National Aeronautics and Space Administration

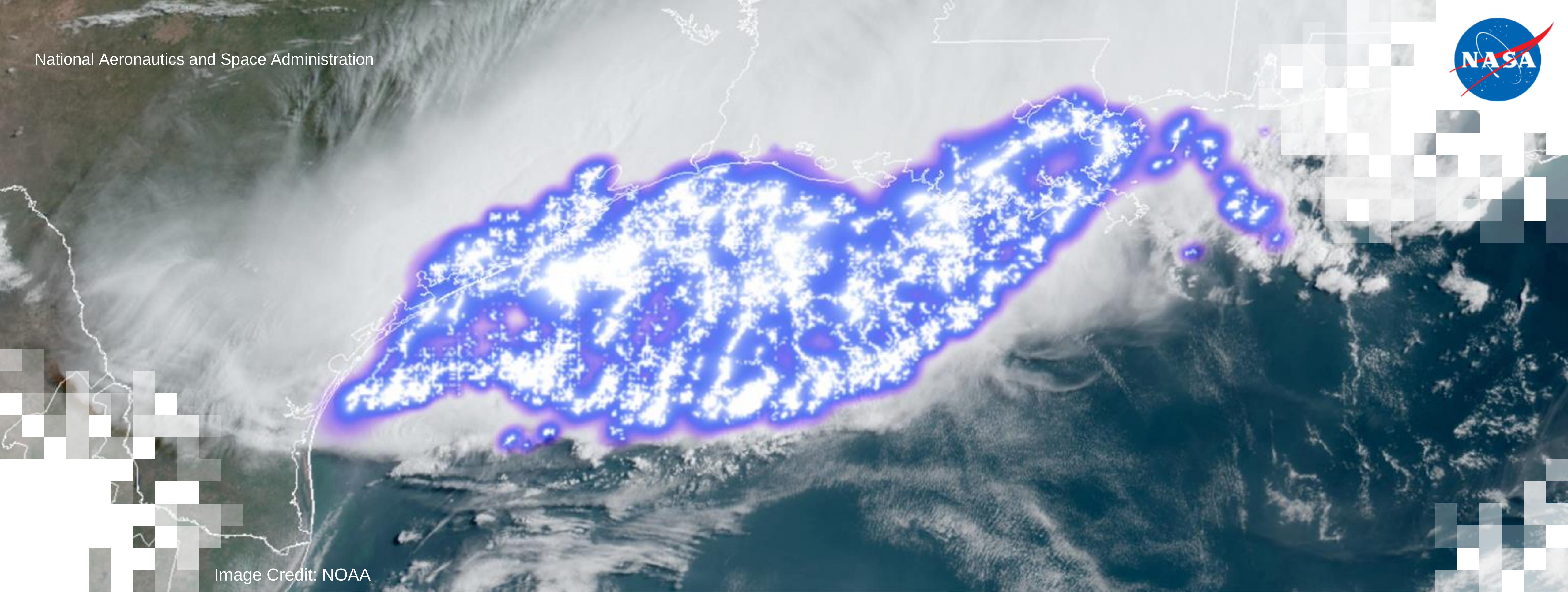
Image Credit: NOAA

Introduction to Lightning Observations and Applications

Part 1: Background and History of Lightning Measurements

Amita Mehta (NASA & UMBC GESTAR II) and Steven Goodman (NASA)

March 26, 2024

About ARSET

- **ARSET provides accessible, relevant, and cost-free training on remote sensing satellites, sensors, methods, and tools.**
- Trainings include a variety of applications of satellite data and are tailored to audiences with a variety of experience levels.

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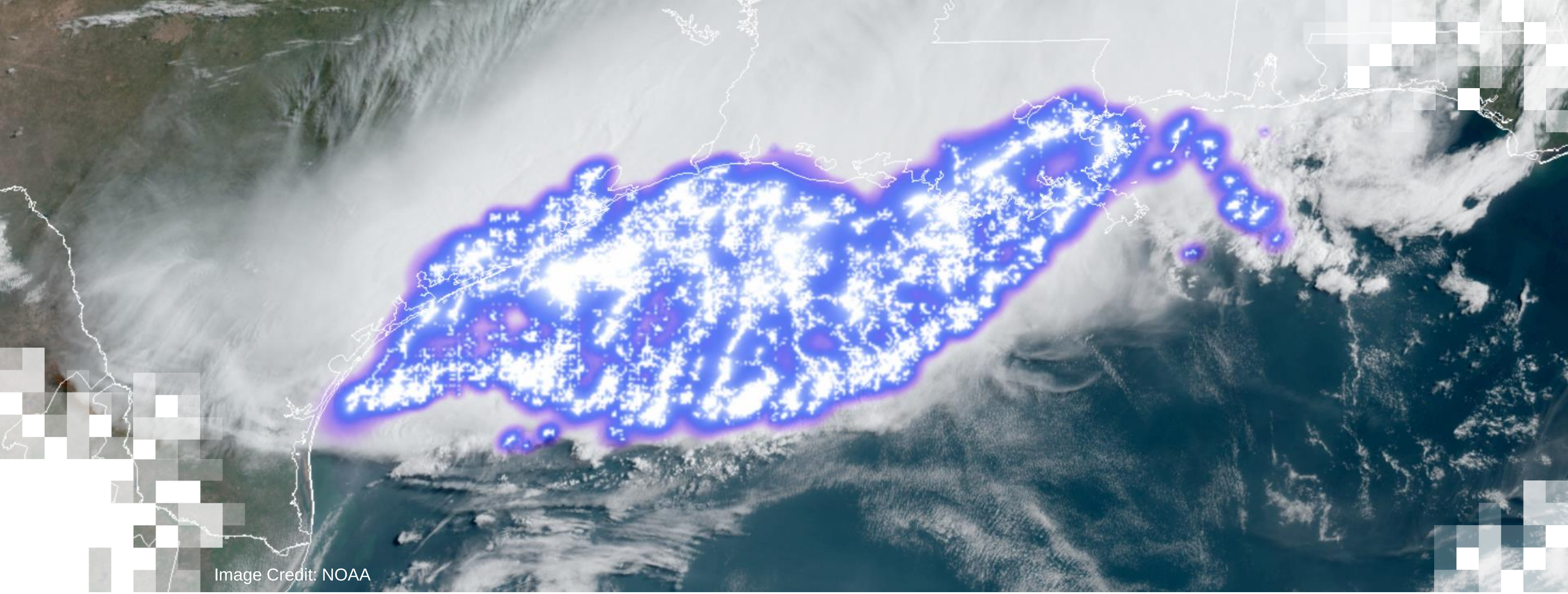


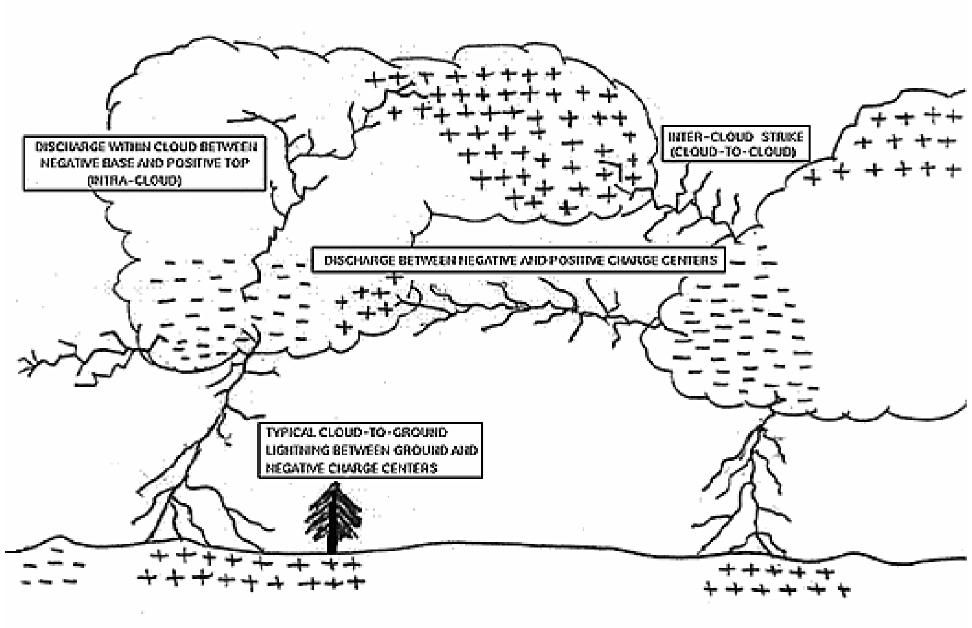
Image Credit: NOAA

Introduction to Lightning Observations and Applications

Background

What is Lightning?

- High-current electrical discharge between positively and negatively charged regions of a thunderstorm.
- Can occur within a cloud, between clouds, and between clouds and the ground.
- As ice particles within storm clouds grow, collide, and break apart, smaller particles acquire a positive charge and larger particles acquire a negative charge.
- These particles are separated under the influence of gravity and updrafts within the storm, building electrical potential within clouds and between clouds and the ground.



NASA-GHRC Lightning Primer

What is Lightning?

- Intra-cloud lightning is the most common.
- Cloud-to-ground lightning makes up ~20% of total lightning.
- Lightning heats the air to 30,000° C (54,000° F), five times hotter than the surface of the Sun. Makes the air hot and expand explosively, producing booming sound waves – thunder.
- [2]Sound travels at 330 m/sec, whereas Light travels at 300,000 km/sec. Therefore, thunder takes 5 seconds to travel a mile while lightning travels the same distance in 5 microseconds!

Credit: NOAA

Credit: GORDON GARRADD/SCIENCE PHOTO LIBRARY

Why Study Lightning?

- [1]Approximately 24,000 fatalities and ten times more injuries result worldwide from lightning.
- [1]More than 70% of lightning-strike survivors suffer from health impacts and permanent disabilities.
- Lighting is responsible for igniting many wildfires (Lightning-Caused Wildfires).
- Lightning strikes on power lines and electrical poles result in power outages (Common Causes of Power Outages).
- Lightning strikes generate an electromagnetic pulse that creates a high-voltage power surge and damages electronics and electrical appliances and equipment on the ground.
- [2]It is predicted that over the US, a warming climate is likely to increase lightning strikes. For every 1 degree C of warming, lightning strikes will go up by approximately 12%.

Lightning strike in slow motion (Source: NOAA)

[1]Jensen et al; 2023 [2]Romp et al; 2014

Training Learning Objectives

By the end of this training, participants will be able to:

- Identify common lightning causes, patterns, and potential for causing damage
- Identify how space- and ground-based lightning observations are used to monitor lightning frequency and intensity
- Identify resources for accessing lightning data products

Prerequisites

- Fundamentals of Remote Sensing

Training Outline

Part 1

Background and History of Lightning Measurements

March 26, 2024

Time

Part 2

Overview of Current Lightning Data Products from Remote Sensing and Ground-based Measurements

March 28, 2024

Time

Part 3

Overview of Geostationary Lightning Mapper (GLM), Lightning Data Access, and Applications

April 2, 2024

Time

Homework

Opens April 2 – Due April 17 – Posted on Training Webpage

A certificate of completion will be awarded to those who attend all live sessions and complete the homework assignment before the given due date.

How to Ask Questions

- Please put your questions in the Questions box and we will address them at the end of the webinar.
- Feel free to enter your questions as we go. We will try to get to all of the questions during the Q&A session after the webinar.
- The remainder of the questions will be answered in the Q&A document, which will be posted to the training website about a week after the training.

Part 1 – Trainers

Amita Mehta

ARSET Instructor

NASA-UMBC-GESTAR II

Steven Goodman

Guest Instructor

Senior Advisor, GeoXO Program

Thunderbolt Global Analytics
NASA-GSFC

Christopher Schulz

Guest Contributor

Research AST, Meteorological Studies

NASA-MSFC

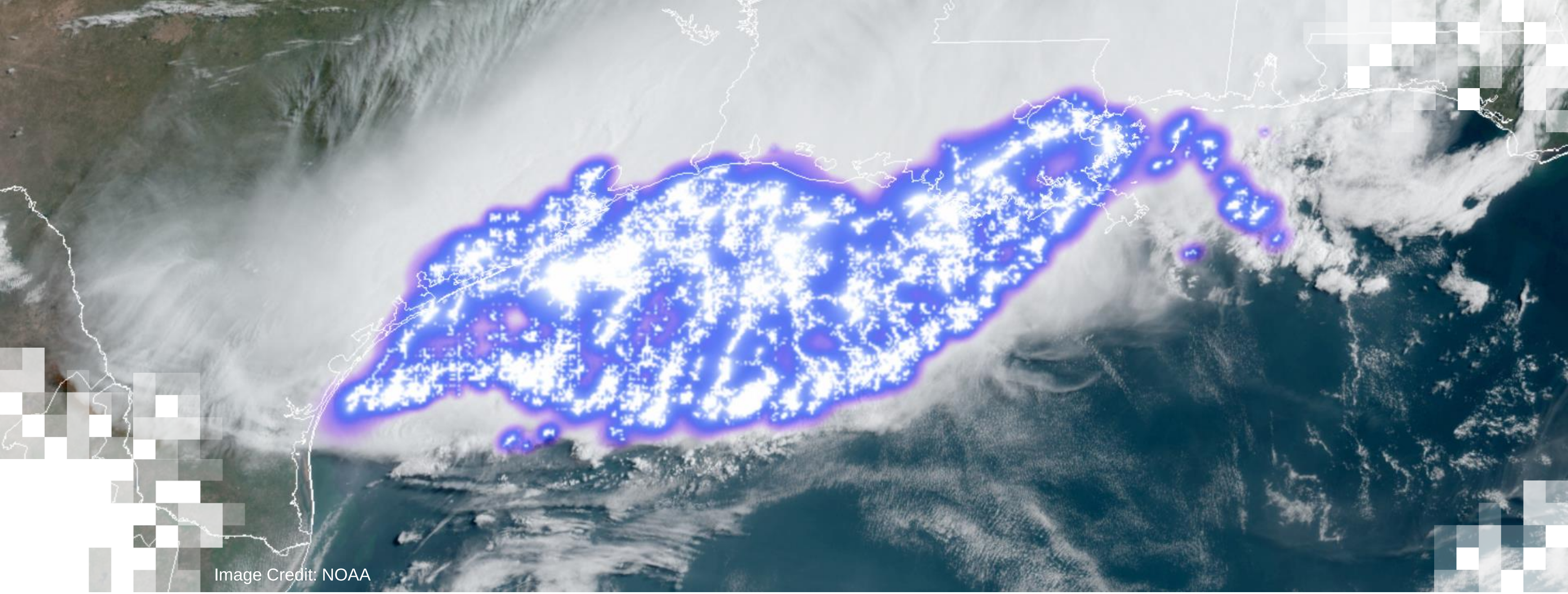


Image Credit: NOAA

Part 1

History of Lightning Measurements

Part 1 Objectives

By the end of Part 1, participants will be familiar with:

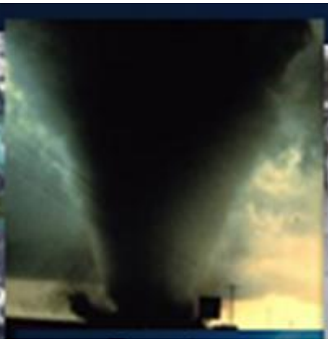
- Weather Impacts: Societal Benefits of Observing Lightning
- Early History of Lightning Observations
- Observing Lightning from Space
- Lightning - Climate Variability and Change

Weather Impacts on Society: Lightning Societal Benefits

- Improved forecaster and public situational awareness and confidence resulting in more accurate severe storm warnings (improved lead time, reduced false alarms) to save lives and property
- Diagnosing convective storm structure and evolution
- Aviation and marine convective weather hazards
- Wildfire ignition
- Tropical cyclone intensity change
- Decadal changes of extreme weather – thunderstorms/lightning intensity and distribution
- Low data latency


