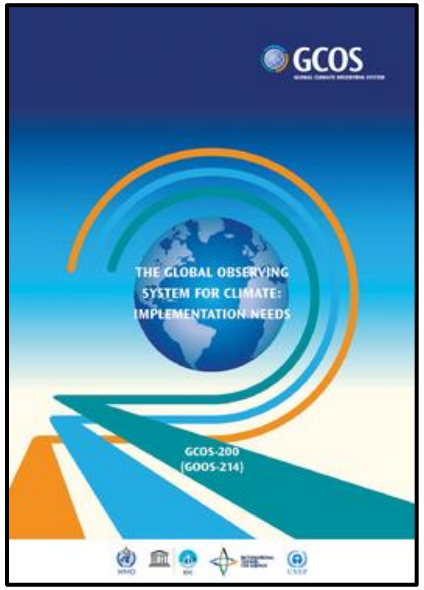
# Lightning : An Essential Climate Variable

## WMO/GCOS Task Team on Lightning Observation For Climate Applications (TT-LOCA)

*AOPC-27 June 27-30, 2022*

**Updates since the AOPC-26 April Meeting**

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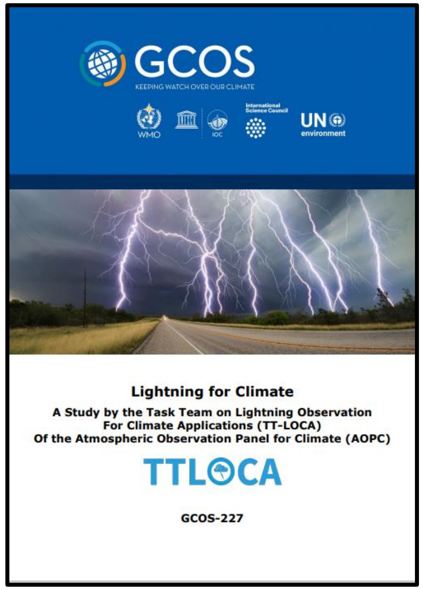


# Why Lightning for Climate?

Due to the relevance and use of **lightning data as a climatological variable**, lightning has been added to the list of Essential Climate Variables (ECV) in the **2016 WMO Global Climate Observing System (GCOS) Implementation Plan (IP) (GCOS, 2016),** including a first attempt to **define the requirements for climate monitoring of lightning** measurements.

Action 29 of the IP called for defining "**the requirement for lightning measurements, including data exchange, for climate monitoring and to encourage space agencies and operators of ground-based systems to strive for global coverage and <u>reprocessing</u> of existing datasets".**

**The TT-LOCA created to address these questions; renewed through 2021**

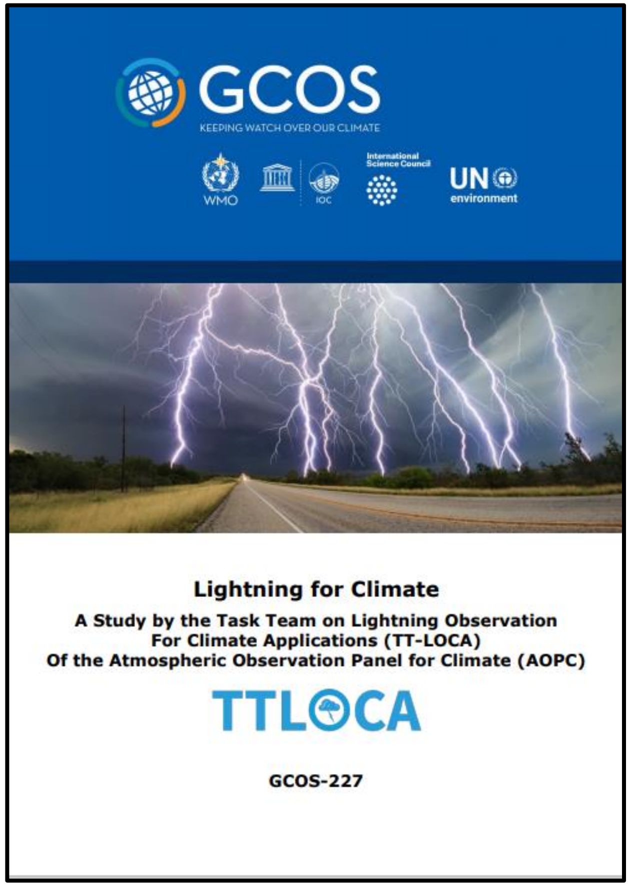
# Lightning for Climate: Value Proposition

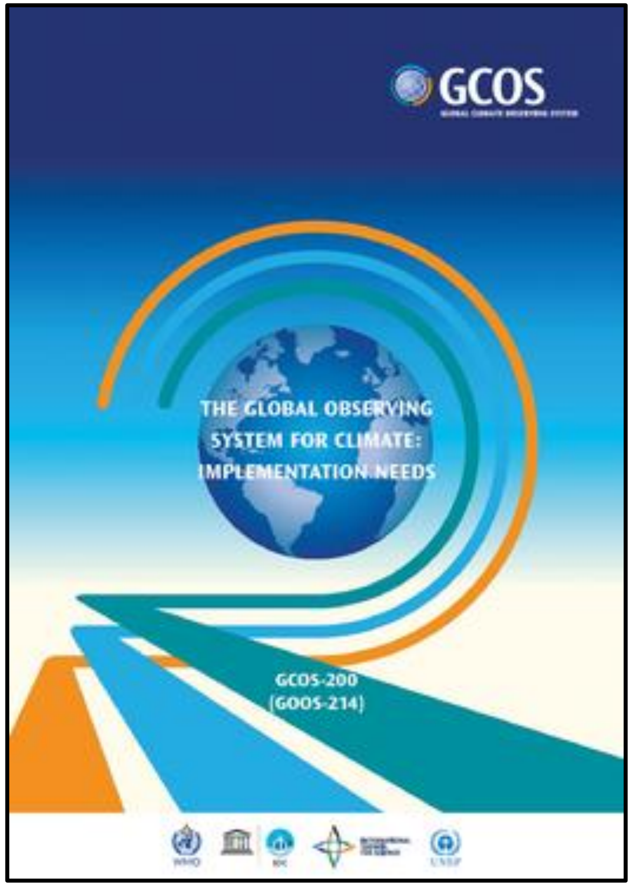
ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climate events to underlying causes, and to underpin climate services.

**Space-based and VLF ground-based lightning network data are complementary** in the information they provide (flash energy, size, duration, extent). Regional ground-based lightning networks would be a useful addition as they also provide more definitive information on flash type to compare or add to the Lightning ECV database.

**Although most lightning occurs in the continental tropics and mid-latitudes, recent observations are indicating an increase in lightning at high latitudes associated with a warming arctic.** Monthly, daily and even hourly data are available.

