flash density (McCaul et al. (2009)





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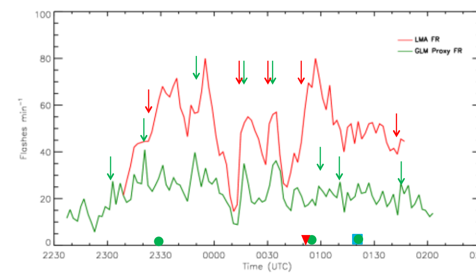

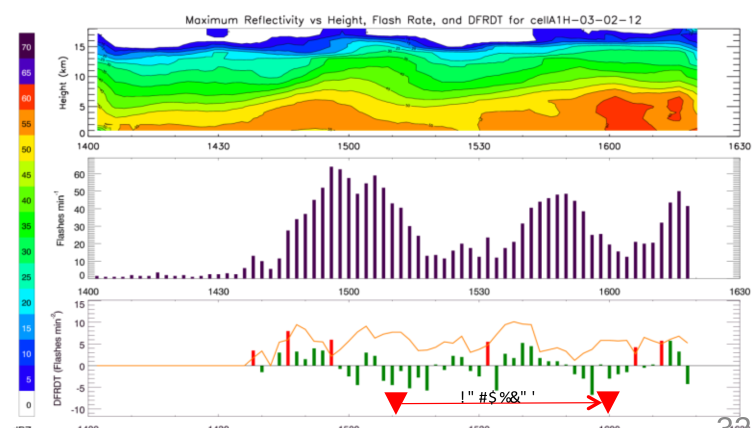

Per-cell monitoring of lightning, using local LMAs where available (pseudo-GLM data), GLD360/ENTLN, and GLM when available to provide per-storm statistics.