Lightning


Hurricanes


Tornadoes

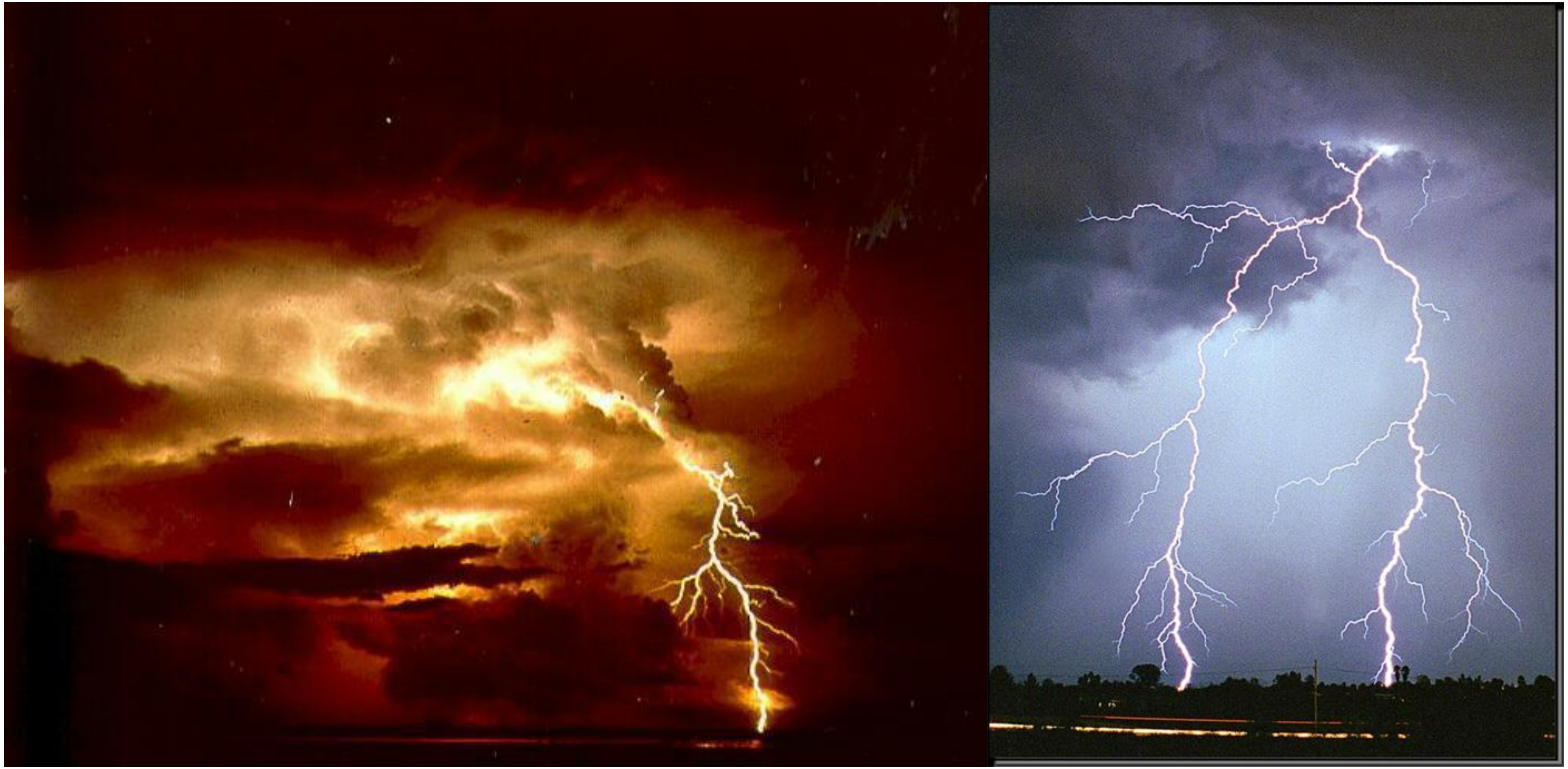

Floods


Forest Fires

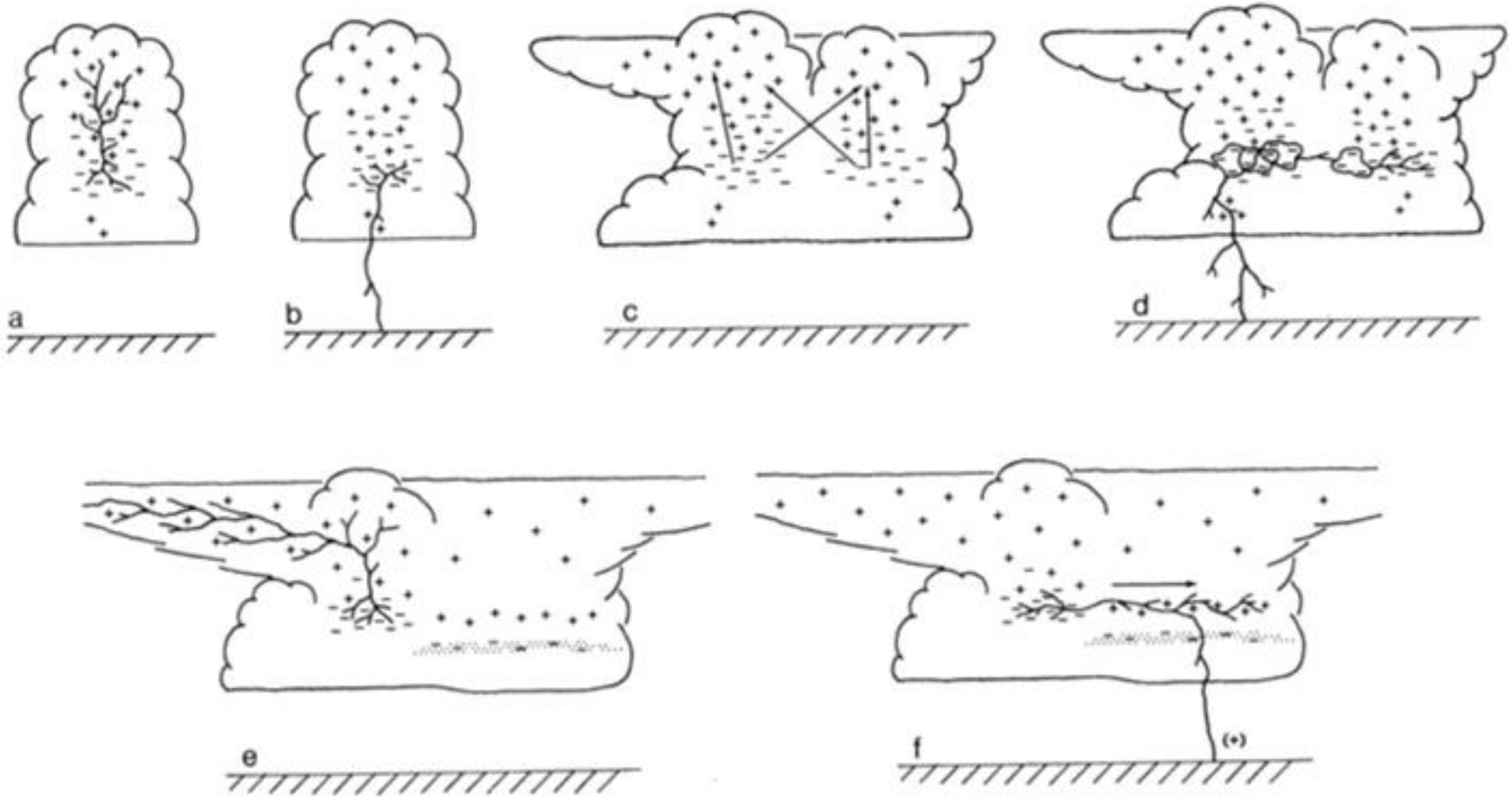

Volcanic Ash


Blizzards

Lightning In-Cloud and Cloud-to-Ground
(We call this total lightning.)



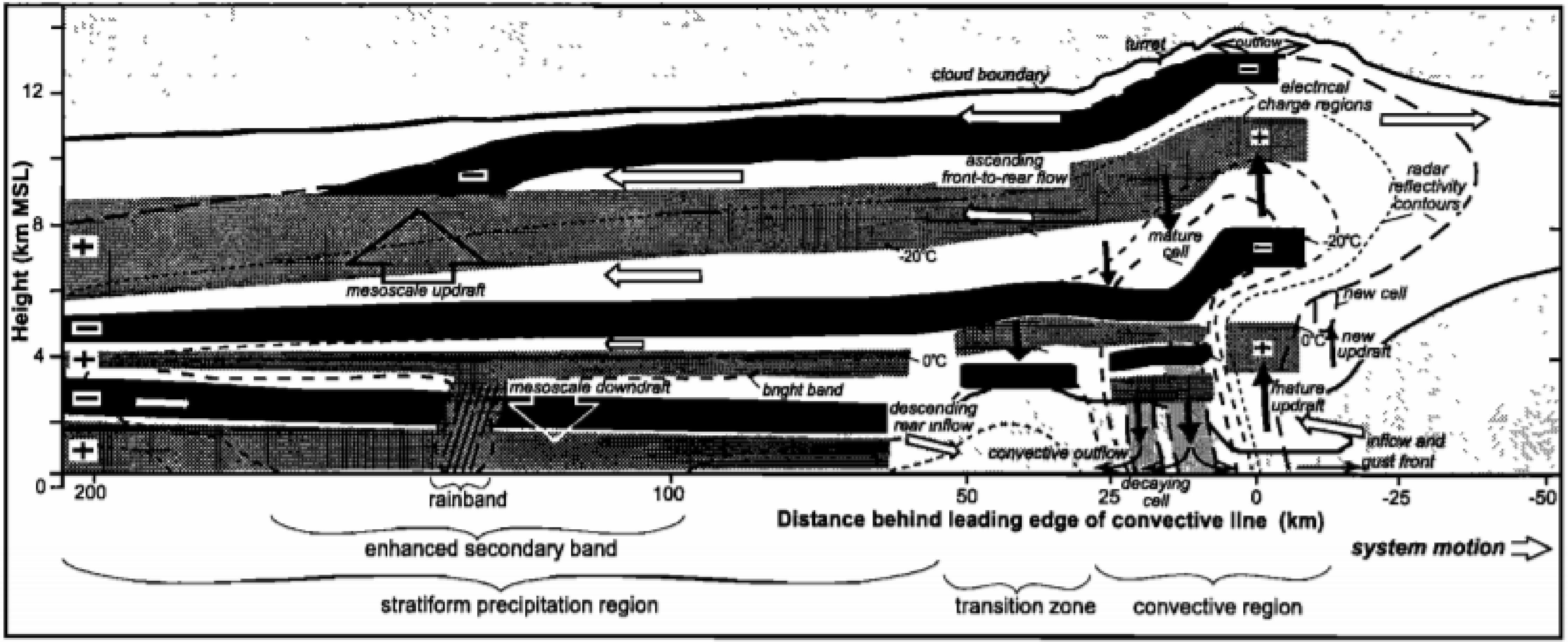
Lightning Initiation



From Krehbiel, P., 1986: “The Electrical Structure of Thunderstorms,” *The Earth’s Electrical Environment*, National Academy Press, 90-113.

MCS Electrical Structure: Leading Convective Line to Trailing Stratiform

- Conceptual model of the charge structure in mesoscale convective systems. Positive charge regions have light shading and negative charge regions have dark shading.

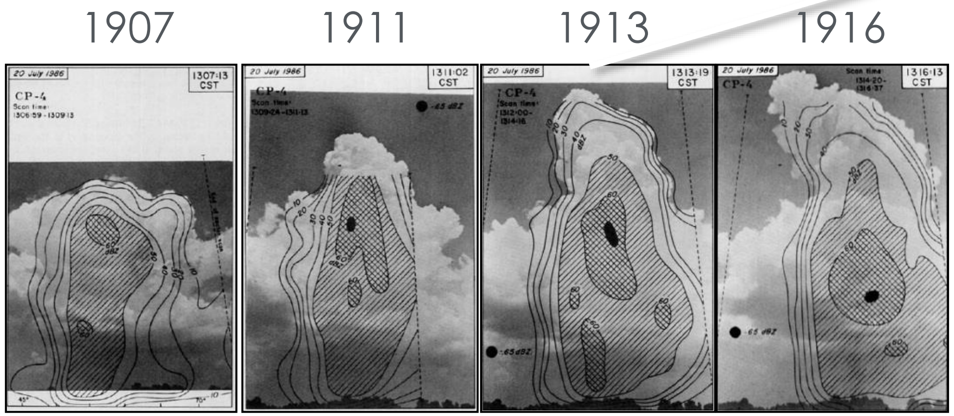


Stolzenburg, M., W. D. Rust, B. F. Smull, and T. C. Marshall (1998), Electrical structure in thunderstorm convective regions: 1. Mesoscale convective systems, *J. Geophys. Res.*, 103(D12), 14059–14078, doi: 10.1029/97JD03546

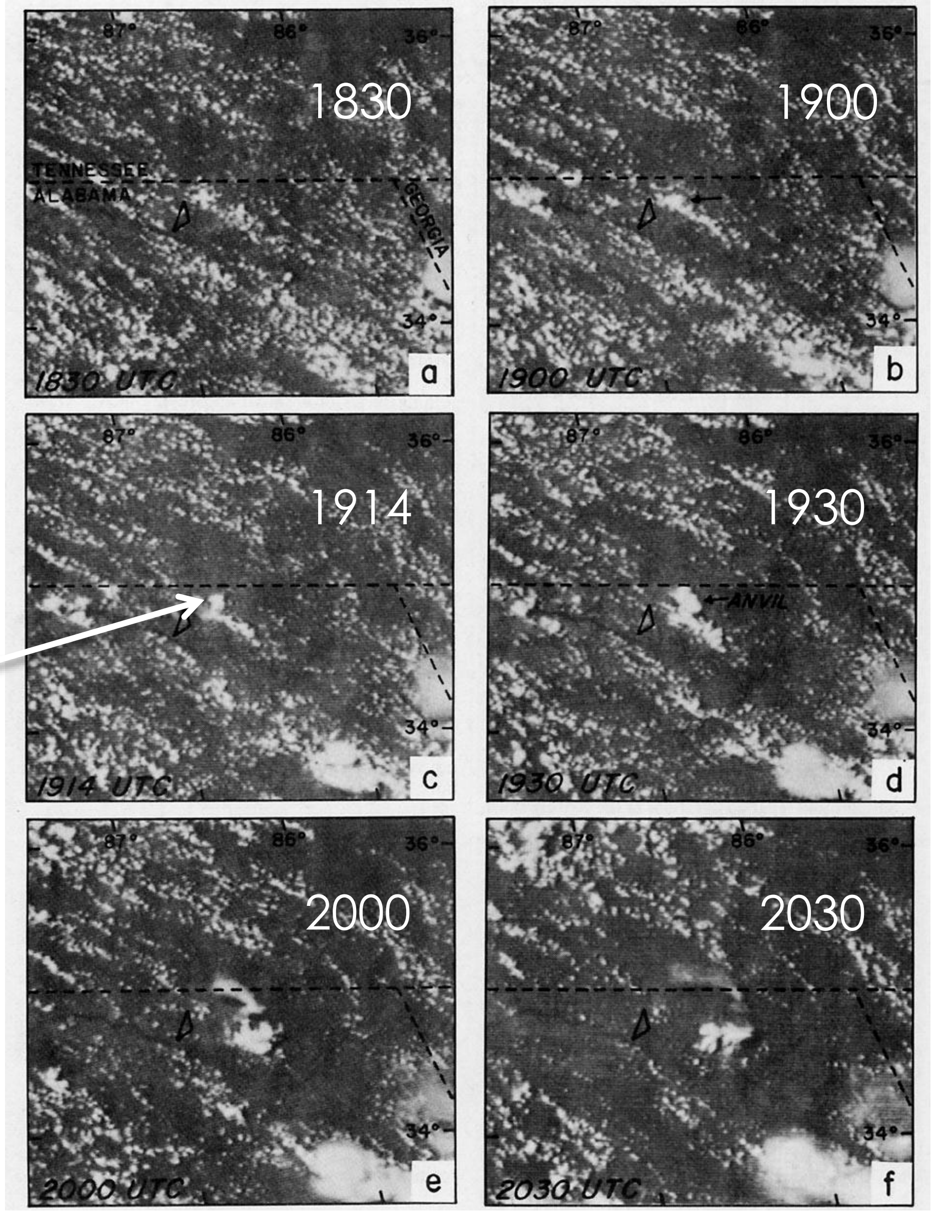
An air mass thunderstorm lifetime is an hour or less.

- Small Air Mass Thunderstorm
  - Huntsville “Monrovia” Microburst, 20 July 1986
  - Pulse air mass storm, 65 dBZ max Z
  - Pea-sized hail, 40 kt outflow
  - 110 total lightning, 6 CG strikes

Cloud top temperatures continue cooling after reaching the mature stage as cirrus anvil fills imager fov

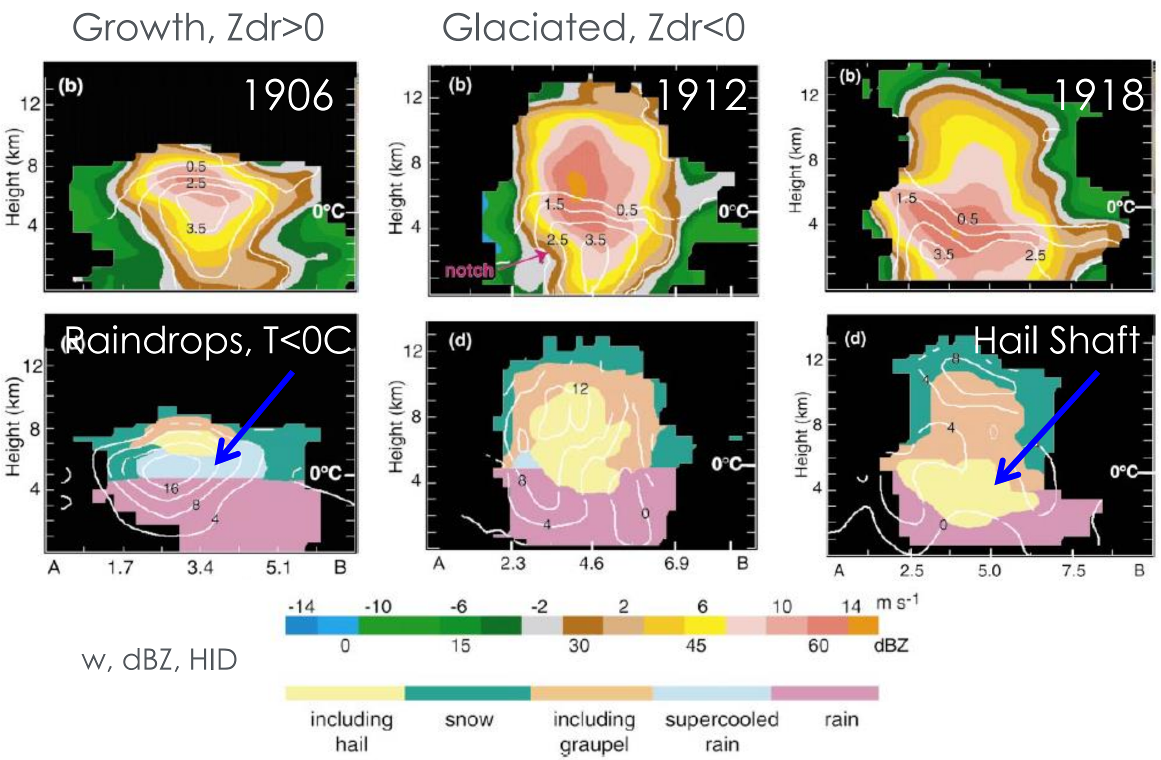


From Wakimoto and Bringi, 1988; Photos, K. Knupp



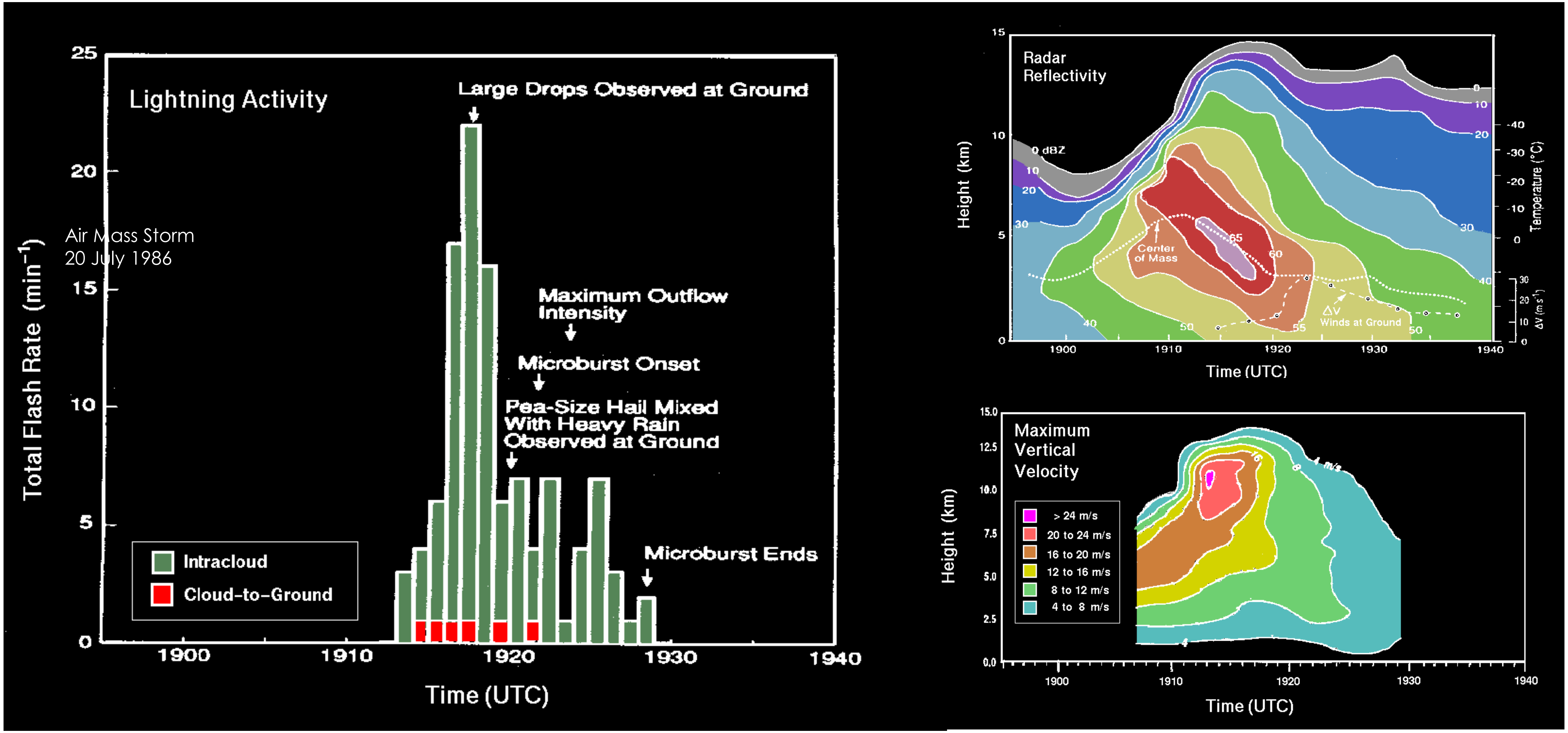
Lightning Connection to Storm Updraft, Storm Growth, and Decay