The Thunder Day observation at meteorological stations is a long-term WMO database. There is some evidence that this quantity has also been increasing at high latitudes. **Lightning has long been associated with severe and high impact mesoscale weather phenomena, precipitation, NOx, aerosols, tropospheric temperature and moisture. Lightning-initiated wildfires and the threat to public safety are increasing concerns.**




Global Climate Observing System (GCOS)

# Essential Climate Variables

## Atmosphere

### Surface

- Precipitation
- Pressure
- Radiation budget
- Temperature
- Water vapour
- Wind speed and direction

### Upper-air

- Earth radiation budget
- Lightning
- Temperature
- Water vapor
- Wind speed and direction

### Atmospheric Composition

- Aerosols
- Carbon dioxide, methane and other greenhouse gases
- Clouds
- Ozone
- Precursors for aerosols and ozone

## Land

### Hydrosphere

- Groundwater
- Lakes
- River discharge

### Cryosphere

- Glaciers
- Ice sheets and ice shelves
- Permafrost
- Snow

### Biosphere

- Above-ground biomass
- Albedo
- Evaporation from land
- Fire
- Fraction of absorbed photosynthetically active radiation (FAPAR)
- Land cover
- Land surface temperature
- Leaf area index
- Soil carbon
- Soil moisture

### Anthroposphere

- Anthropogenic Greenhouse gas fluxes
- Anthropogenic water use

## Ocean

### Physical

- Ocean surface heat flux
- Sea ice
- Sea level
- Sea state
- Sea surface currents
- Sea surface salinity
- Sea surface stress
- Sea surface temperature
- Subsurface currents
- Subsurface salinity
- Subsurface temperature

### Biogeochemical

- Inorganic carbon
- Nitrous oxide
- Nutrients
- Ocean colour
- Oxygen
- Transient tracers

### Biological/ecosystems

- Marine habitats
- Plankton

(https://gcos.w

# Anatomy of a Lightning Flash

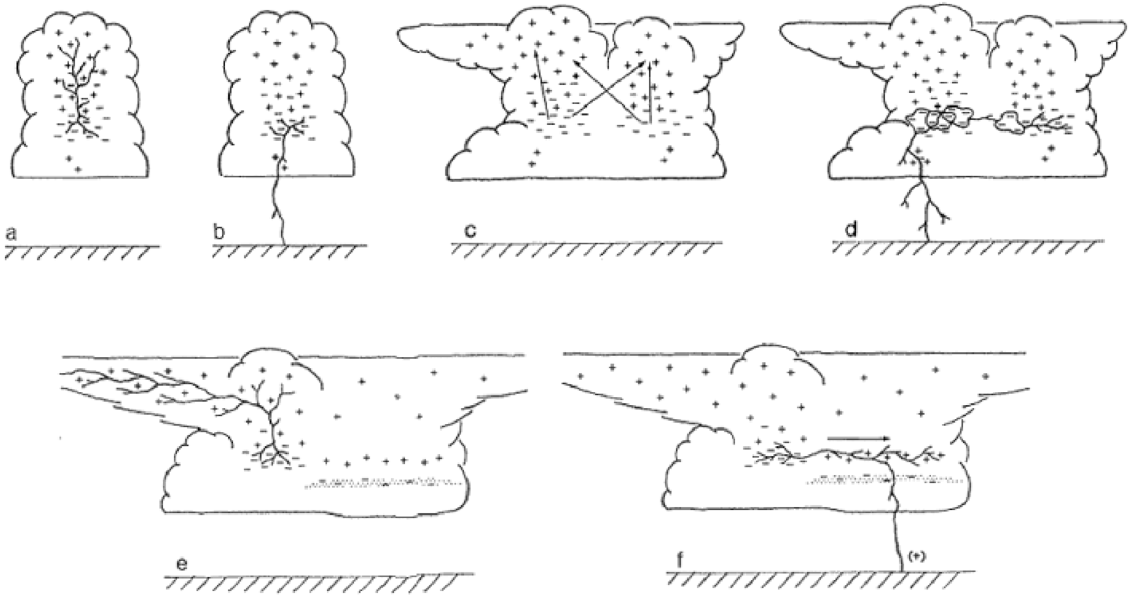
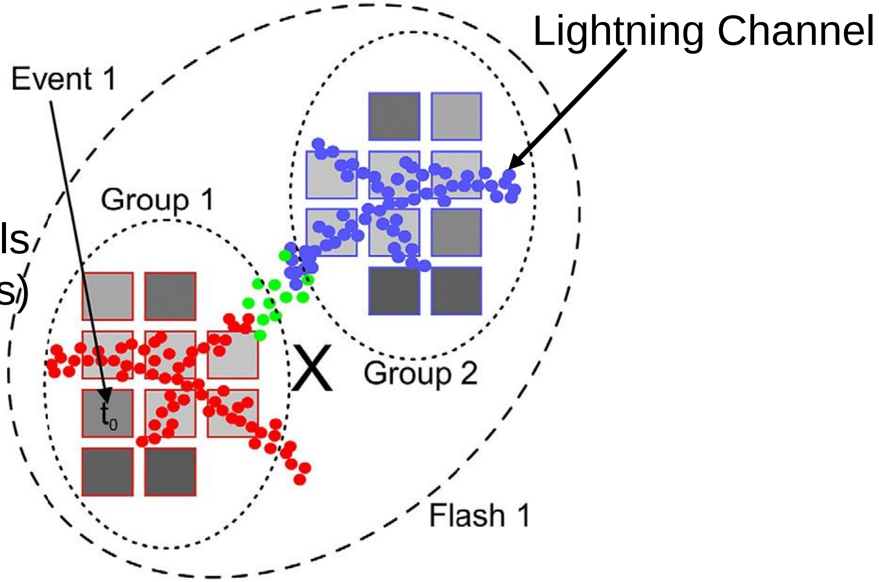



Figure 8.11 The apparent evolution of lightning with time in a thunderstorm, based on a variety of observations in different storms. See text for explanation. The dendritic structure of the lightning has been guessed in all cases except for the multicellular intracloud discharge of part c. The dotted region in the dissipating part of the storm in parts e and f represents the radar brightband from melting snowflakes.

View of lightning at night from the International Space Station (ISS)

Lightning shows up as a puddle of light at cloud top

GLM top down space View of illuminated pixels (lightning events)