- **Total Lightning** – Responds to updraft velocity and concentration, phase, type of hydrometeors (the collection of precipitation particle types in the cloud – water drops, ice crystals, graupel pellets, hail, snow), integrated flux of particles
- **Dual-Pol WX Radar** – Responds to concentration, size, phase, and type of hydrometeors – integrated over small volumes



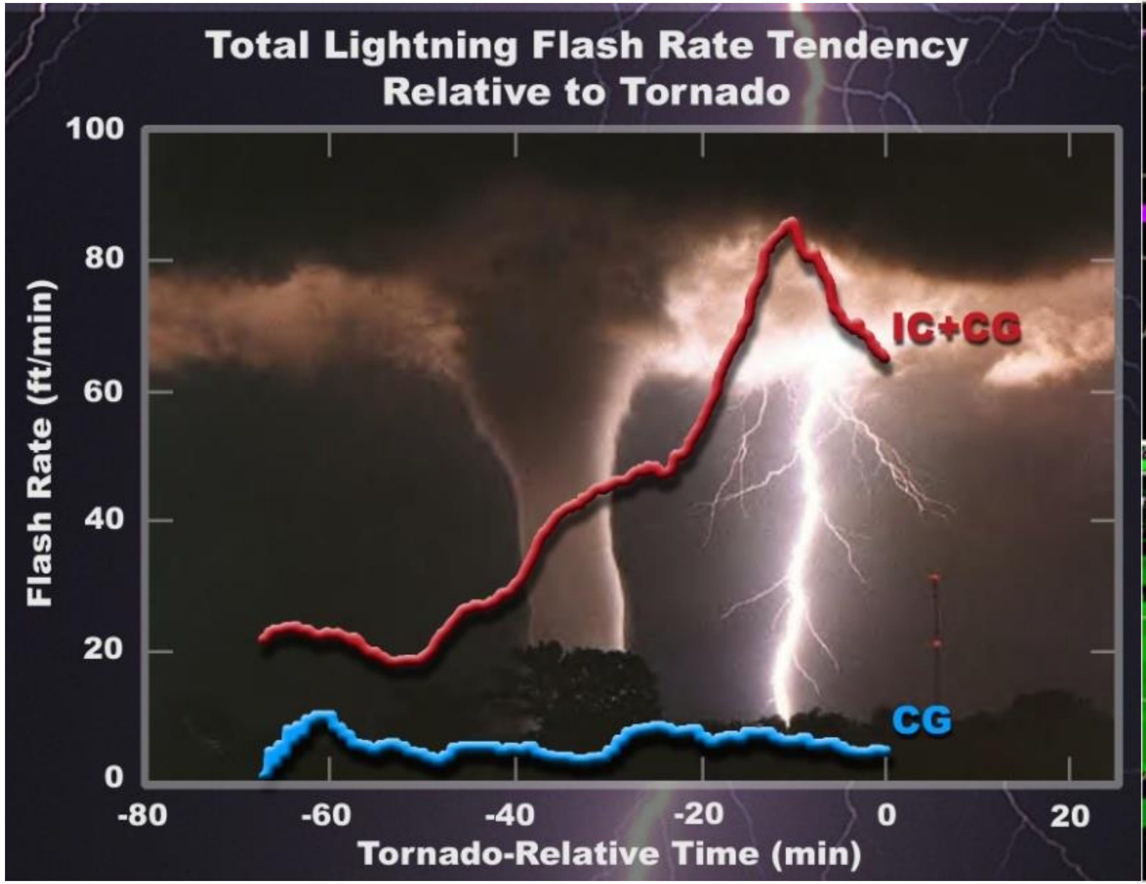
Adapted from Goodman et al, GRL, 1988; Wakimoto and Bringi, MWR, 1988; Kingsmill and Wakimoto, MWR,1991, Zeng et al., 2001, Gatlin and Goodman, JTECH, 2010

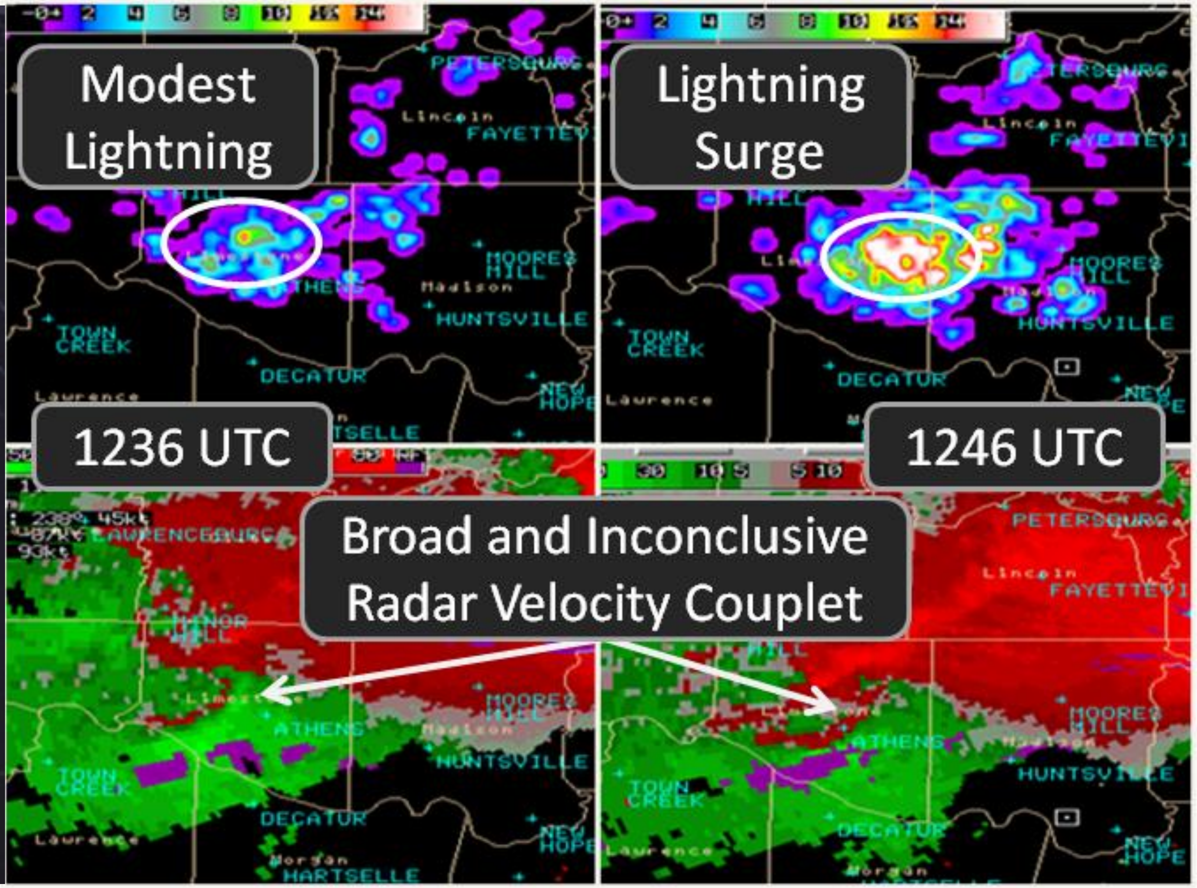
Thunderstorm Lifecycle



Adapted from Goodman et al, GRL, 1988; Wakimoto and Bringi, MWR, 1988; Kingsmill and Wakimoto, MWR,1991, Zeng et al., 2001, Gatlin and Goodman, JTECH, 2010

Lightning “Jump” Trends Depict Storm Intensification




Modest Lightning

Lightning Surge

1236 UTC

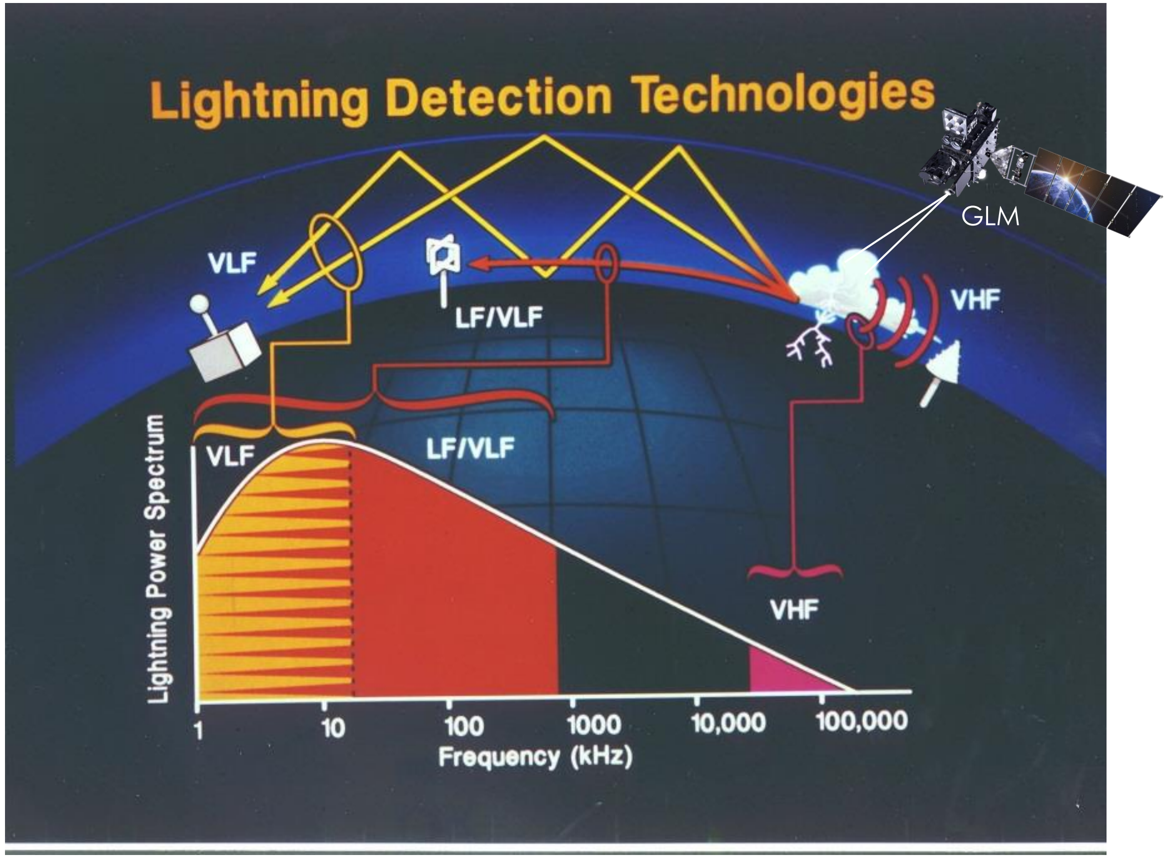
1246 UTC

Broad and Inconclusive Radar Velocity Couplet

National Average for Tornado Warning Lead-Time is 14 Minutes

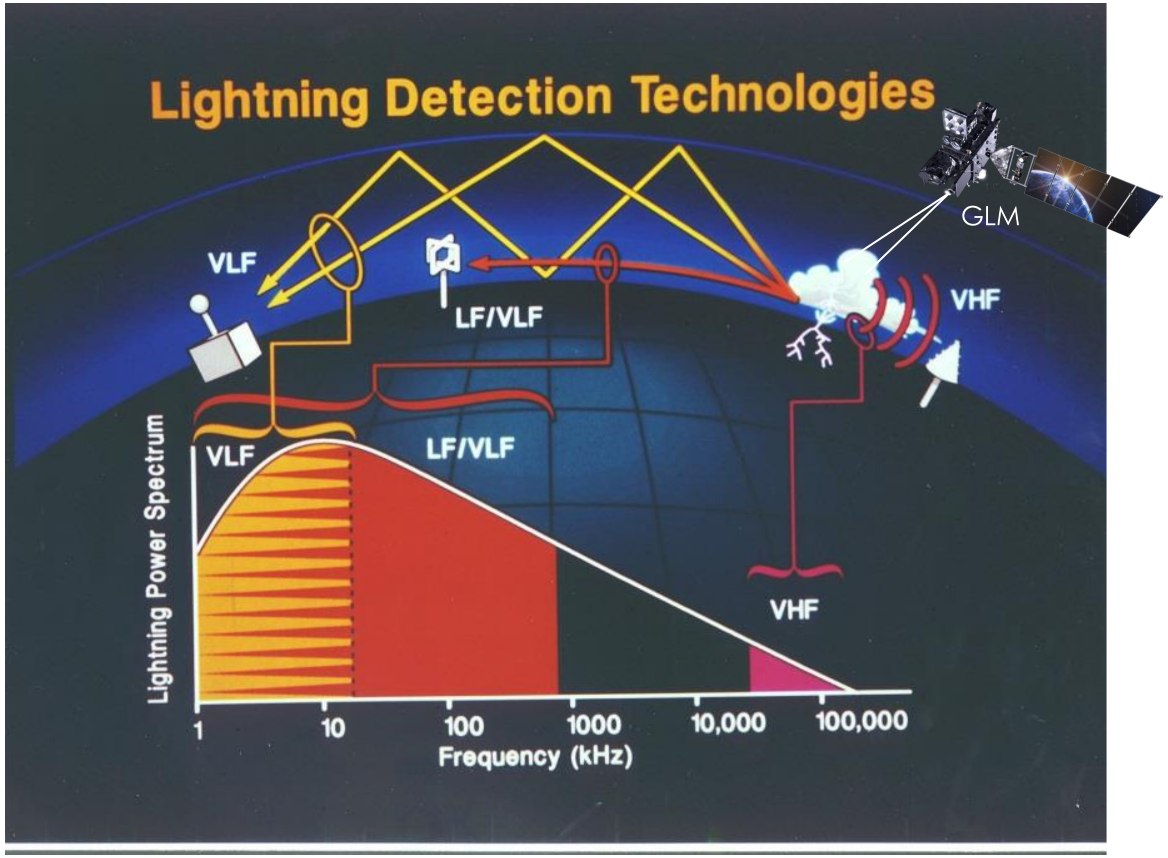
Lightning Detection Systems – Detection and Mapping

- **Available Information as Input to Weather Forecasting Models and Decision Support Systems:**
  - Thunder heard by human observer
  - Local electric field mill networks
  - High speed digital video cameras, all-sky cameras
  - Short-range VHF in-cloud lightning mapping (60-180 MHZ)
  - National cloud-to-ground lightning mapping (LF, 500 kHZ)
  - International long range sferics networks (VLF, 10 kHZ)
  - Sub-Orbital: Planes, Balloons, UAVs (electrical, magnetic, optical)
  - Lightning optical imagers orbiting Earth (GEO, LEO)