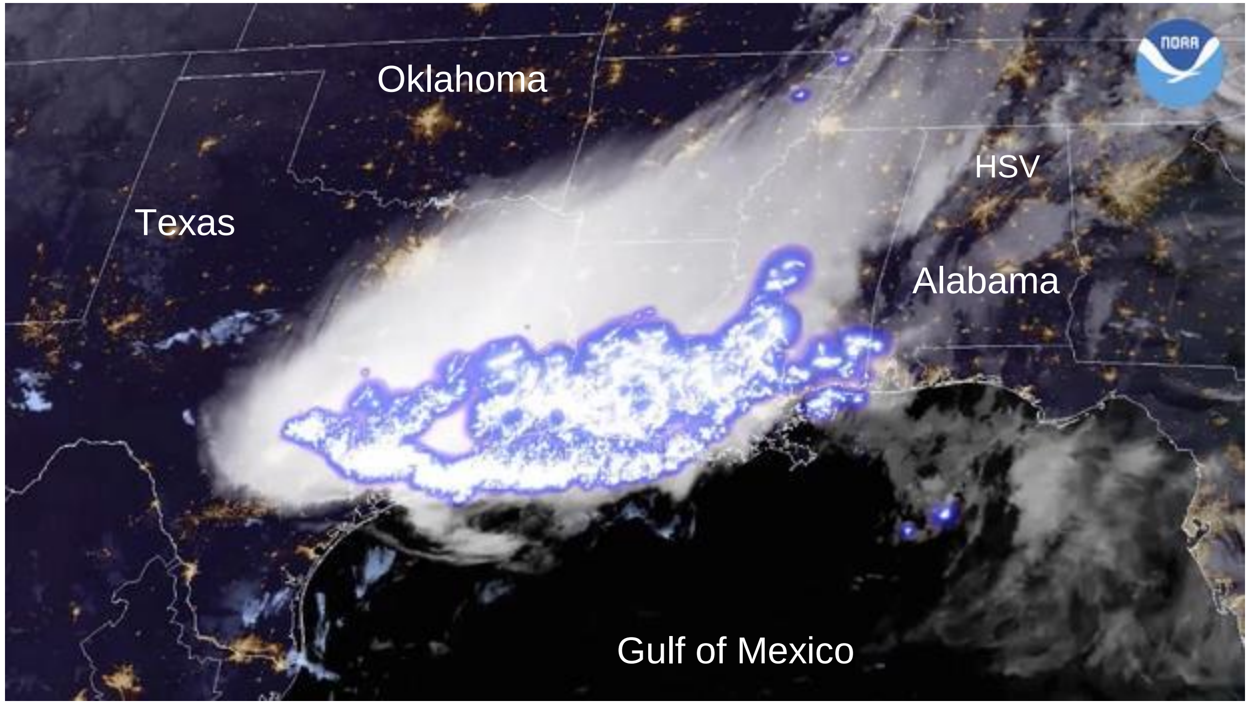
# Longest Lightning Flash Ever?

World record flash covered a horizontal distance of 768 km (477.2 miles) on 29 April 2020

## Flash Overview (WMO Certified World Record)

• GLM can uniquely map the flash extent and duration. The record distance, or peak flash extent, stretched from 75 miles southwest of Houston, Texas to 25 miles north of Biloxi, Mississippi (sum of channel lengths was much longer). This single flash produced 8000 optical groups (strokes).

- This dangerous *Megaflash produced 86 cloud-to-ground strokes during its 8 second duration. The lightning can strike ground anytime during the flash anywhere along its path.
- In regions prone to megaflashes, this risk to public safety should be understood when conducting outdoor activities, even following passage of strong lines of storms (yes, even if the rain has stopped).




*A Megaflash is a lightning flash with horizontal extent > 100 km

Courtesy of Scott Rudlosky and Michael Peterson

# 2022 AOPC IP – Lightning Actions

Accomplishments, Status, and Plans

# Action C5: ECV-specific Satellite Data Processing Method Improvements

- Activity
  - Reprocess the LEO NASA 25+ year Lightning Imaging Sensor (LIS) data set from the Optical Transient Detector OTD, 1995-2000), LIS on the Tropical Rainfall Measuring Mission (TRMM-LIS, 1997-2015) and International Space Station (ISS-LIS, 2017-Present).
  - Reprocess the GEO Geostationary Lightning Mapper (GLM) on GOES-16/17/18 (2017 - Present)
- Status and Plans
  - NASA funding the reprocessing of the OTD/LIS full data set archived at the Global Hydrometeorology Resource Center DAAC.
  - The ISS-LIS will continue collecting data in 2022-2023 (from a newly relocated position on the ISS to make room for another instrument). End of Mission TBD.
  - The OTD/LIS global lightning time series and anomaly to be published in the 2021 AMS Bulletin Special Issue on Climate; already invited to update the results at the end of 2022
  - NOAA GOES-R Program is funding the reprocessing for GLM starting this summer.

# Action C5: ECV-specific Satellite Data Processing Method Improvements

- Status and Plans (con't)
  - Reprocess the data to remove known artefacts and allow for new and improved products using ML/AI (e.g., megaflashes, flash type, continuing current). An Enterprise science algorithm is planned that would be applied to all space-based instruments similar to GLM (e.g., forthcoming MTG-Lightning Imager).
  - Year 1 GLM Reprocessing – address artefacts
  - Year 2 GLM Reprocessing (if funded) – address ML/AI enhanced products
  - Available 2024
- Means of Assessing Progress
  - Validated and updated 0.1x0.1 deg product for satellites and ground based lightning RF data sets (GLD360, WWLLN, TBD Regional networks); ThunderHour grids for GLD360, ENGLN, WWLLN, GLM
  - Validated and updated space and RF ground-based lightning data at 0.1x0.1 deg grids (at monthly cadence).

# Action D5: Undertake Additional Data Rescue Activities

- Activity
  - Continue efforts to advance the rescue of key historical data records from hard copy or image form via an appropriate combination of professional, citizen science and class-based activities.
  - The Thunder Day observation at meteorological stations is a long-term WMO database.
- Status and Plans
  - TT-LOCA team member E. Williams has reached out to NMHS to back-fill missing records.
  - Copernicus at ECMWF offered stewardship of the recovered data set.
- Means of Assessing Progress
  - New funded data rescue efforts leading to the provision of additional data rescued to recognised global repositories for relevant ECVs via a variety of approaches (professional keying, citizen science, participatory learning).
  - Methodology can follow that of Lavigne et al. (JGR, 2019) where 43 years and 8000 Thunder Day station reports were correlated to 16 years of TRMM/LIS satellite data to examine trends in global lightning activity. (Lavigne et al., 2019, JGR https://doi.org/10.1029/2018JD029920).

# Remaining and Additional Activities

- Activity
  - TT-LOCA planned sunset after the 2-year extension through 2021. Consider extension or naming a liaison to the AOPC to further coordination through 2024 to evaluate the space-based and ground-based ECV data sets, reprocessing, and initial results from the MTG-LI.
  - Continue outreach to operators of regional ground-based lightning networks to provide ECV compatible data sets.
  - Brief Summary drafted on "Access to Global Lightning via Schumann Resonances" by TT-LOCA WG members E. Williams and C. Price.
  - Continue plan to utilize the GRUAN balloon sounding network (also WMO) to measure ionospheric potential to study the Global Electric Circuit.
  - Complete a summary report to follow the initial GCOS-227 Report "Lightning for Climate". Report format to be discussed at AOPC-27 with WMO-CGOS leads Caterina Tassone and Tim Oakley.
- ECV Data Stewardship
  - Global VLF operators (GLD360, ENGLN, WWLLN) offered to provide stewardship, maintain and update their ECV product (monthly gridded product, Thunder Hour)
  - NCEI - stewardship of operational and GLM reprocessed data
  - NASA – GHRC stewardship of the OTD/LIS reprocessed data, and Cloud Service landing page (to be developed and coordinated with NCEI) for all Lightning ECV products.