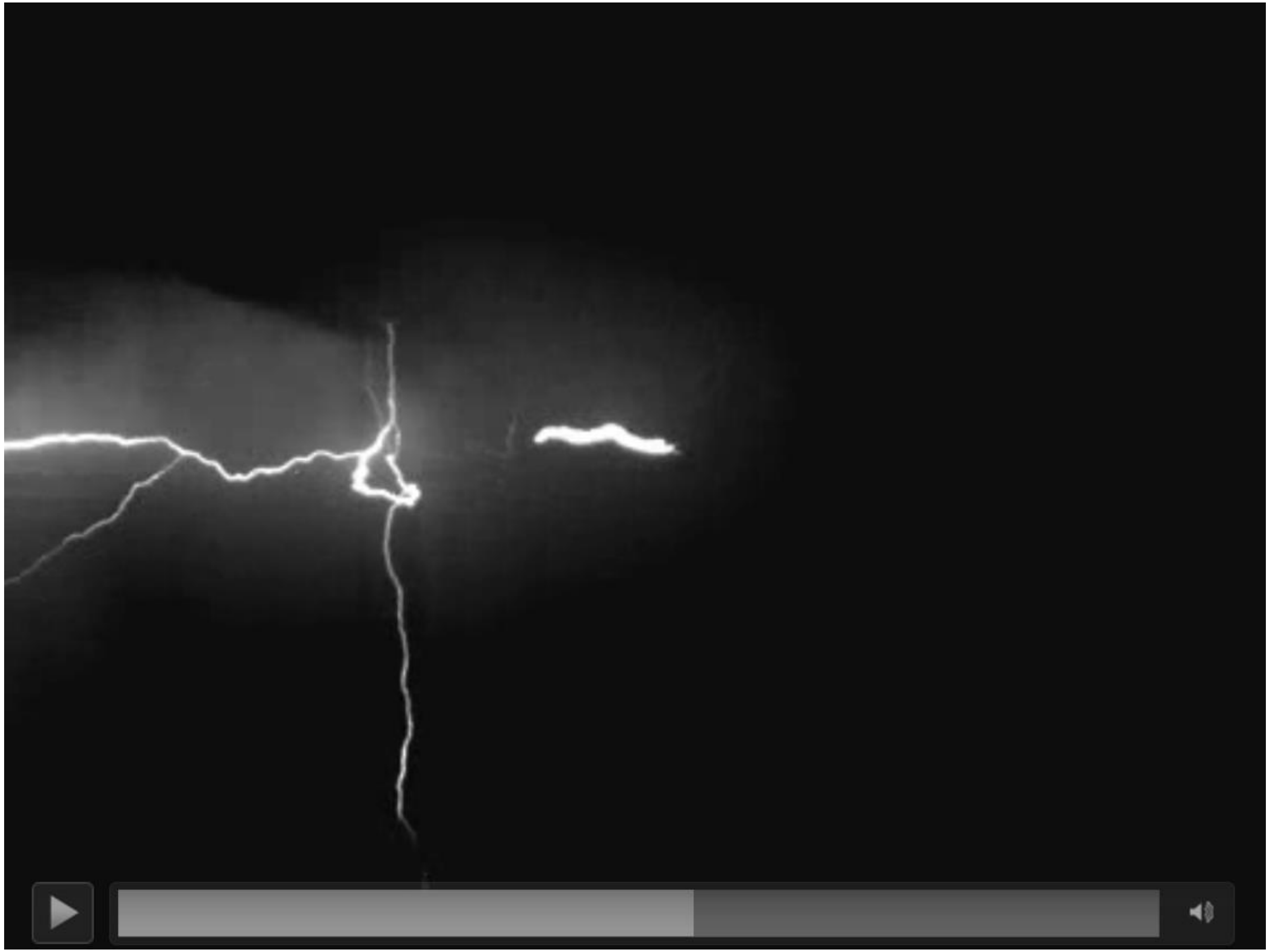


Lightning Detection Systems – Key Performance Measures

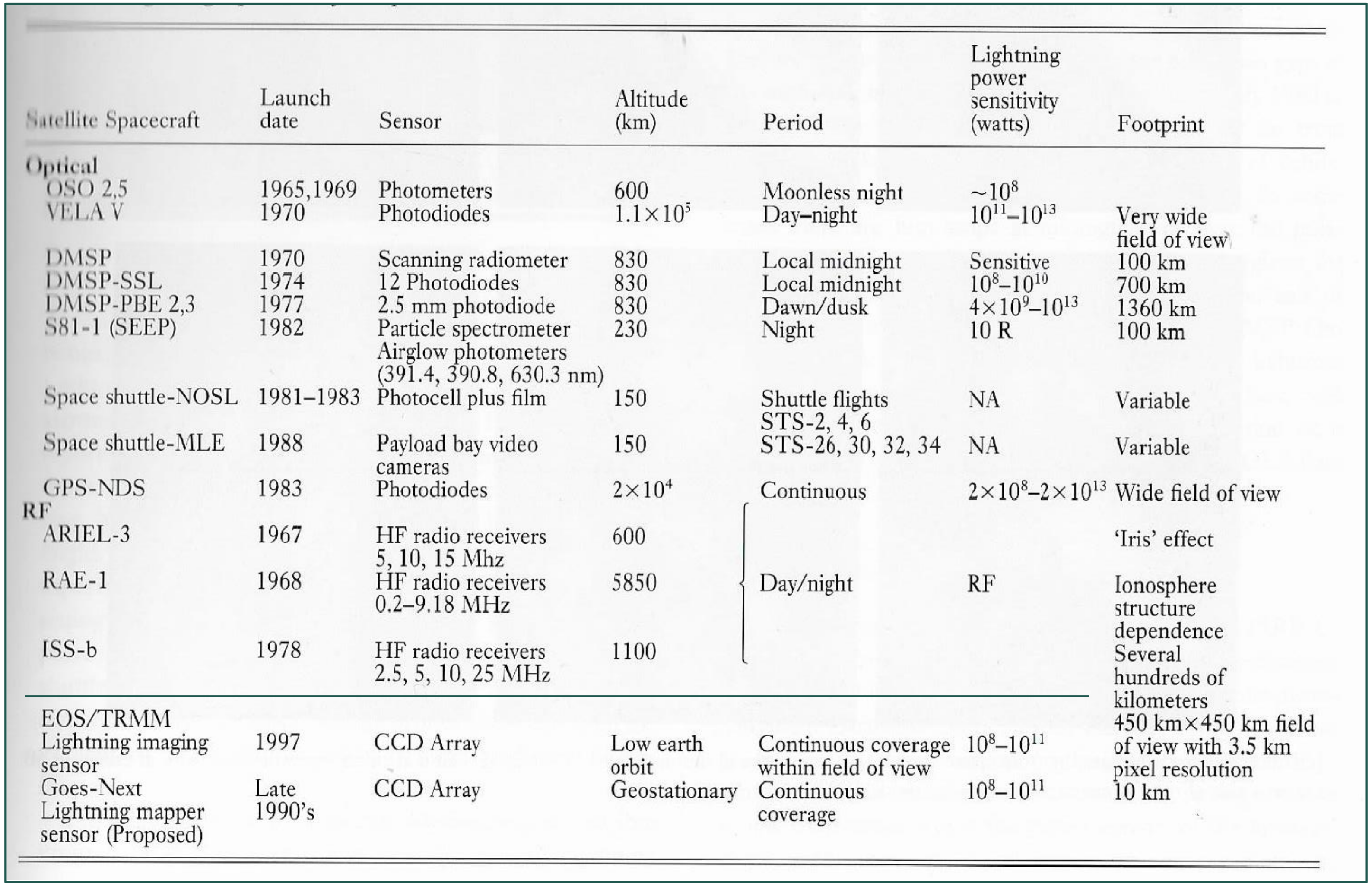
- **Key Performance Measures:**
  - Detection Efficiency
  - Location Accuracy
  - Flash Type
  - Stability
  - Consistency



High Speed Digital Video – Lightning Flash 7500 fps



Lightning Observations from Space – Early History



Satellite Spacecraft	Launch date	Sensor	Altitude (km)	Period	Lightning power sensitivity (watts)	Footprint
Optical						
OSO 2,5	1965,1969	Photometers	600	Moonless night	$\sim 10^8$	
VELA V	1970	Photodiodes	1.1×10^5	Day–night	10^{11}–10^{13}	Very wide field of view
DMSP	1970	Scanning radiometer	830	Local midnight	Sensitive	100 km
DMSP-SSL	1974	12 Photodiodes	830	Local midnight	10^8–10^{10}	700 km
DMSP-PBE 2,3	1977	2.5 mm photodiode	830	Dawn/dusk	4×10^9–10^{13}	1360 km
S81-1 (SEEP)	1982	Particle spectrometer Airglow photometers (391.4, 390.8, 630.3 nm)	230	Night	10 R	100 km
Space shuttle-NOSL	1981–1983	Photocell plus film	150	Shuttle flights STS-2, 4, 6	NA	Variable
Space shuttle-MLE	1988	Payload bay video cameras	150	STS-26, 30, 32, 34	NA	Variable
GPS-NDS	1983	Photodiodes	2×10^4	Continuous	2×10^8–2×10^{13}	Wide field of view
RF						
ARIEL-3	1967	HF radio receivers 5, 10, 15 Mhz	600	Day/night	RF	'Iris' effect
RAE-1	1968	HF radio receivers 0.2–9.18 MHz	5850			Ionosphere structure dependence
ISS-b	1978	HF radio receivers 2.5, 5, 10, 25 MHz	1100			Several hundreds of kilometers
EOS/TRMM Lightning imaging sensor	1997	CCD Array	Low earth orbit	Continuous coverage within field of view	10^8–10^{11}	450 km×450 km field of view with 3.5 km pixel resolution
Goes-Next Lightning mapper sensor (Proposed)	Late 1990's	CCD Array	Geostationary	Continuous coverage	10^8–10^{11}	10 km

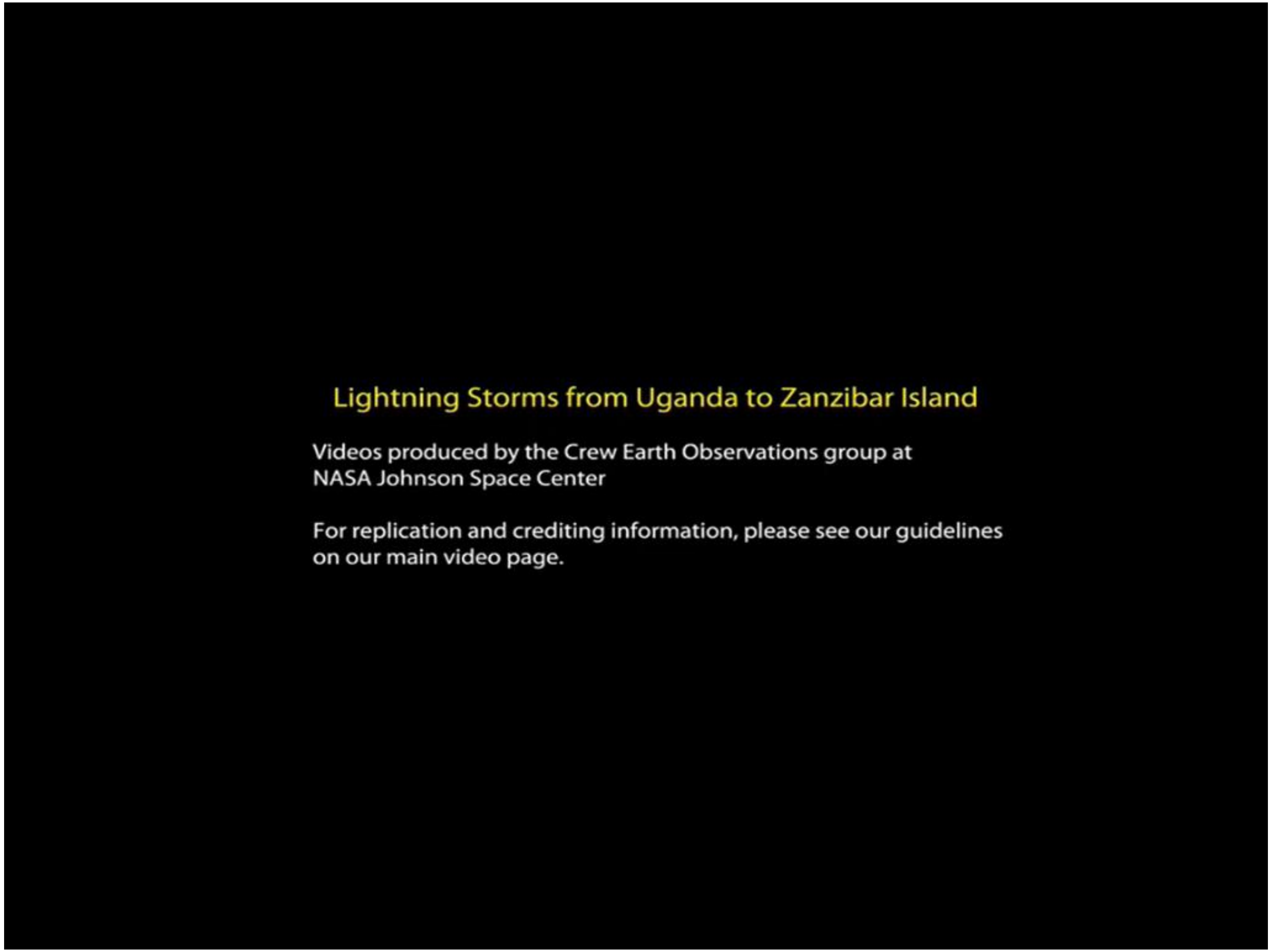
Goodman and Christian, 1993

Early Observations

- The fact that lightning could be seen from high altitudes was noted in anecdotal form by the early U-2 pilots, and more focused observations were reported by the Apollo and early Space Shuttle flights. Simple camera systems were used to record what they saw.

U-2 (NASA 709) in flight over Golden Gate Bridge, San Francisco, CA, 1988

Astronauts have observed lightning from space since the 1960s.

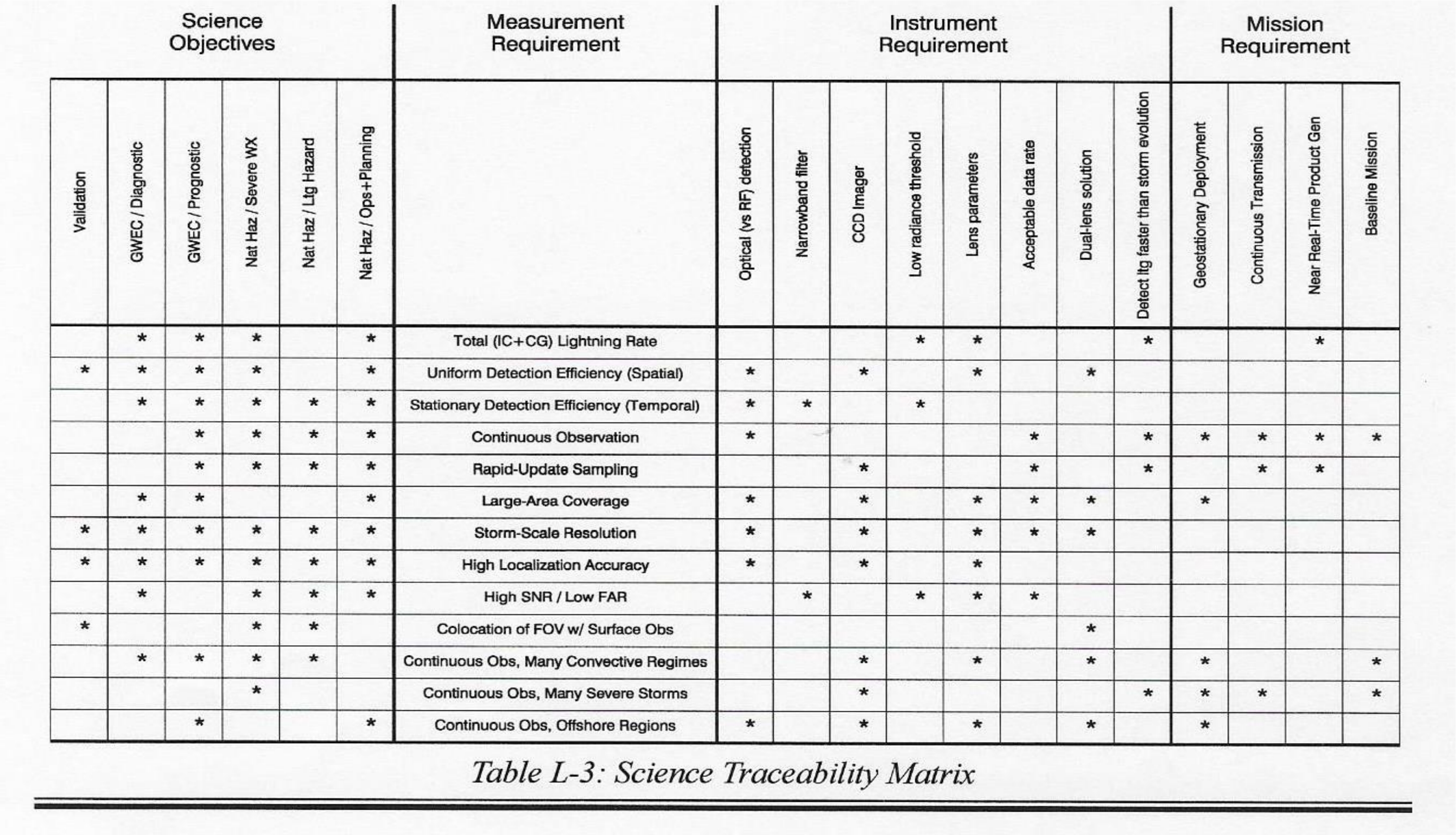


Lightning Storms from Uganda to Zanzibar Island

Videos produced by the Crew Earth Observations group at
NASA Johnson Space Center

For replication and crediting information, please see our guidelines
on our main video page.

Lightning Science Traceability Matrix



Science Objectives						Measurement Requirement	Instrument Requirement								Mission Requirement			
Validation	GWEC / Diagnostic	GWEC / Prognostic	Nat Haz / Severe WX	Nat Haz / Ltg Hazard	Nat Haz / Ops+Planning		Optical (vs RF) detection	Narrowband filter	CCD Imager	Low radiance threshold	Lens parameters	Acceptable data rate	Dual-lens solution	Detect ltg faster than storm evolution	Geostationary Deployment	Continuous Transmission	Near Real-Time Product Gen	Baseline Mission
	*	*	*		*	Total (IC+CG) Lightning Rate				*	*			*			*	
*	*	*	*		*	Uniform Detection Efficiency (Spatial)	*		*		*		*					
	*	*	*	*	*	Stationary Detection Efficiency (Temporal)	*	*		*								
		*	*	*	*	Continuous Observation	*					*		*	*	*	*	*
		*	*	*	*	Rapid-Update Sampling			*			*		*		*	*	
	*	*			*	Large-Area Coverage	*		*		*	*	*		*			
*	*	*	*	*	*	Storm-Scale Resolution	*		*		*	*	*					
*	*	*	*	*	*	High Localization Accuracy	*		*		*							
	*		*	*	*	High SNR / Low FAR		*		*	*	*						
*			*	*		Colocation of FOV w/ Surface Obs							*					
	*	*	*	*		Continuous Obs, Many Convective Regimes			*		*		*		*			*
			*			Continuous Obs, Many Severe Storms			*					*	*	*		*
		*			*	Continuous Obs, Offshore Regions	*		*		*		*		*			

Table L-3: Science Traceability Matrix

GLM Lightning Detection – How it Works

- **Lightning from Space:**
  - Lightning appears like a pool of light on the top of the cloud as the discharge lights up the cloud like a light bulb.
- **Daytime Challenge:**
  - During the day, sunlight reflected from the cloud top totally “swamps out” and masks the lightning signal. Daytime lightning detection drove the design.

International Space Station (ISS) Image, April 30, 2012

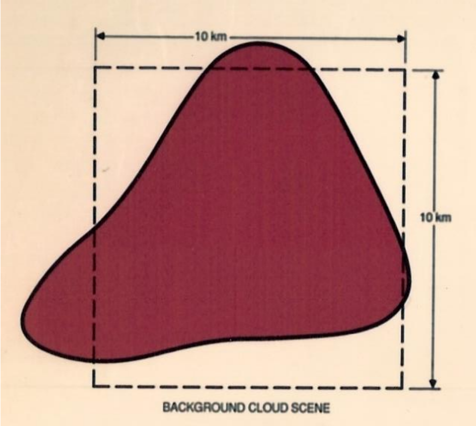
GLM Lightning Detection – How it Works

- **The Solution:**
  - Special techniques must be applied to extract the weak, transient lightning signal from the bright background noise.

Spatial

Optimal sampling of lightning scene relative to background scene.

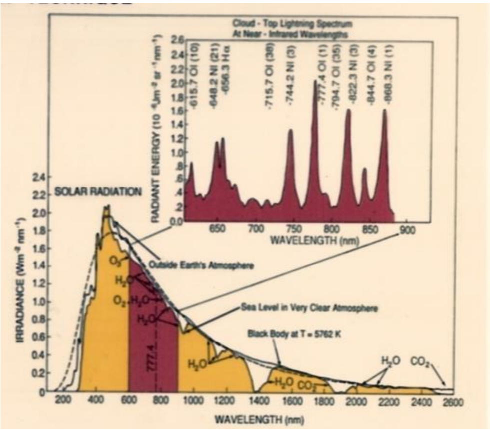
Pixel field-of-view 4-10 km.



Spectral

Optimal sampling of lightning signal relative to background signal.

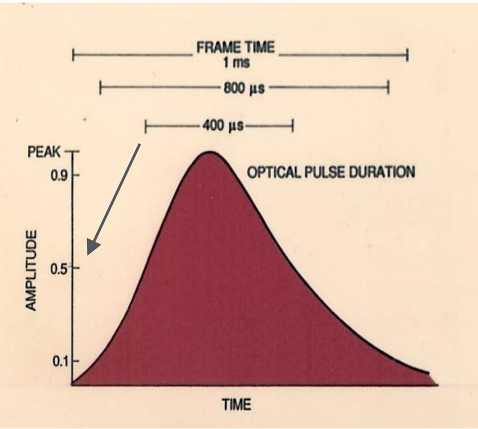
LIS uses 1nm filter at 777.4 nm.



Temporal

Optimal sampling of lightning pulse relative to background signal.

LIS/GLM use 2 ms frame rate.