# Future Plans

- TT-LOCA planned sunset after the 2-year extension through 2021. Consider extension or naming a liaison to the AOPC to further coordination through 2024 to evaluate the space-based and ground-based ECV data sets, reprocessing, and initial results from the MTG-LI.
- Continue outreach to operators of regional ground-based lightning networks to provide ECV compatible data sets.
- Continue gathering of NMHS Thunder Day records.
- Ionospheric potential - Participated in the last GRUAN science meeting (in November) and are now slated to make simultaneous measurements of Vi from two GRUAN sites: Graciosa Island and Lauder in New Zealand, once the sensors now under contract are ready for flight.
- Continue collaboration with data producers and stewards: NCEI, NASA, EUMETSAT, CMA and commercial providers to deliver a data set for verification, cross-validation, and science.
- Develop a cloud service landing page at the NASA GHRC DAAC coordinated with NOAA and other partners.
- Complete a summary report to follow the initial GCOS-227 Report “Lightning for Climate”. Report format to be discussed at AOPC-27 with WMO-CGOS leads Caterina Tassone and Tim Oakley.

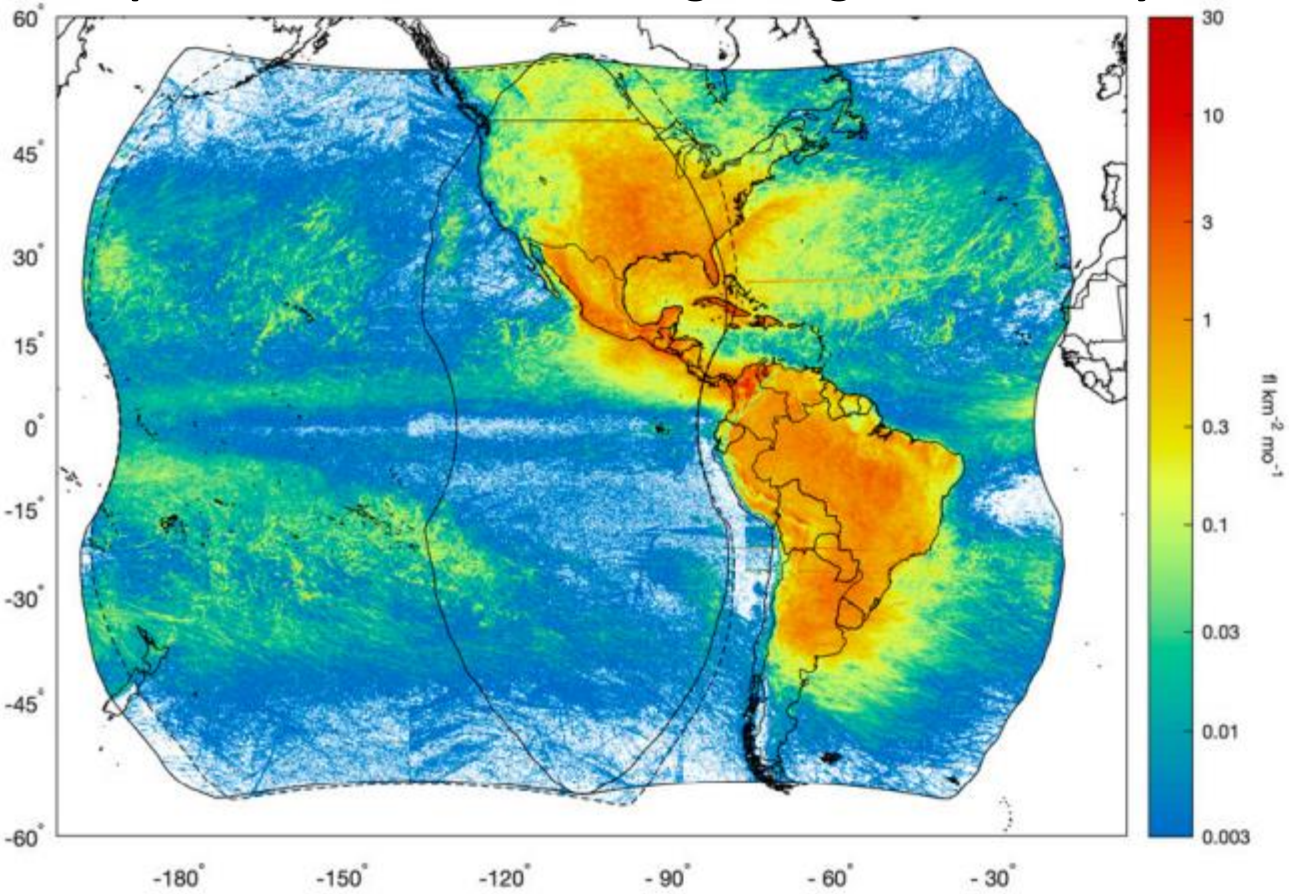
# Back-Up

# Lightning Data Requirements

- **Total Lightning Stroke Density**
  - **Consistent, Harmonized Data**
- **Global 10 km x 10 km (0.1 x 0.1 deg)**
- **Temporal (Monthly, Daily, Hourly)**

- **Space-based Optical:**
  - **NASA TRMM/ISS - LIS**
  - **NOAA/NASA GOES - GLM**
  - **CMA FY-4 - LMI**
  - **EUMETSAT MTG - LI**
- **Ground-based RF (commercial data):**
  - **GLD360 (Vaisala)**
  - **ENTLN (Earth Networks)**
  - **WWLLN (Univ. Washington)**
  - **Regional Networks (IC/CG)**

**Space-based: GLM Total Lightning Flash Density**

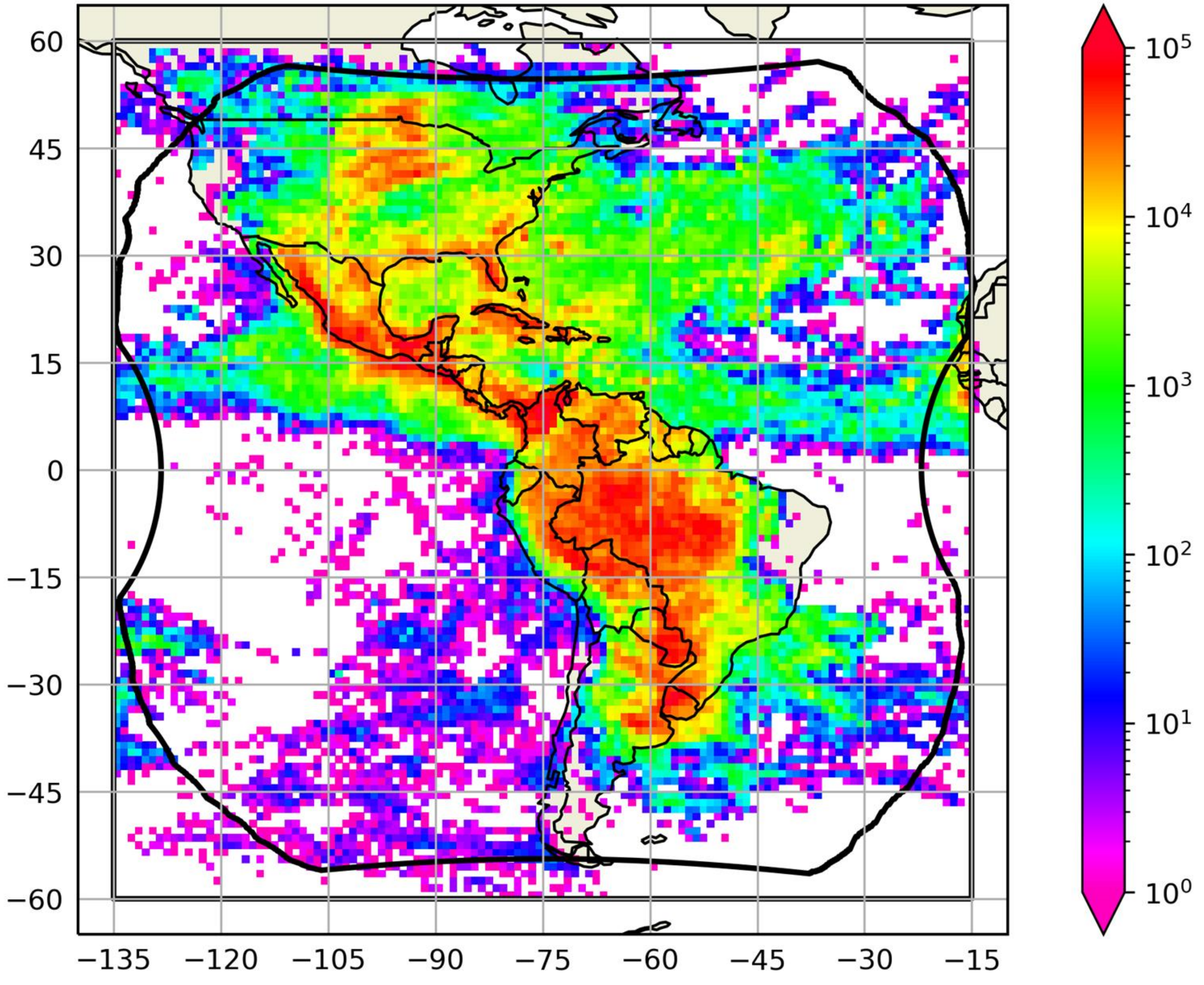



Combined G16 and G17 GLM flash densities from 1 Dec 2018 to 31 May 2020 with units of flash count per square kilometer per month (after Rudlosky and Virts, 2021, MWR, DOI: 10.1175/MWR-D-20-0242.1).

# GLD360 and GLM flash accumulation September 2018

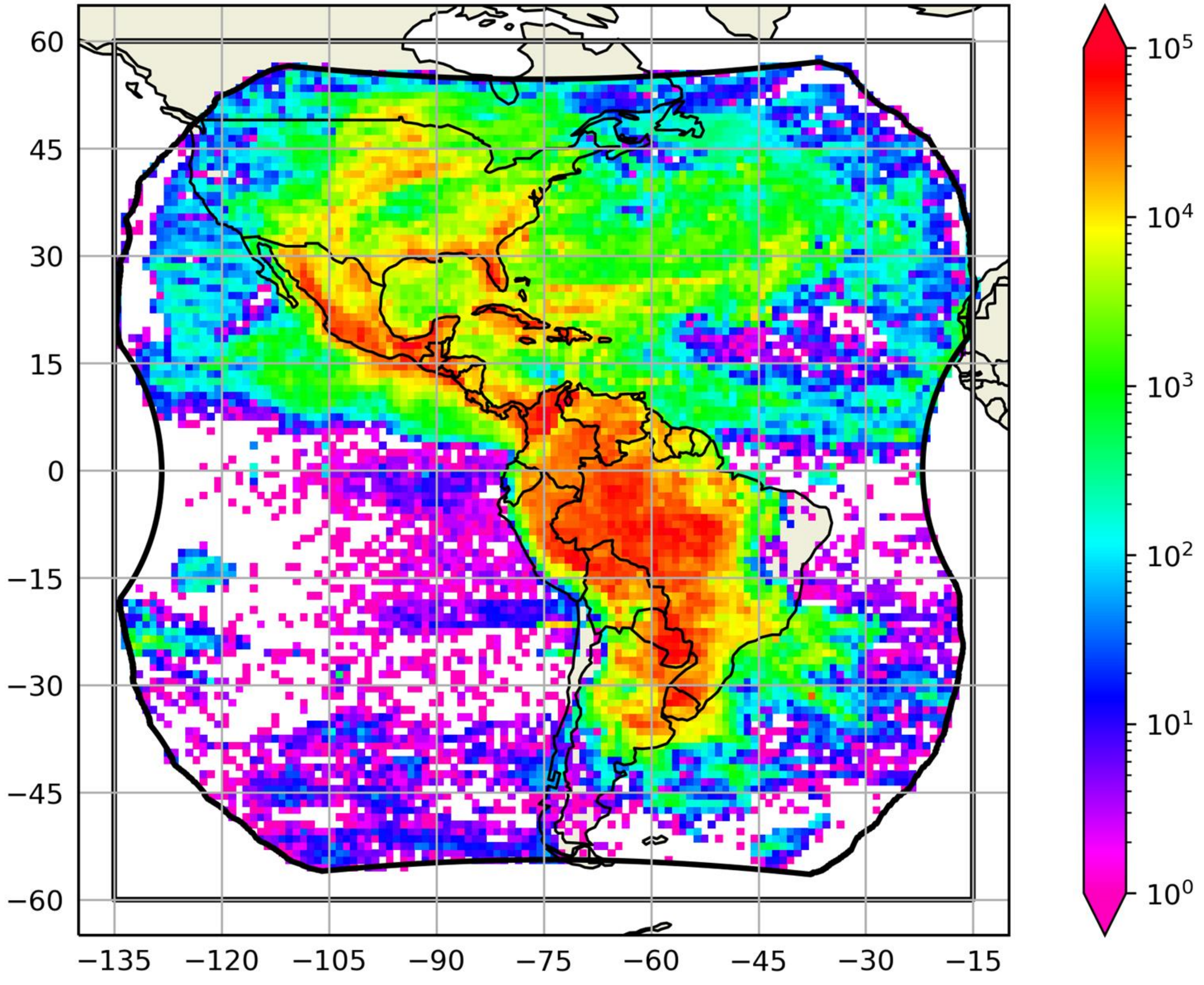
GLD360 Accumulated Flashes Gld 2018-09

**GLD360**




GLM Accumulated Flashes Gld 2018-09

**GLM**



# Lightning Products and Services

NCEI provides access to lightning flash summaries by county and state, gridded lightning frequency products, and other data derived from internal products. Data is available in standard formats through direct download, and web services that allow spatial and temporal subsetting. The National Lightning Detection Network (NLDN) dataset is available for the continental United States.

Data Access

## Public Products

Limited public availability outside NOAA

### Severe Weather Database Inventory (SWDI) Lightning Tile Summaries

This product summarizes the number of cloud-to-ground lightning flashes for each day in 0.10-degree tiles. These tiles are part of the NCEI Severe Weather Data Inventory and can be accessed using the SWDI GIS-based search tool or RESTful web services.