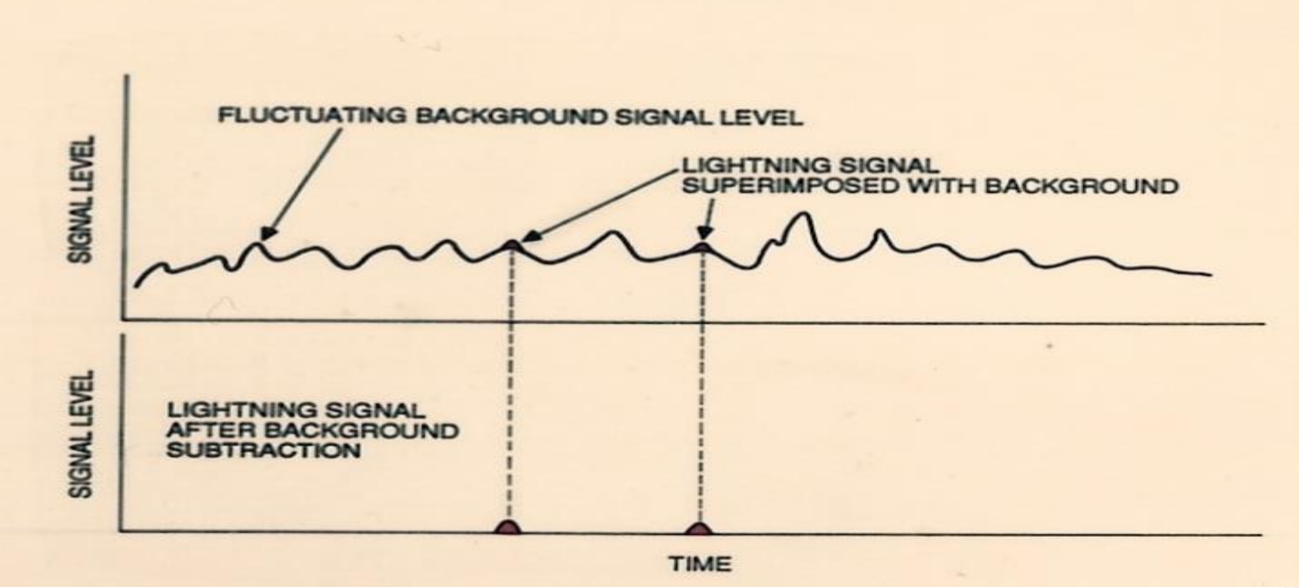
GLM Lightning Detection – How it Works

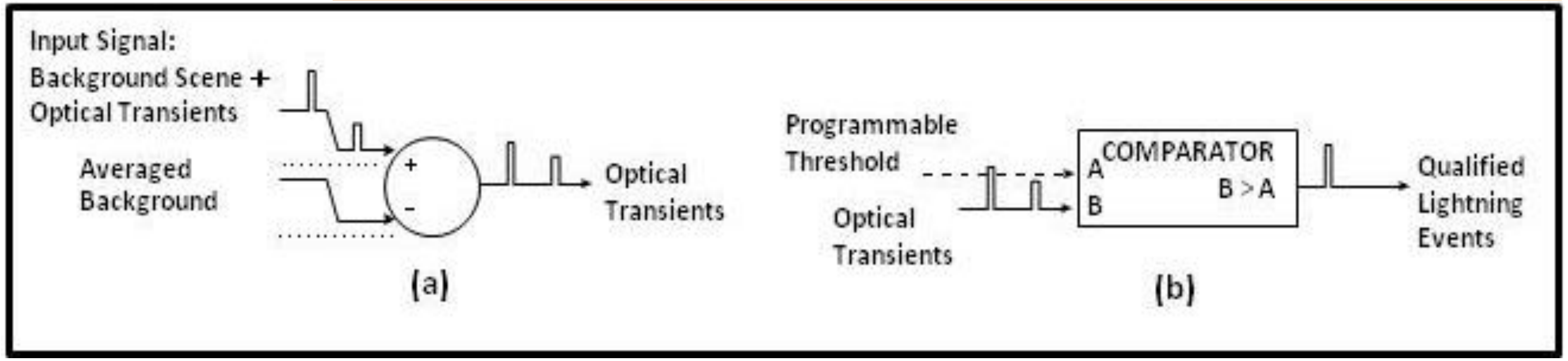
- Even with spatial, spectral, and temporal filters, background signal can exceed lightning signal by 100 to 1 at the focal plane.
- The first step is a **frame-by-frame background subtraction** to produce a lightning-only signal.
- Filtering results in 10^5 reduction in data rate requirements while maintaining high detection efficiency for lightning.

Background Subtraction

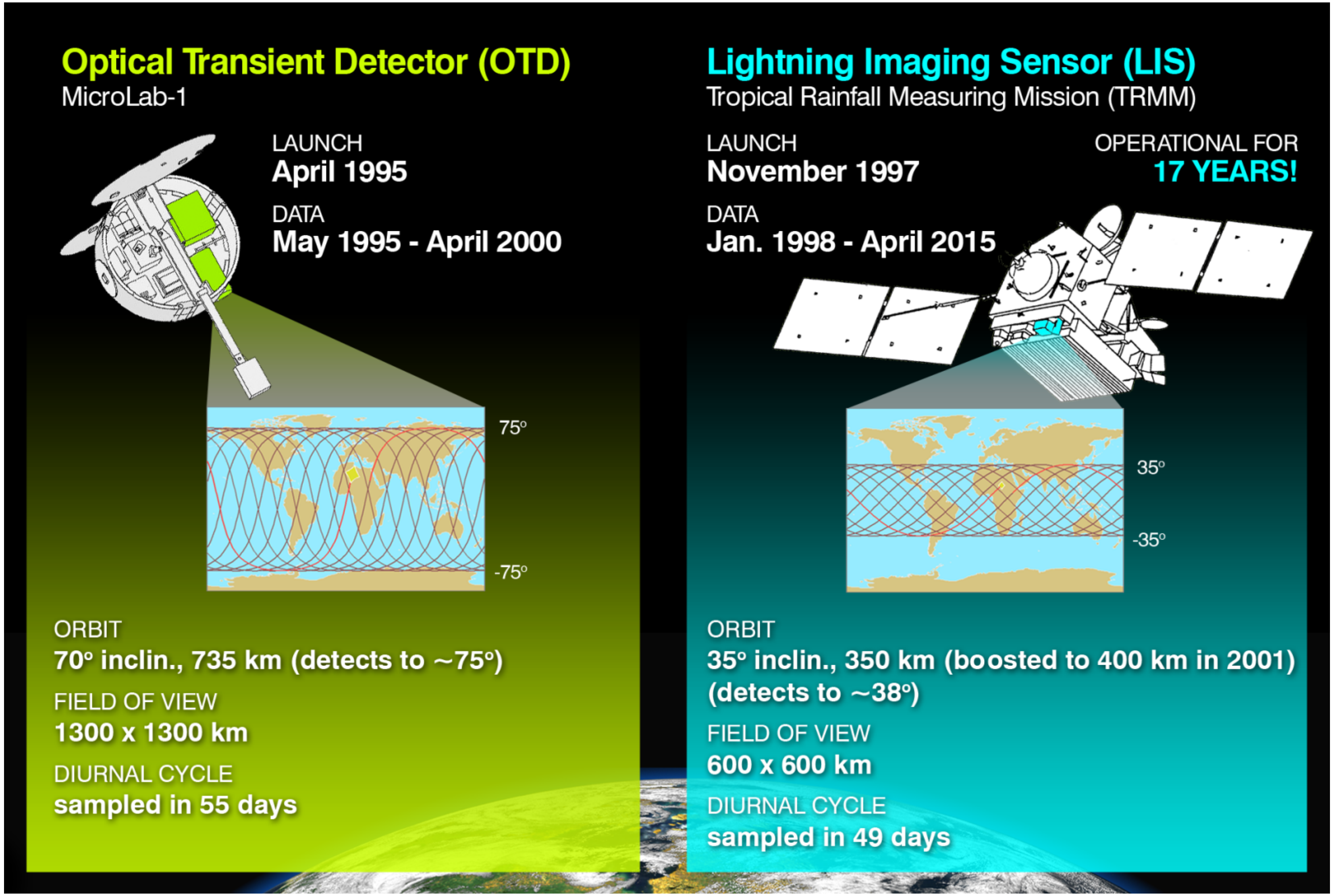
Optimal subtraction of background signal levels at each pixel.

Transient events selected for processing.





OTD and LIS



Optical Transient Detector (OTD)

MicroLab-1

LAUNCH
April 1995

DATA
May 1995 - April 2000

ORBIT
70° inclin., 735 km (detects to ~75°)

FIELD OF VIEW
1300 x 1300 km

DIURNAL CYCLE
sampled in 55 days

Lightning Imaging Sensor (LIS)

Tropical Rainfall Measuring Mission (TRMM)

LAUNCH
November 1997

OPERATIONAL FOR
17 YEARS!

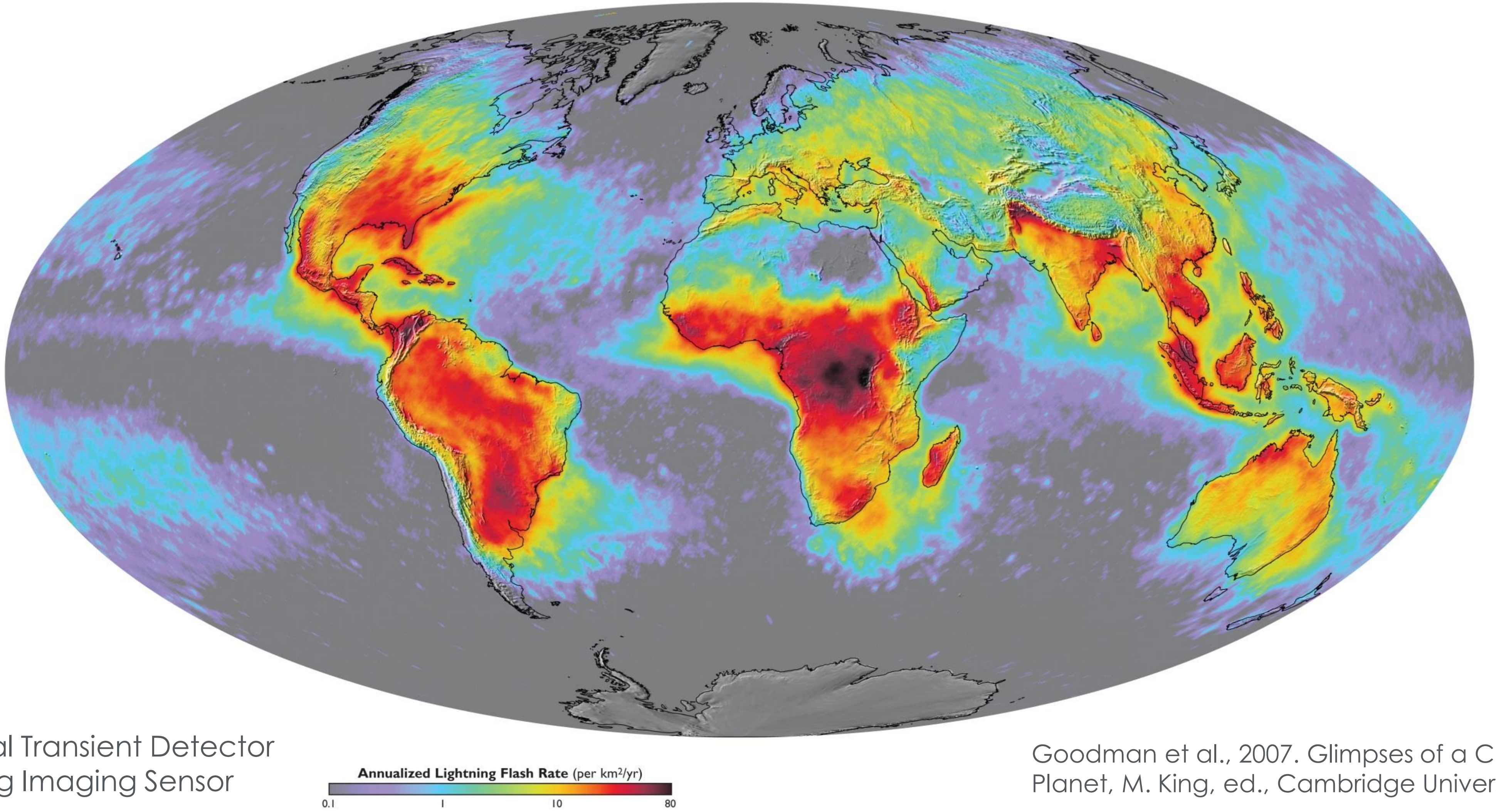
DATA
Jan. 1998 - April 2015

ORBIT
35° inclin., 350 km (boosted to 400 km in 2001) (detects to ~38°)

FIELD OF VIEW
600 x 600 km

DIURNAL CYCLE
sampled in 49 days

Global Distribution of Lightning: Early Results

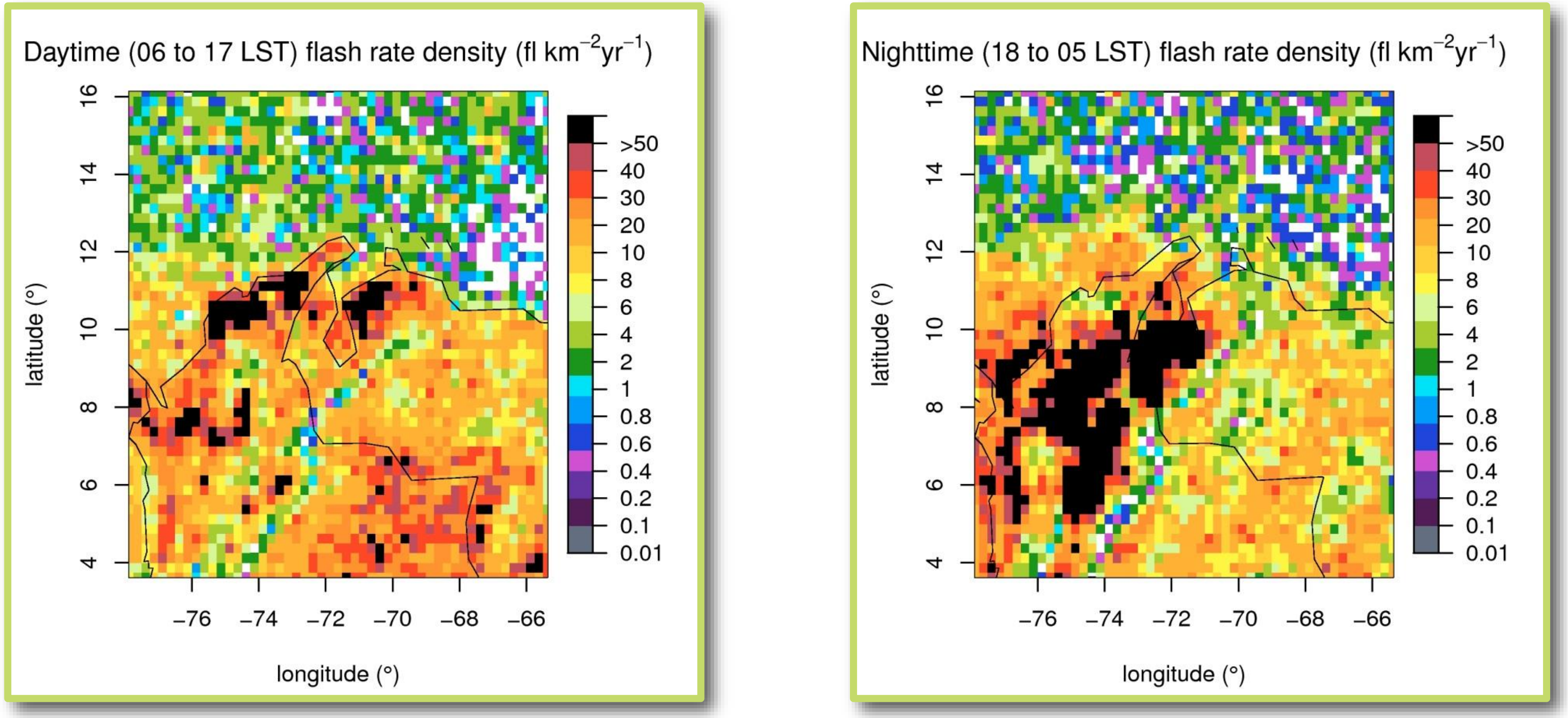


OTD – Optical Transient Detector
LIS – Lightning Imaging Sensor

Goodman et al., 2007. Glimpses of a Changing Planet, M. King, ed., Cambridge University Press

Lake Maracaibo, Venezuela

- Has the greatest lightning frequency on Earth



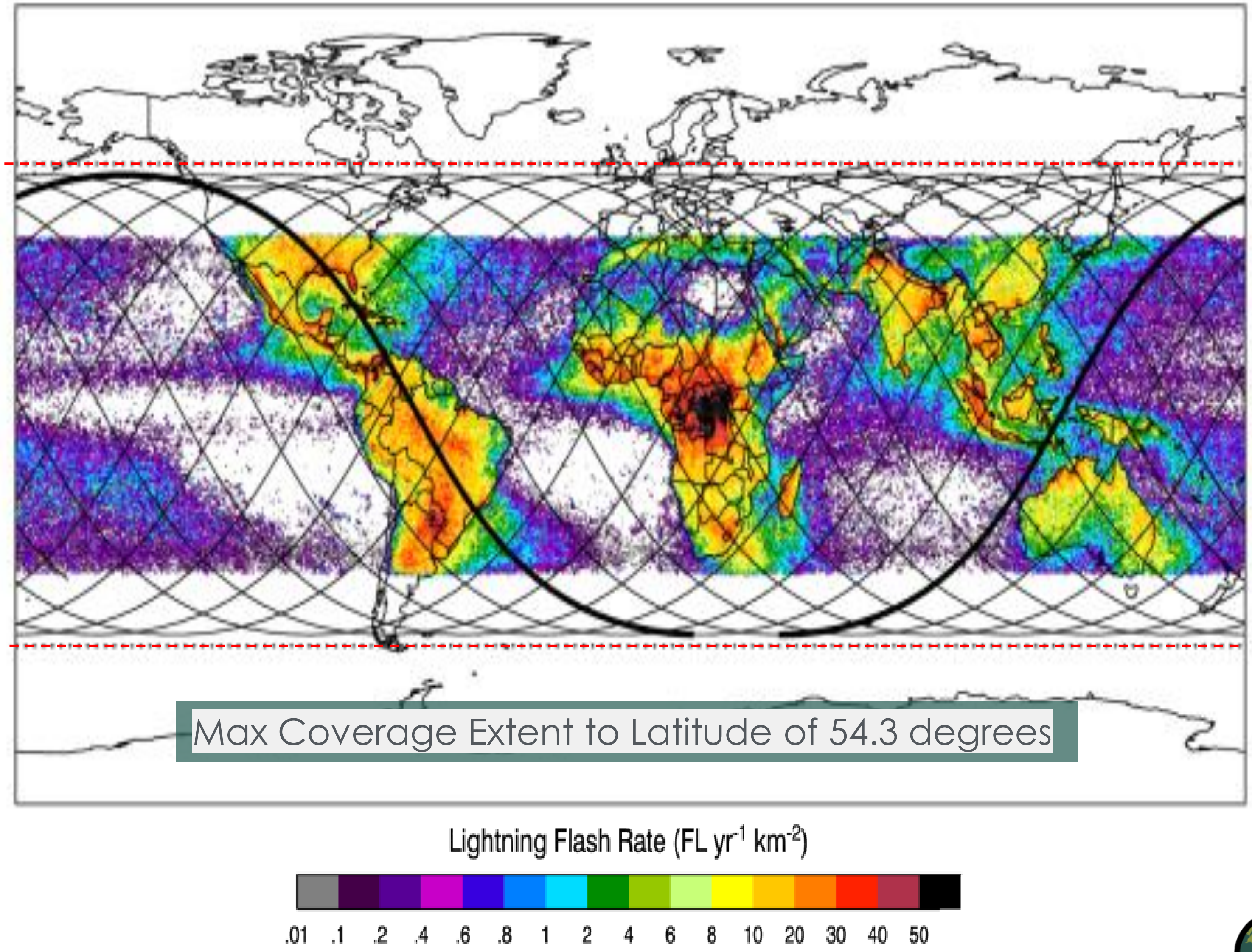
Daytime (06 to 17 LST) flash rate density (fl $km^{-2}yr^{-1}$)