Launch SWDI

http://thunderhours.earthnetworks.com/

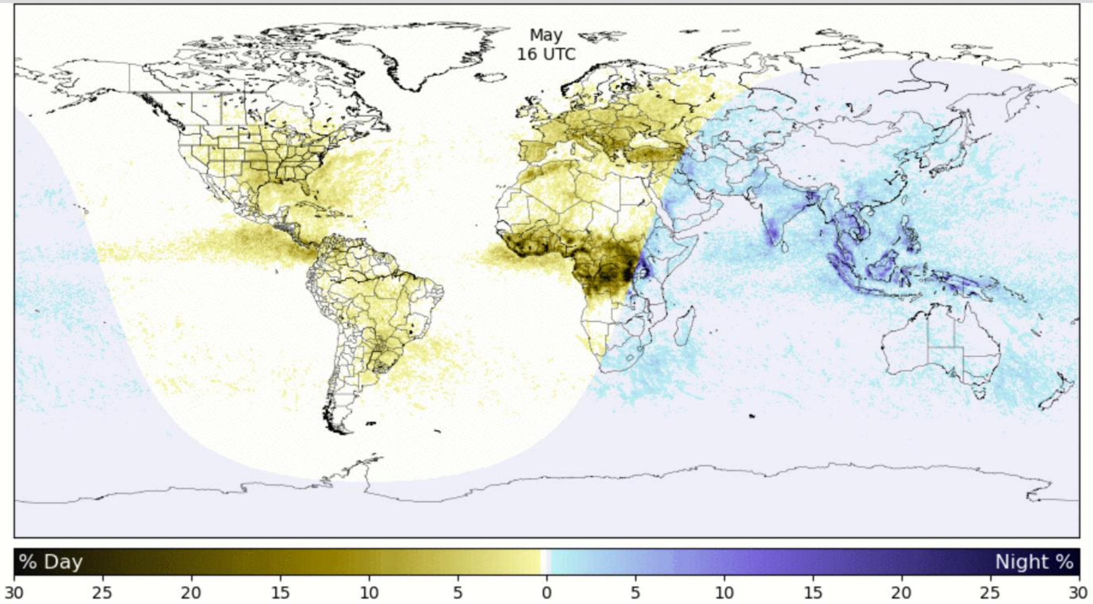
EARTH NETWORKS Earth Networks Thunder Hour Repository

# What is a Thunder Hour?

A **thunder hour** is defined simply as an hour during which you can hear thunder. Thunder hours are an extention of the **thunder day**, a day in which you can hear thunder, which is the basis of the longest lightning climatologies available.

# What can you do with Thunder Hours?

This is where things start to get interesting. Even though the concept of a thunder hour is quite simple, it turns out that many synoptic and seasonal weather patterns show up very clearly in thunder hour datasets. Below is an animation of global thunder activity showing many of these features. The data in the animation are the hourly probabilities of thunder each month averaged over five years - a shorter timespan than most climatologies.




**Why work with thunder instead of flashes?**

# Metadata

- **Metadata** – Product = Total Lightning Stroke Density
  - Satellite imagers optical flash density vs ground-based RF network stroke density (Global and Regional Networks)
  - How is satellite event/group/flash related to RF strokes

- **Toward harmonized, consistent space and ground-based data set(s)**
  - Desire for # stations (ground-based), Detection Efficiency, resolution (time, space), and other cal/val performance parameters (e.g., network flash type – IC/CG discrimination) needed to make a climate data set most useful.
  - Note no network or space measurement is 100% DE effective over its entire coverage area.

# Objectives and Goals for GLM Reprocessing

- The primary goal of the proposed research is to remove artifacts from the GLM-16/17/18 data
    - Improve FAR
    - Produce a high integrity science data set for weather and climate studies
- This is the first GLM science data reprocessing since launch
- We will

(1) Integrate existing algorithms used in the GLM ground system, the scientific community, and legacy NASA instruments into a single Lightning Enterprise Science Algorithm (LESA) suite

(2) Remove the artificial termination of groups and flashes that can mask the true extent of flashes

(3) Remove the artificial separation between the L0 to L1b and L1b to L2 processing code sets to improve processing efficiency and filtering/artifact removal accuracy

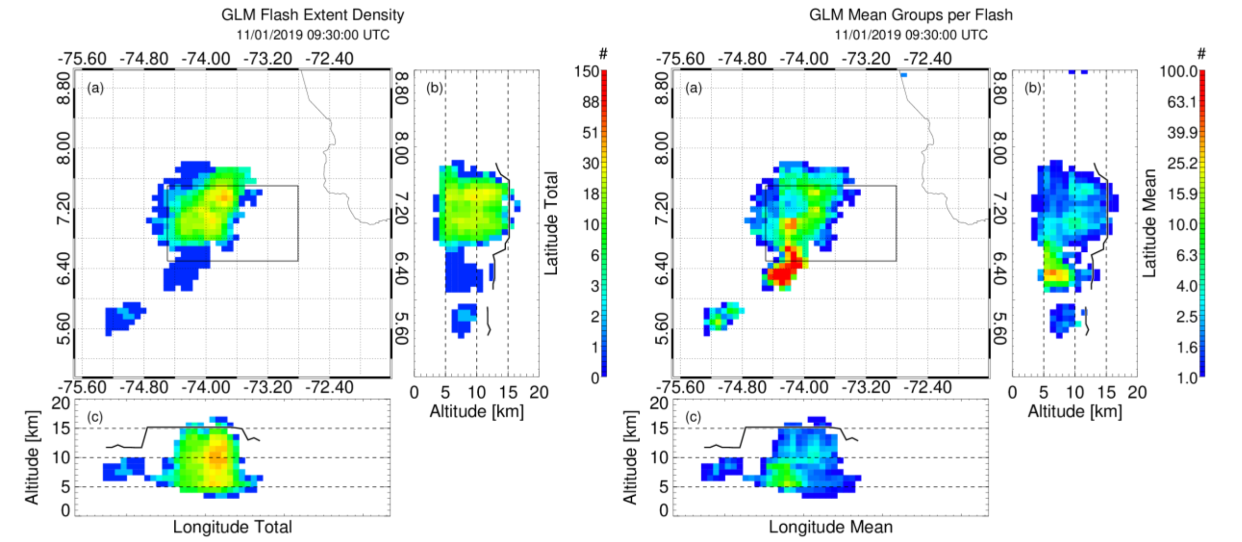
(4) Make the algorithm suite available to the research community (through a cloud service provider)

Work will include improved artifact filter tracking and processing statistics, and tagging (rather than immediately removing) events, groups, flashes that are not considered lightning

# Machine Learning and Artificial Intelligence Techniques (1/2) (Future Work…)

### 1. Vertical Structure of Lightning from 2D GLM maps

- **Machine Learning/Artificial Intelligence (ML/AI)** based products are expected to enhance the useability of the GLM (and other orbital sensor) data.
- The Machine Learning methods find which combination of GLM group metrics describing the <u>amplitude</u>, <u>extent</u>, and <u>texture</u> of the group <u>spatial energy distributions</u> provided the best balance between altitude prediction accuracy and computational expense. The resulting **<u>Random Forest model</u>** was able to reproduce the GLM-matched LMA altitude distributions throughout the time history of the thunderstorm with a median absolute error of 1.33 km and also correctly map the vertical development of individual flashes.
- The figure to the upper right box illustrates an initial example of a ML technique to estimate the heights of GLM groups within the cloud mass based on the spatial distributions of GLM energies from individual GLM groups.
  - These methods can be used to convert the existing 2D GLM gridded products into volumetric products.
  - These 3D grids, if constructed for the full disk, would provide a more comprehensive picture of lightning activity across the GLM domain than the current 2D grids.