Nighttime (18 to 05 LST) flash rate density (fl $km^{-2}yr^{-1}$)

Total lightning observed during daytime (left) and nighttime (right) by the NASA TRMM Lightning Imaging Sensor

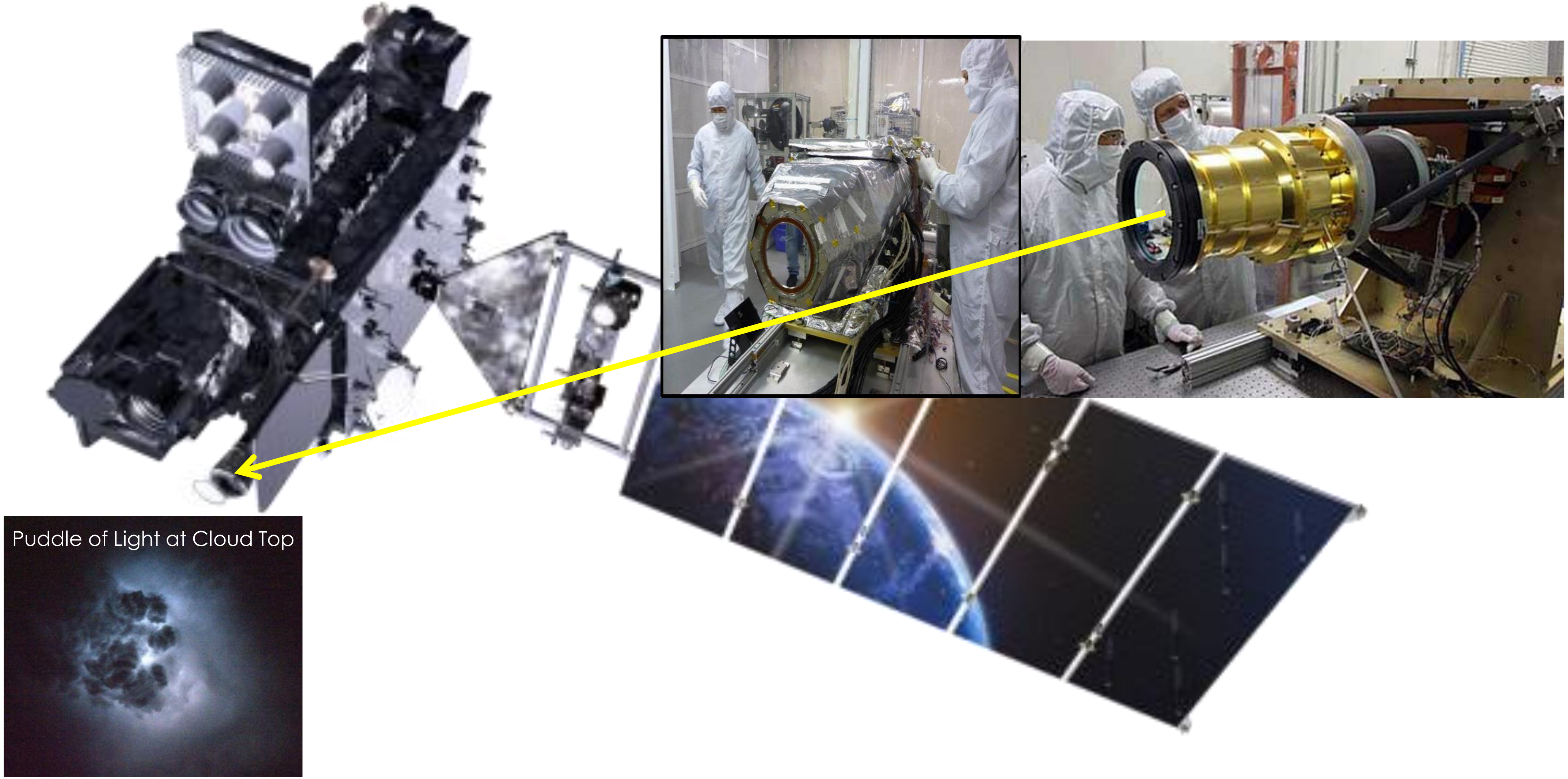
LIS on the International Space Station (ISS) – Greater Coverage

- February 2017 – November 2023
- Global Coverage (%) of all lightning for LIS/ISS (between red dashed lines) = 81% (98%)
- Global Coverage of LIS/TRMM (data shown above) = 62% (90%)



Max Coverage Extent to Latitude of 54.3 degrees

The GOES Geostationary Lightning Mapper (GLM)



The GLM Instrument

- GLM is a near-IR staring detector that continuously maps in-cloud & cloud-to-ground lightning with near uniform spatial resolution.


Credit: Lockheed Martin

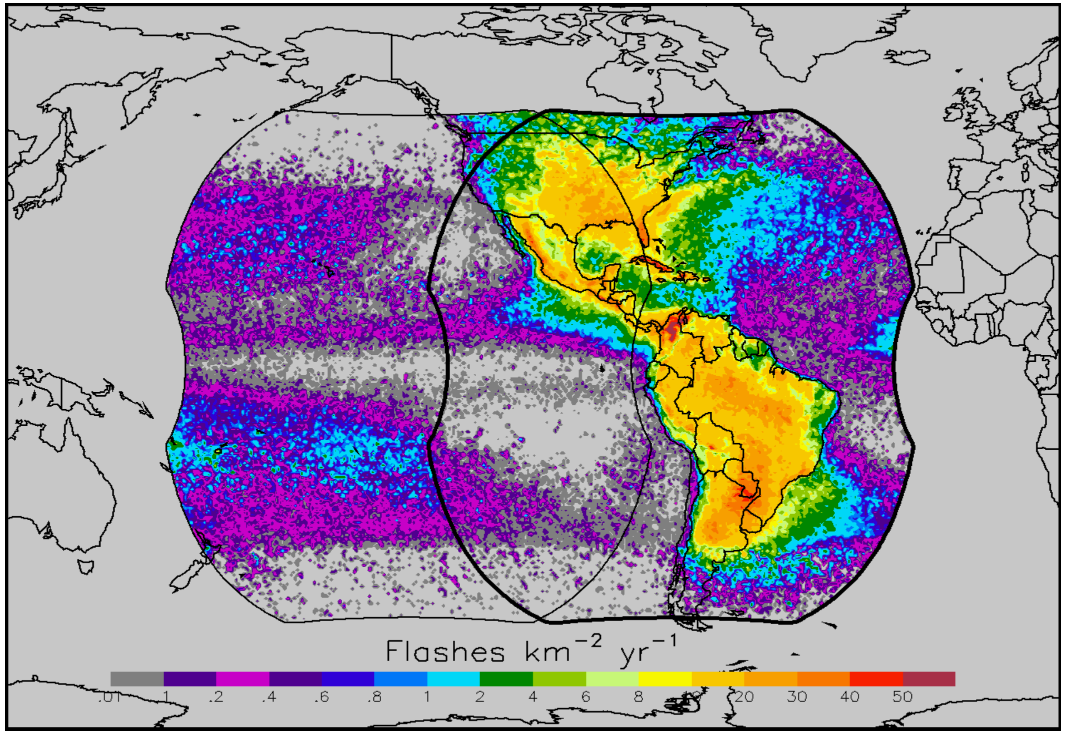
GLM Electronics Unit and Sensor Unit

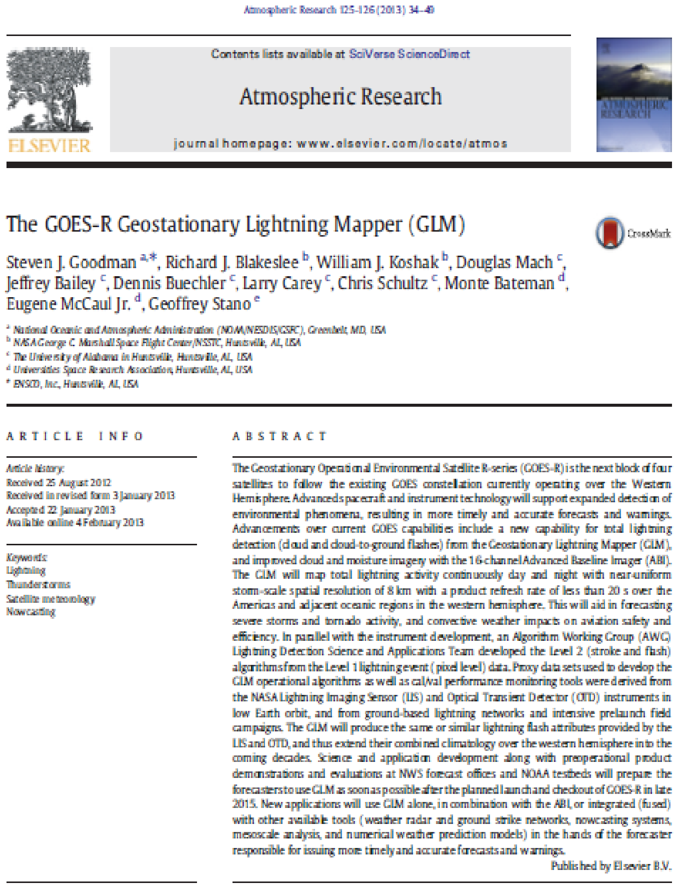

Credit: Lockheed Martin

ABI and GLM Installed on GOES-R

GLM Field of View – GOES E, W

- Combined field-of-view of the Geostationary Lightning Mapper (GLM) from the East (bold outline centered at 75W and West (thin outline centered at 137W positions. The lightning statistics are derived from measurements from the LIS (January 1998-December 2010) and the Optical Transient Detector (OTD) (May 1995-March 2000) (Cecil et al., Atmos. Res., 2012).

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The GOES-R Geostationary Lightning Mapper (GLM)

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A R T I C L E I N F O

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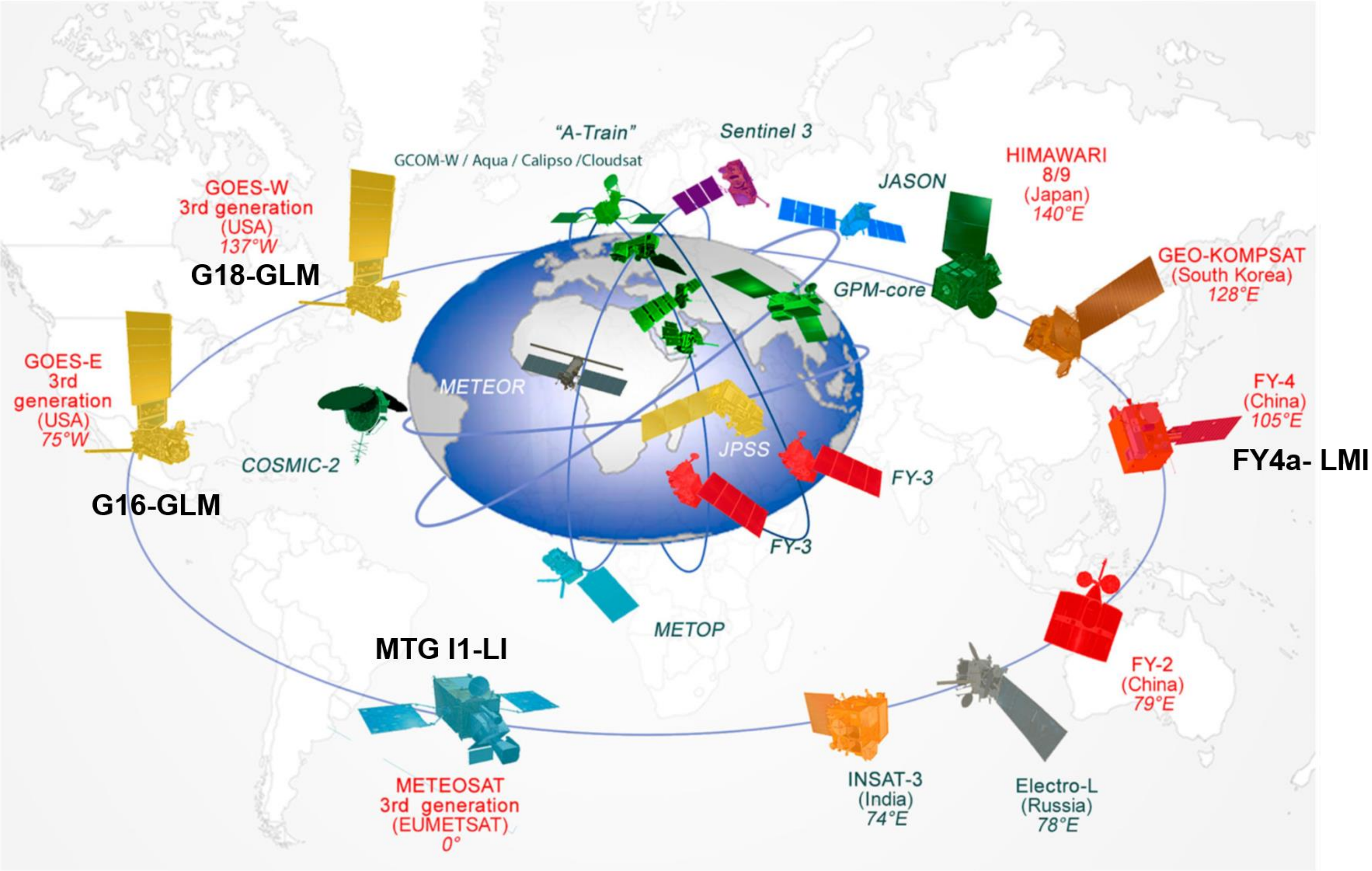
A B S T R A C T

The Geostationary Operational Environmental Satellite R-series (GOES-R) is the next block of four satellites to follow the existing GOES constellation currently operating over the Western Hemisphere. Advanced spacecraft and instrument technology will support expanded detection of environmental phenomena, resulting in more timely and accurate forecasts and warnings. Advancements over current GOES capabilities include a new capability for total lightning detection (cloud and cloud-to-ground flashes) from the Geostationary Lightning Mapper (GLM), and improved cloud and moisture imagery with the 16-channel Advanced Baseline Imager (ABI). The GLM will map total lightning activity continuously day and night with near-uniform storm-scale spatial resolution of 8 km with a product refresh rate of less than 20 s over the Americas and adjacent oceanic regions in the western hemisphere. This will aid in forecasting severe storms and tornado activity, and convective weather impacts on aviation safety and efficiency. In parallel with the instrument development, an Algorithm Working Group (AWG) Lightning Detection Science and Applications Team developed the Level 2 (stroke and flash) algorithms from the Level 1 lightning event (pixel level) data. Proxy data sets used to develop the GLM operational algorithms as well as cal/val performance monitoring tools were derived from the NASA Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) instruments in low Earth orbit, and from ground-based lightning networks and intensive prelaunch field campaigns. The GLM will produce the same or similar lightning flash attributes provided by the LIS and OTD, and thus extend their combined climatology over the western hemisphere into the coming decades. Science and application development along with preoperational product demonstrations and evaluations at NWS forecast offices and NOAA testbeds will prepare the forecasters to use GLM as soon as possible after the planned launch and checkout of GOES-R in late 2015. New applications will use GLM alone, in combination with the ABI, or integrated (fused) with other available tools (weather radar and ground strike networks, nowcasting systems, mesoscale analysis, and numerical weather prediction models) in the hands of the forecaster responsible for issuing more timely and accurate forecasts and warnings.

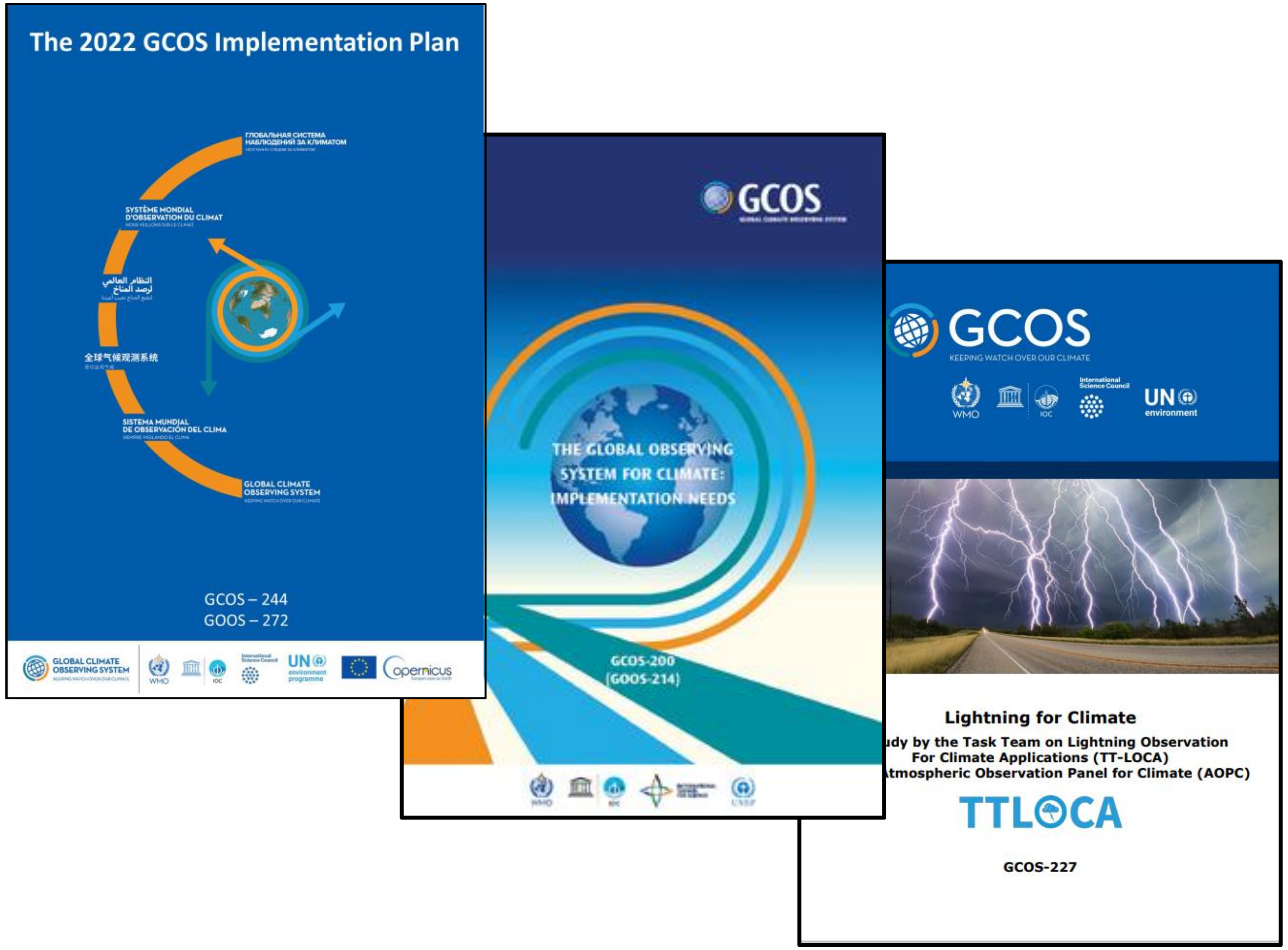
Published by Elsevier B.V.

The Global Satellite Observing System – Building the Geo-Ring



Lightning for Climate Value Proposition

- **Why Lightning for Climate**
  - An **Essential Climate Variable (ECV)** is a physical, chemical, or biological variable or group of linked variables that critically contributes to the characterization of Earth’s climate.
  - ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, guide mitigation and adaptation measures, assess risks, enable attribution of climate events to underlying causes, and underpin climate services.
  - They are required to support the work of the UN Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC).



The 2022 GCOS Implementation Plan

GCOS – 244
GOOS – 272

GCOS

THE GLOBAL OBSERVING SYSTEM FOR CLIMATE: IMPLEMENTATION NEEDS

GCOS-200
(GOOS-214)

GCOS
KEEPING WATCH OVER OUR CLIMATE

Lightning for Climate
udy by the Task Team on Lightning Observation
For Climate Applications (TT-LOCA)
tmospheric Observation Panel for Climate (AOPC)

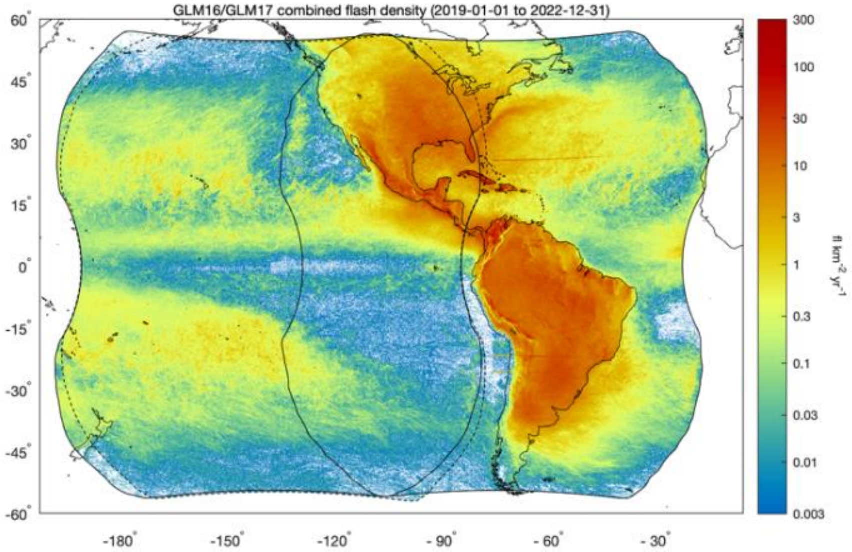
TTLOCA

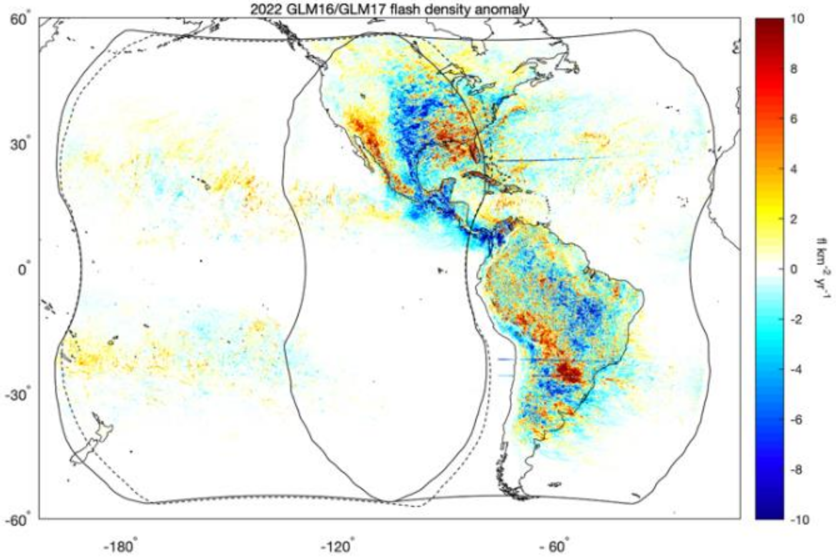
GCOS-227

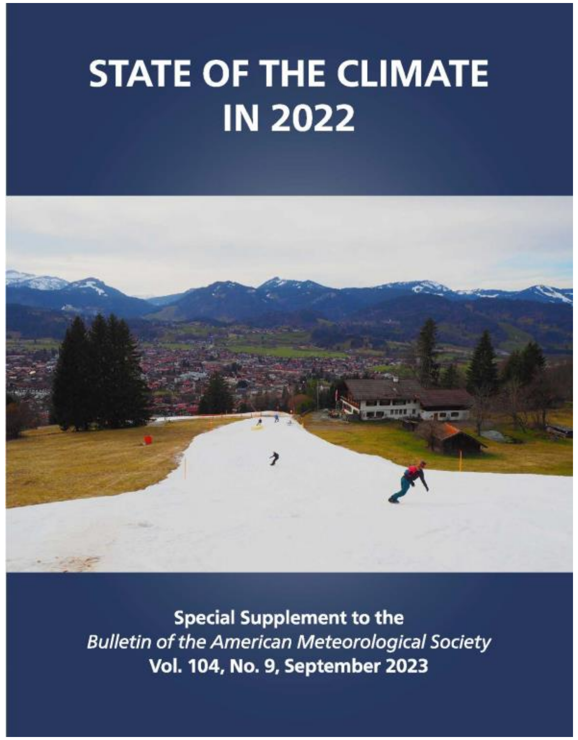
GCOS – Global Climate Observing System

Lightning is one of the Essential Climate Variables (ECVs) in the WMO Global Climate Observing System (GCOS).

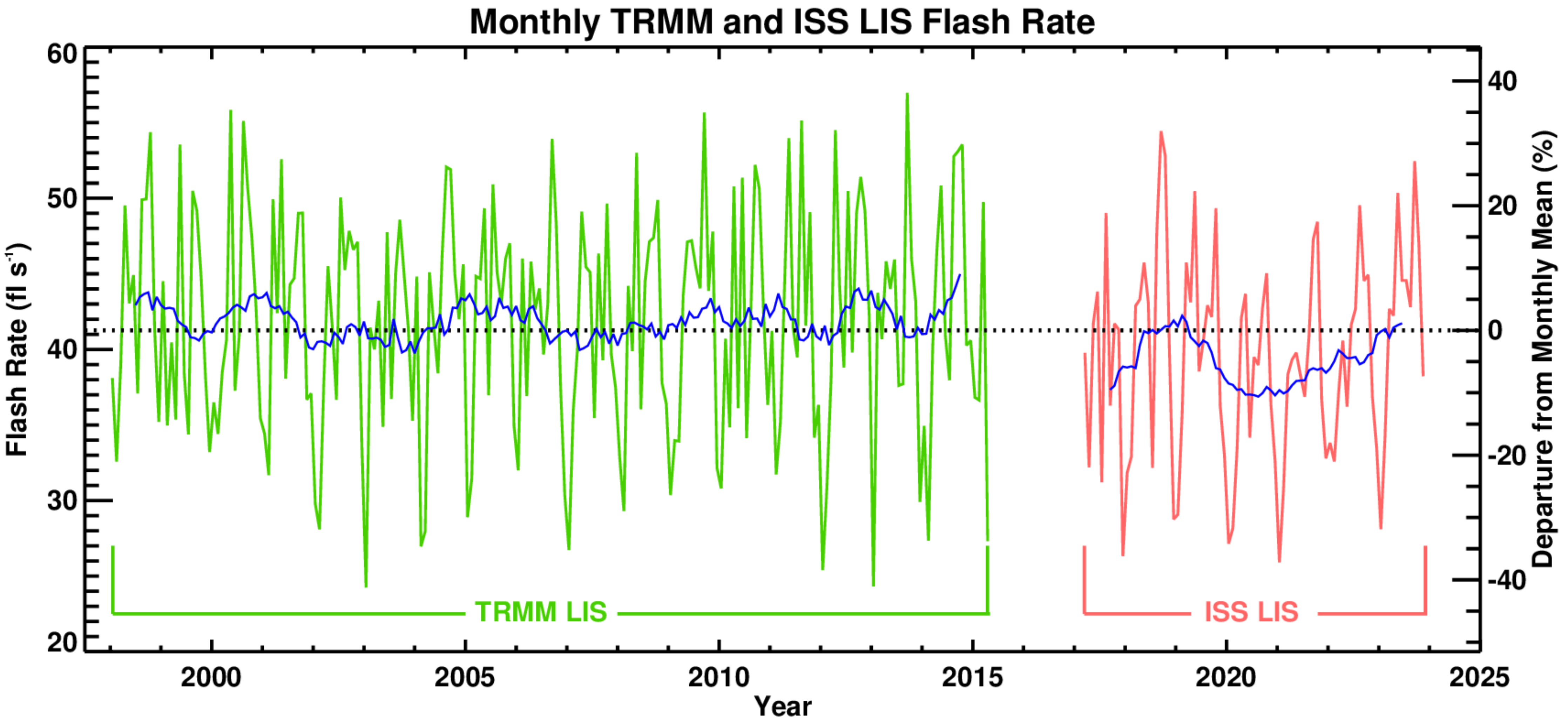
- Combined G16 and G17 combined mean GLM flash density (left) and anomaly (right) for 2022 relative to the 2019-2021 mean.
- Triple-dip 3-year La Niña ending in March 2023
- COVID-19 with reduced industrial emissions






STATE OF THE CLIMATE IN 2022

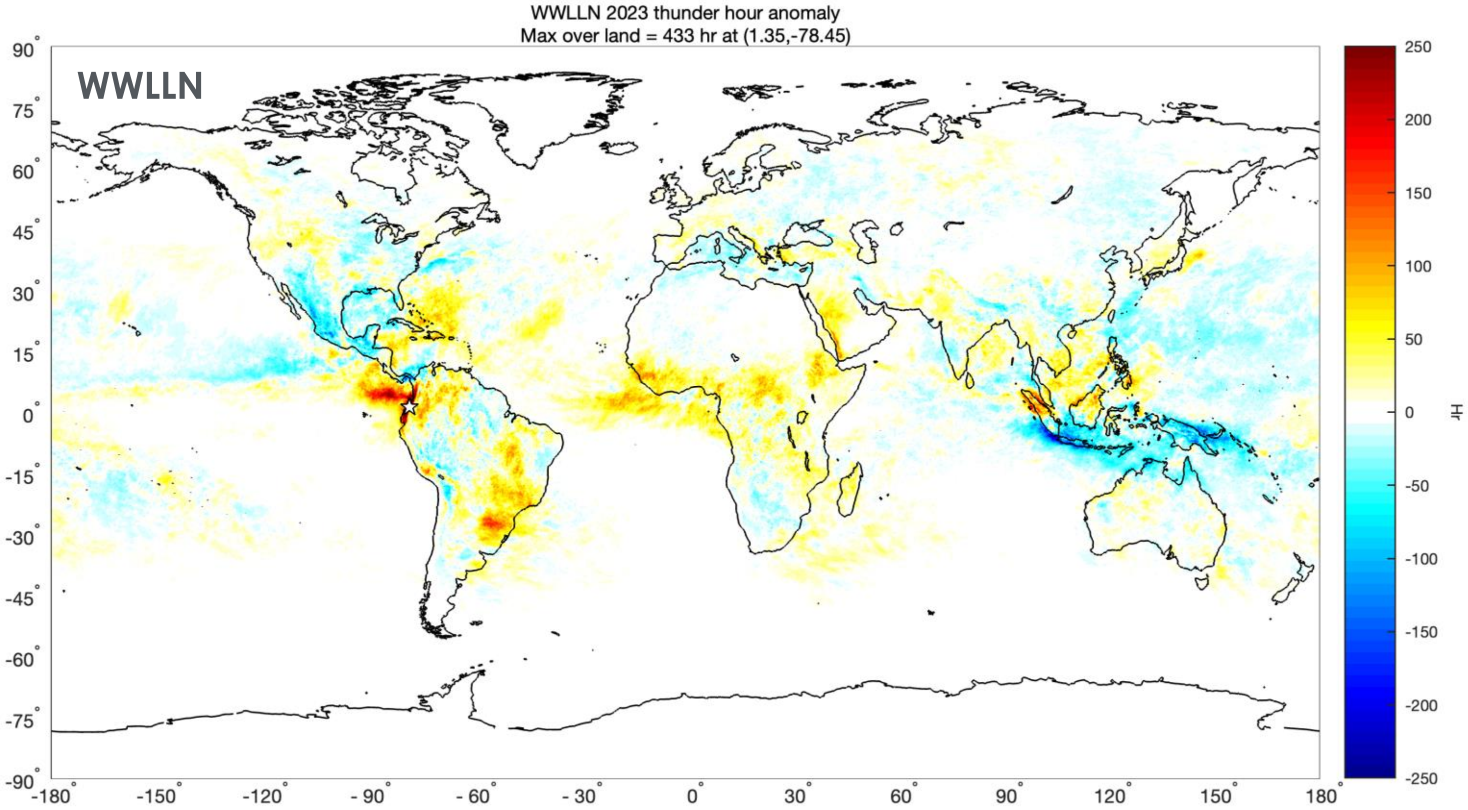
Special Supplement to the
Bulletin of the American Meteorological Society
Vol. 104, No. 9, September 2023

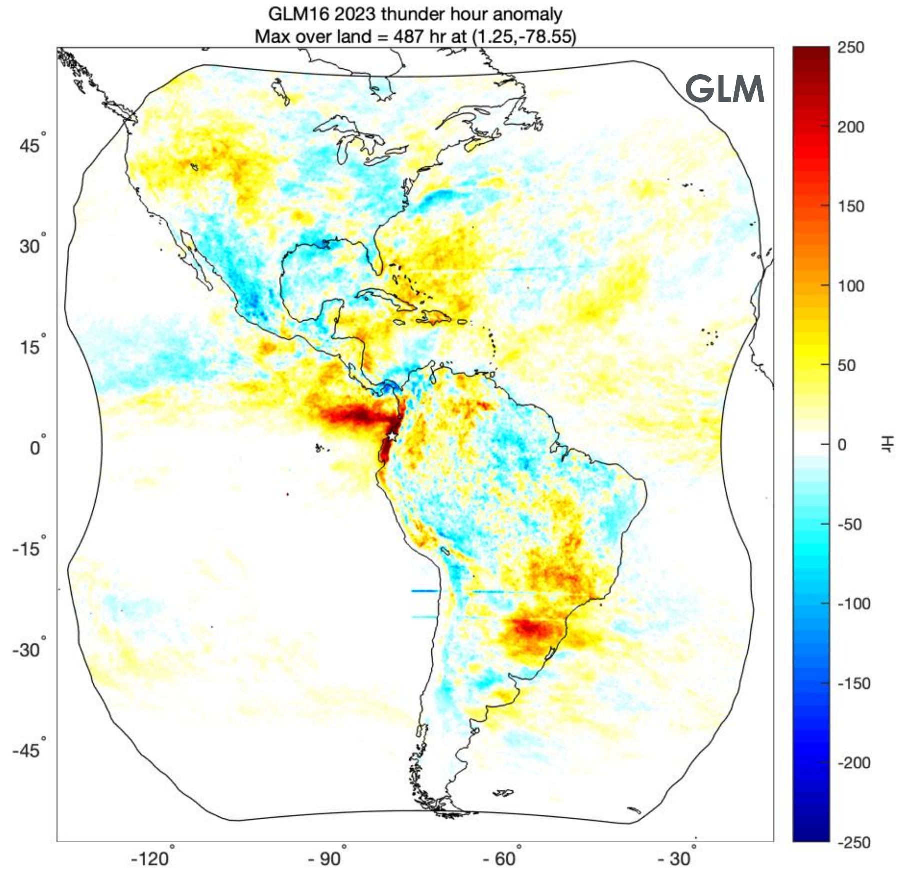

Monthly TRMM and ISS LIS Flash Rate
Flash Rate (fl s^{-1})
60
50
40
30
20
Departure from Monthly Mean (%)
40
20
0
-20
-40
TRMM LIS
ISS LIS
2000
2005
2010
2015
2020
2025
Year

Thunder Hour

- The lifetime of an ordinary thunderstorm is ~1 h and thunder can be heard by a human observer up to ~15 km distance.
- The corresponding definition of the **thunder hour** is that at least two lightning flashes were located within one hour at <15 km distance from a given location.
- The mapping of thunder hours enables the characterization of thunderstorm frequencies around the world that are indicative of high impact weather and lightning hazard.

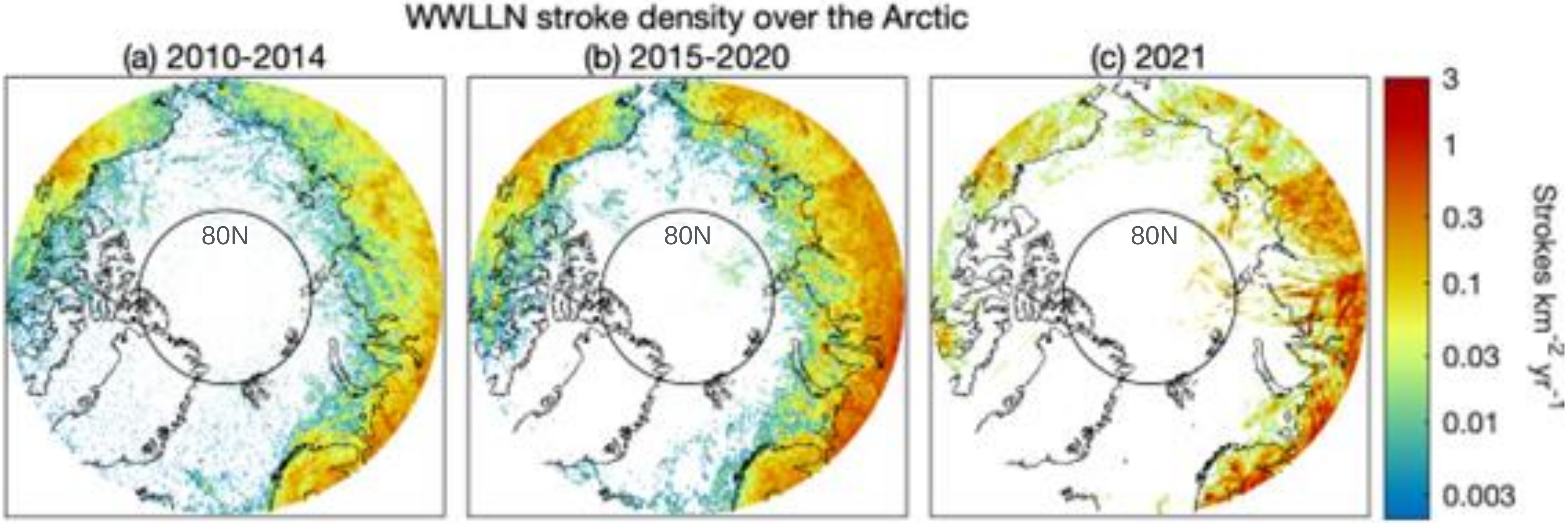
El Niño 2023 Thunder Hour Anomaly





The thunder hour anomalies in 2023 are calculated against the preceding five-year average of annual thunder hours (2018-2022). The resulting thunder hour anomaly map for 2023 exhibits a large enhancement over the Eastern Pacific Ocean and Southeastern Brazil, attributed to increased East Pacific SST associated with the El Niño that started in 2023.