Volumetric Flash Extent Density (FED) valid from 09:30 – 09:45 UTC expressed (a) as a vertical integration and horizontal integration resulting in (b) a latitude-altitude distribution, and (c) a longitude-altitude distribution. The boxed region in (a) represents the Colombian LMA (COLLMA) data domain, while the solid lines in (b) and (c) show the maximum **ABI CTH** coincident with GLM groups at each latitude or longitude (Peterson and Mach, https://doi.org/10.1029/2021EA001945.

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# Machine Learning and Artificial Intelligence Techniques (2/2) (Future Work…)

## 2. Flash Type Discrimination

- **Random Forest** model classification of flashes into **Ground (CG)** or **Cloud (IC)** flashes.
- There are 21 features (Table 2) used to train the model. Two new features termed the slope and shape have been created to attempt to provide more detail about the change in the shape and magnitude of the optical emission with time.
- Random Forest with 200 trees and 80 nodes : Maximum Group Area (MGA) is most important discriminator.
- GLM observes **Total Lightning** and does not distinguish if the lightning is connecting to ground (CG) or remaining in the cloud (IC). In order to distinguish CG and IC flashes, the Random Forest model attempts to classify lightning flashes based on their size, duration, and intensity. The most important flash characteristics for distinguishing flash type are the features related to the areal size of the lightning and the time of day the lightning occurs.
- Overall, moderate success is shown when attempting to divide total lightning into CG and IC over the 2018 period. This information can be used by researchers to improve the use of GLM in the study of different storm types as well as aiding in wildfire forecasting.

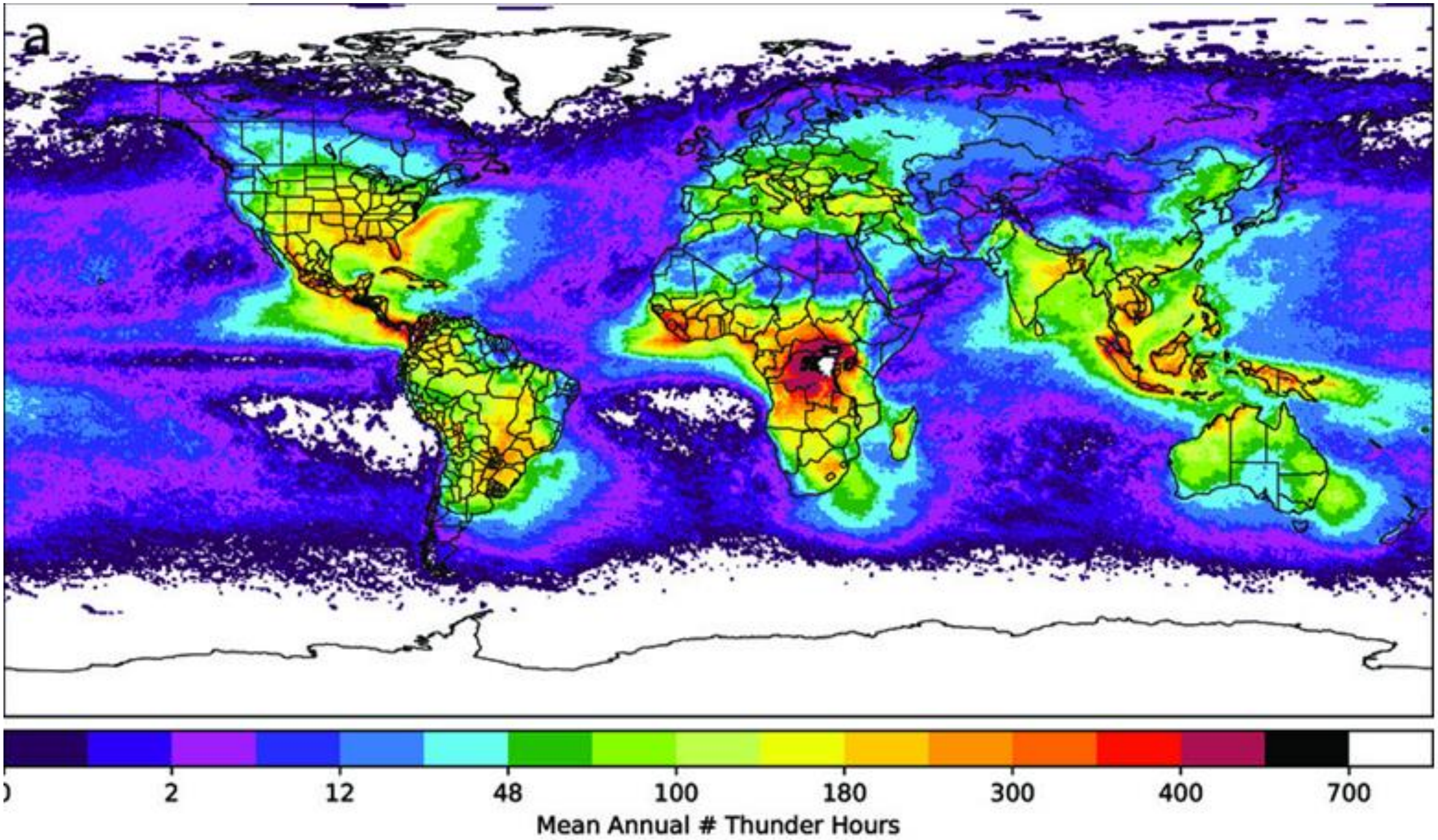
**Table 2**
*Definitions of Geostationary Lightning Mapper (GLM) Flash Characteristics Input as Features Into the Random Forests (RF) Model*

| Features | Definition |
|---|---|
| Spatial features | |
| Maximum group area | The maximum area associated with a single group in the flash |
| Maximum no. of events in a group | Maximum number of events associated with a single group in the flash |
| Footprint | The combined area of all the events comprising a flash |
| Propagation | Furthest separation of groups in a GLM flash divided by the diameter of the flash |
| Elongation | Furthest separation of events in a GLM flash divided by the diameter of the flash |
| Max distance between groups | Max distance between groups in a flash |
| Max distance between events | Max distance between events in a flash |
| Child count | Number of groups in a flash |
| Grandchild count | Number of events in a flash |
| Temporal features | |
| Time-of-day | Time of day in UTC |
| Time illuminated | Amount of time GLM groups were present in a flash |
| Duration | Time length of flash |
| Max time difference | Maximum amount of time between two subsequent groups |
| Number of contiguous groups | Number of groups that occur successively in time |
| Spatiotemporal/other features | |
| Slope | Max energy group in 2nd half minus max energy group in 1st half divided by time difference |
| Shape | Number of groups in first half of flash divided by total number of groups |
| Energy | Total additive energy of a flash |
| Maximum group energy | Maximum energy associated with a group in the flash |
| Mean energy | Average energy for all groups composing a flash |
| Standard dev. of energy | The standard deviation of energy for a flash |
| Energy threshold | Number of groups with an energy above the average group energy for the flash |