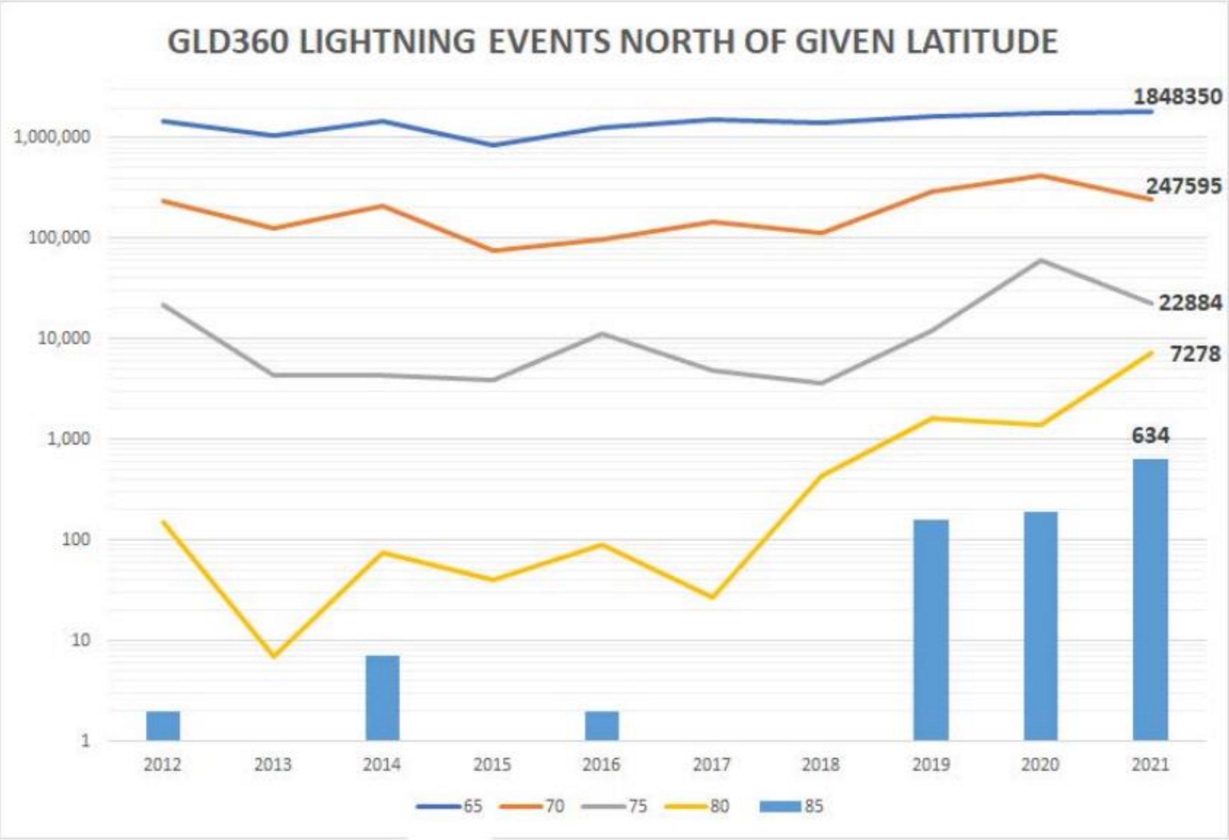
Attribution: How is the increase in high latitude lightning linked to a warming Arctic?



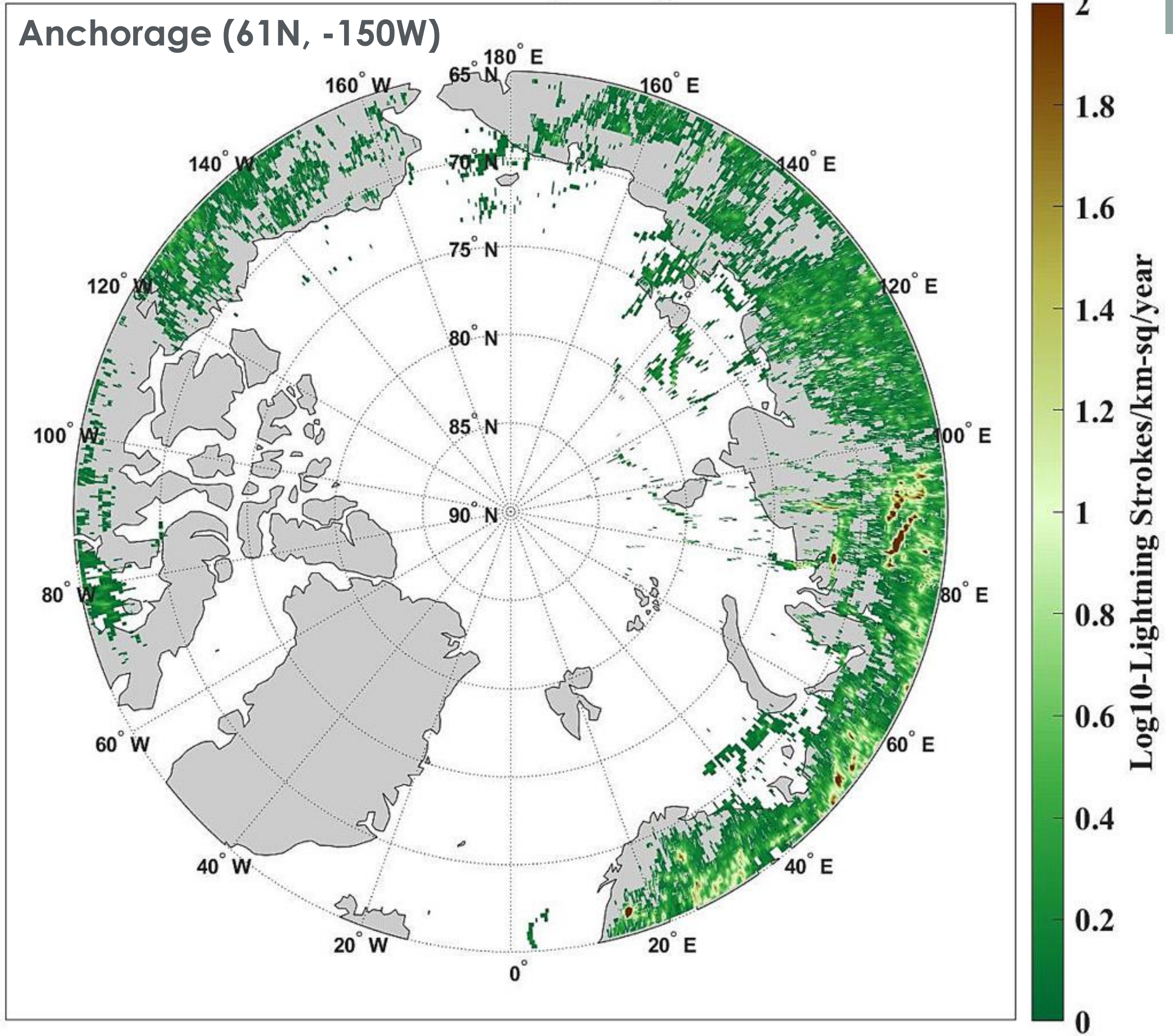
Arctic lightning densities recorded by the World Wide Lightning Location Network (WWLLN) and averaged over the years 2010-2014, 2015-2020, and 2021. The lightning flash densities increased during 2015-2020 when compared to 2010-2014. In 2021, Northern Europe and much of Northern Russia continued to experience higher overall lightning densities. Eastern Russia and Northern North America generally experienced less lightning than the previous 2015-2020 period.

BAMS Special Issue on Climate, 2022

High Latitude Lightning

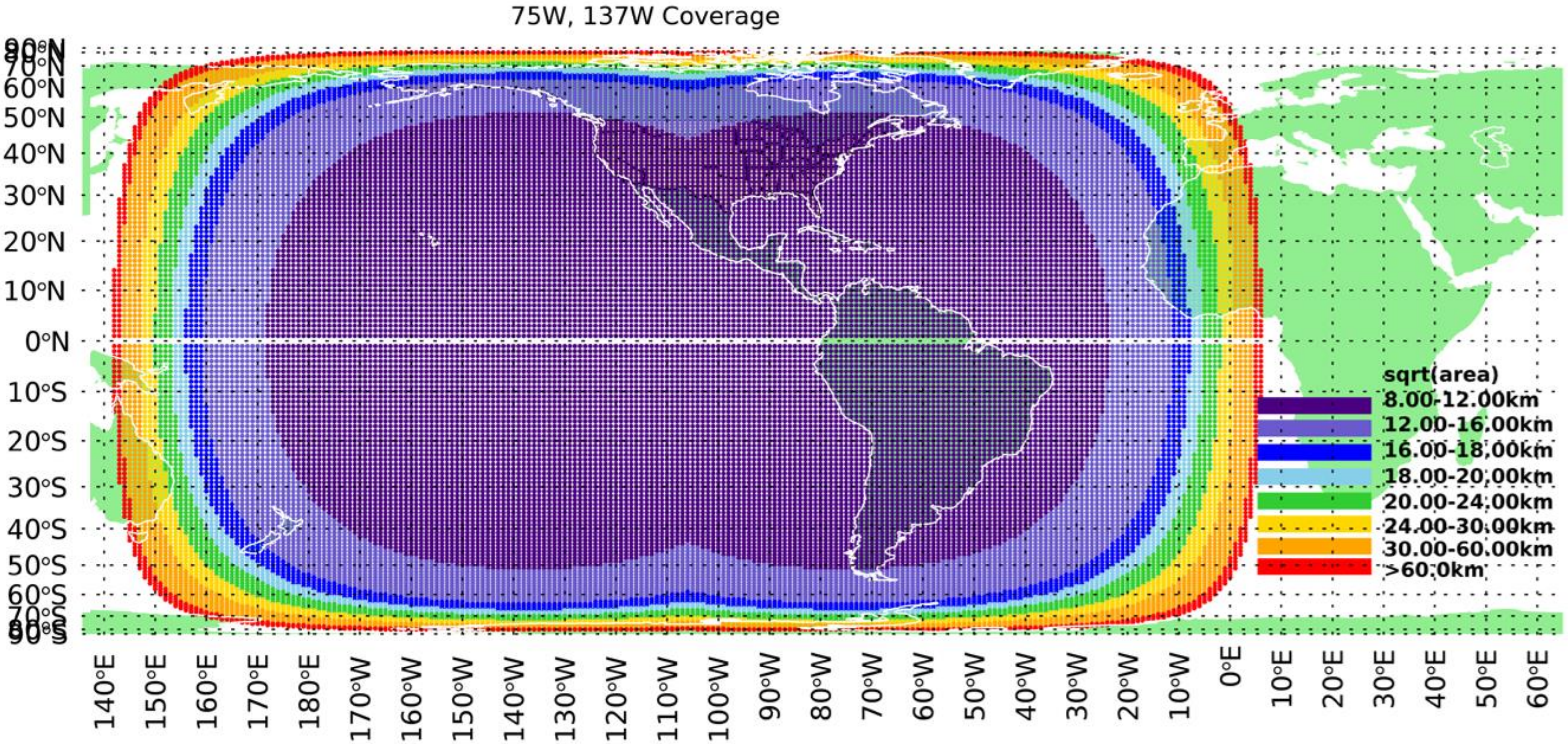

GLD360 LIGHTNING EVENTS NORTH OF GIVEN LATITUDE

Courtesy Vaisala, Inc.


WWLLN Stroke Density Map for JJA 2021

Spatial distribution of lightning stroke density (strokes/ km2/year) in June, July and August (JJA) months of 2021 above 65◦N (Saha et al., Atmos. Res., 2023).

GeoXO Lightning Mapper: *LMX*



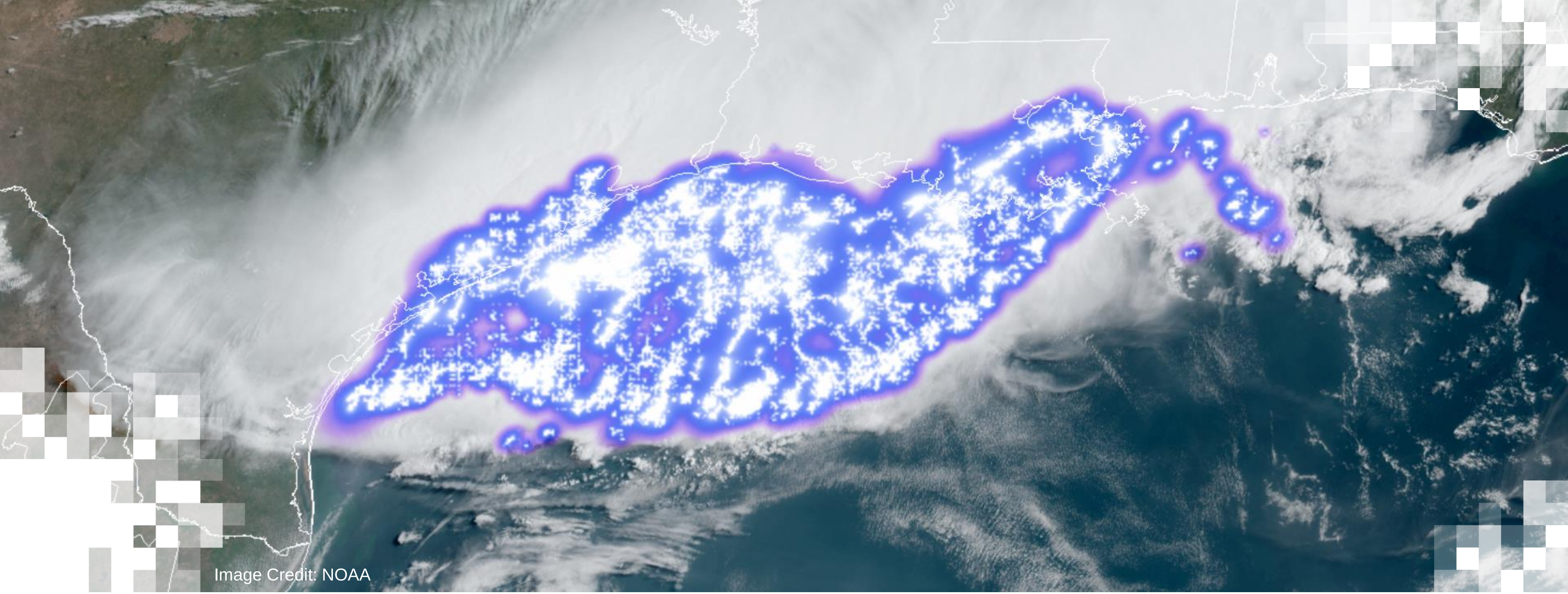


Image Credit: NOAA

Part 1

Summary

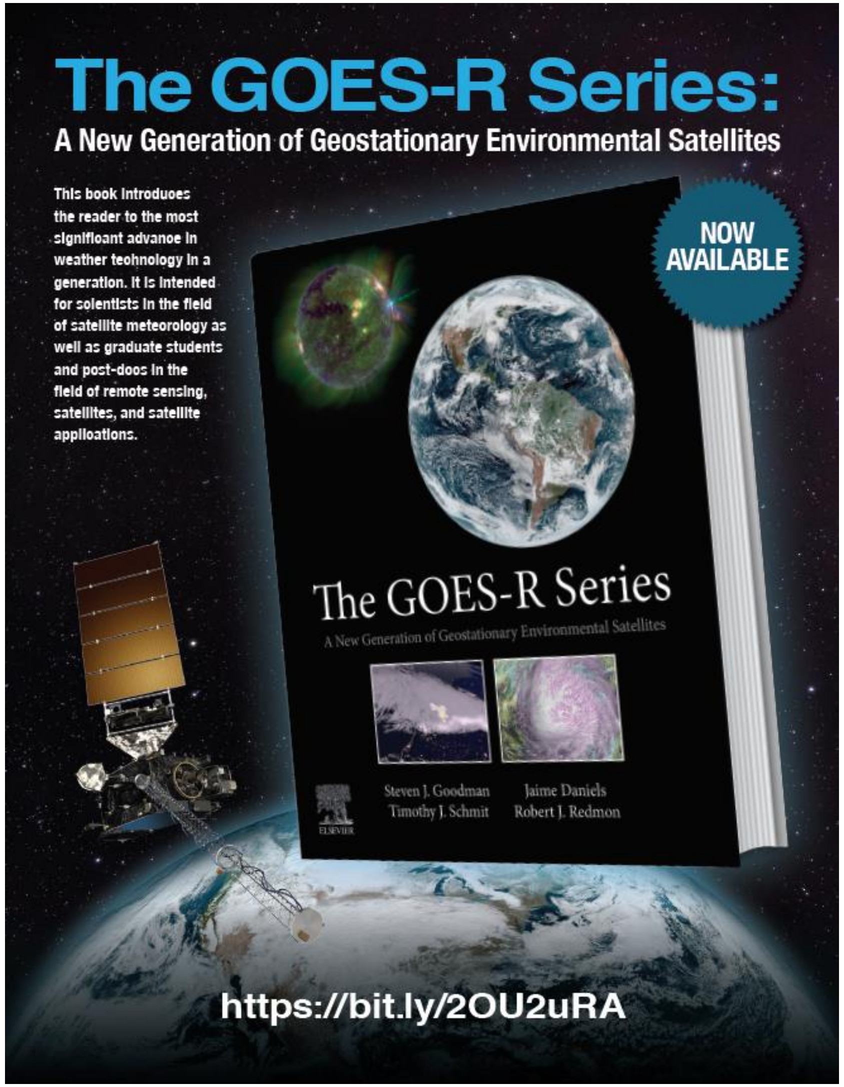
Summary

- Lightning is a global natural hazard of great significance.
- LMX is an evolutionary advancement over GLM.
- How might a lightning ECV be associated with other variables, such as clouds, precipitation, composition, NOx, surface observations (e.g., temperature, severe weather reports), ENSO, MJO, and upper-level humidity?
- Raise lightning safety awareness – collaboration with WHO, WMO Disaster Risk Reduction (Natural Hazards) Programme

Resources

Websites:

- https://www.goes-r.gov/
- https://rammb-slider.cira.colostate.edu/
- https://satelliteliaisonblog.com/
- http://cimss.ssec.wisc.edu/goes/goesdata.html
- https://lightning.umd.edu/glm/
- https://ghrc.nsstc.nasa.gov/lightning/
- https://www.ncdc.noaa.gov/data-access/satellite-data/goes-r-series-satellites



The GOES-R Series:

A New Generation of Geostationary Environmental Satellites

This book introduces the reader to the most significant advance in weather technology in a generation. It is intended for scientists in the field of satellite meteorology as well as graduate students and post-docs in the field of remote sensing, satellites, and satellite applications.

https://bit.ly/2OU2uRA

Homework and Certificates

- **Homework:**
  - One homework assignment
  - Opens on 04/02/2024
  - Access from the training webpage
  - Answers must be submitted via Google Forms
  - **Due by 04/17/2024**

- **Certificate of Completion:**
  - Attend all three live webinars (attendance is recorded automatically)
  - Complete the homework assignment by the deadline
  - You will receive a certificate via email approximately two months after completion of the course.

Contact Information

Trainers:

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Thank You!