Ringhausen et al., Earth and Space Science, 10.1029/2021EA001861

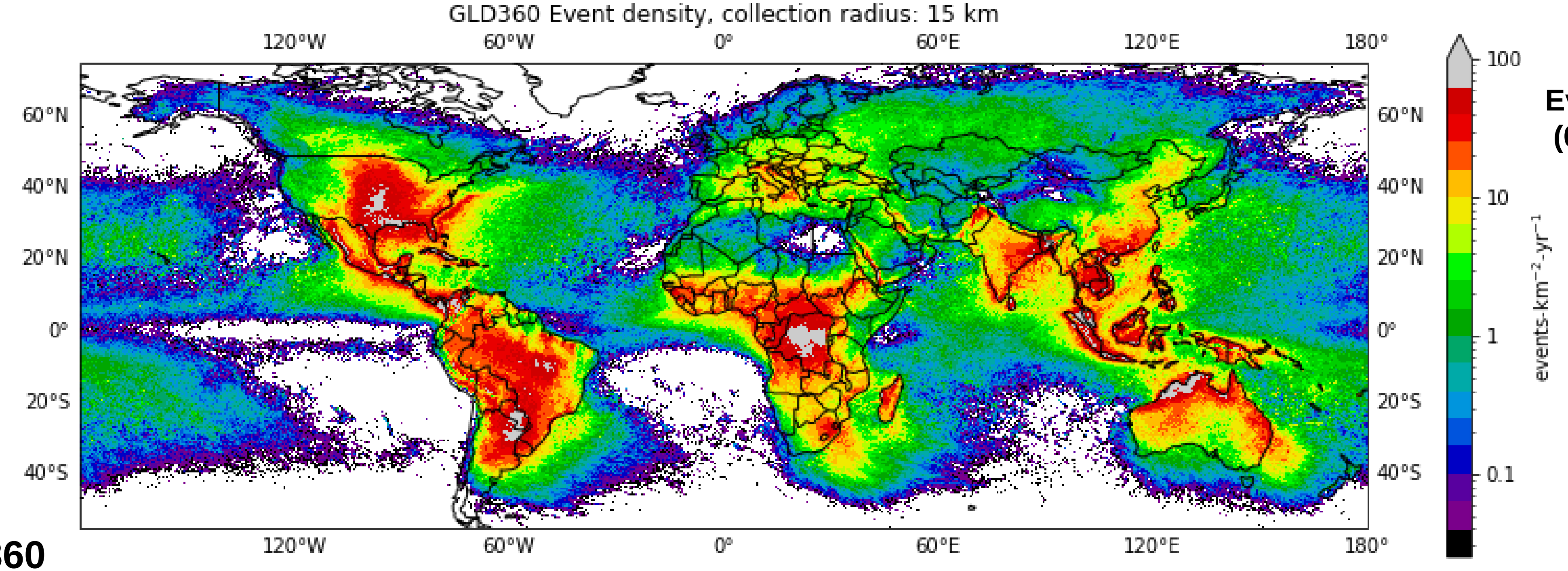
# Thunder Hours

**ENGLN IC+CG**



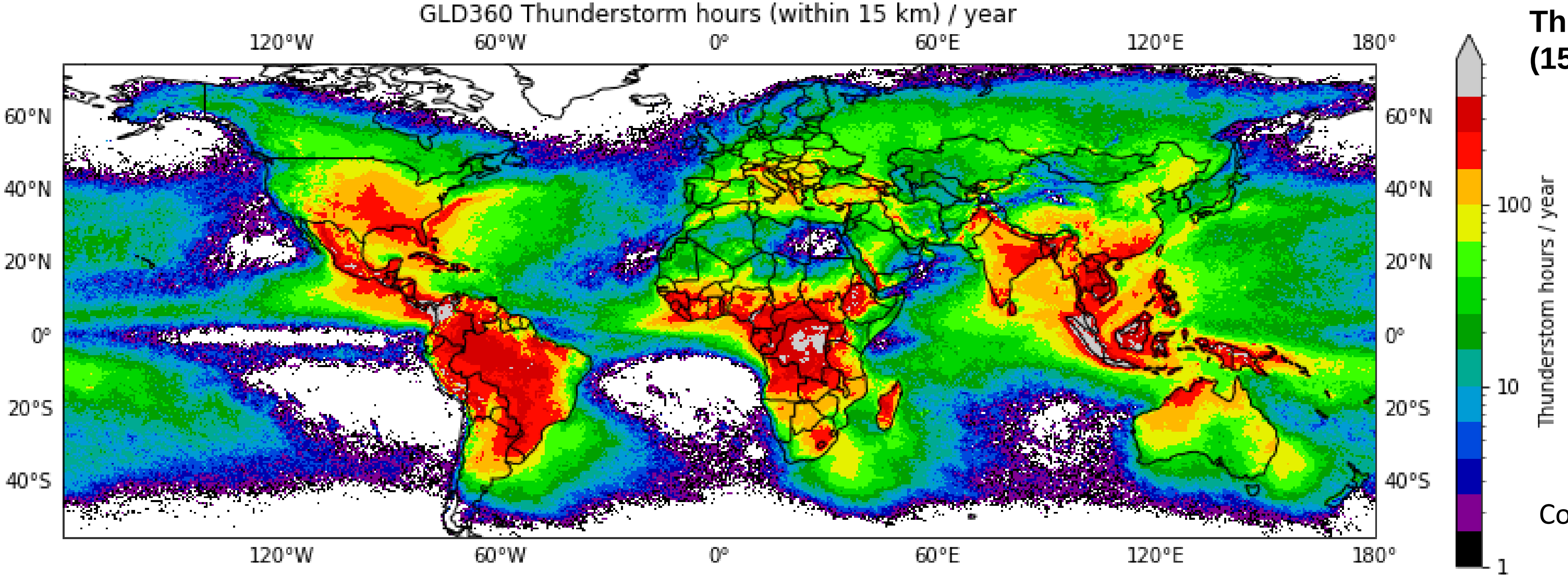

**2015-2019**

Mean annual ENGLN thunder hour counts for the entire globe from 2015-2019.
(DiGangi et al., 2022, BAMS Early Online Release: 10.1175/BAMS-D-20-0198.1.

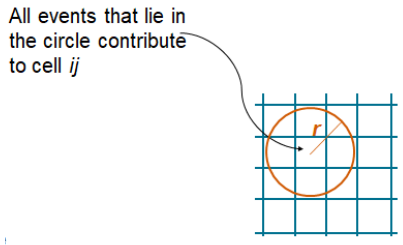



**Event Density 2015-2019 (0.1 deg grid)**

**GLD360 IC+CG**




**Thunder Hours 2015-2019 (15 km radius)**



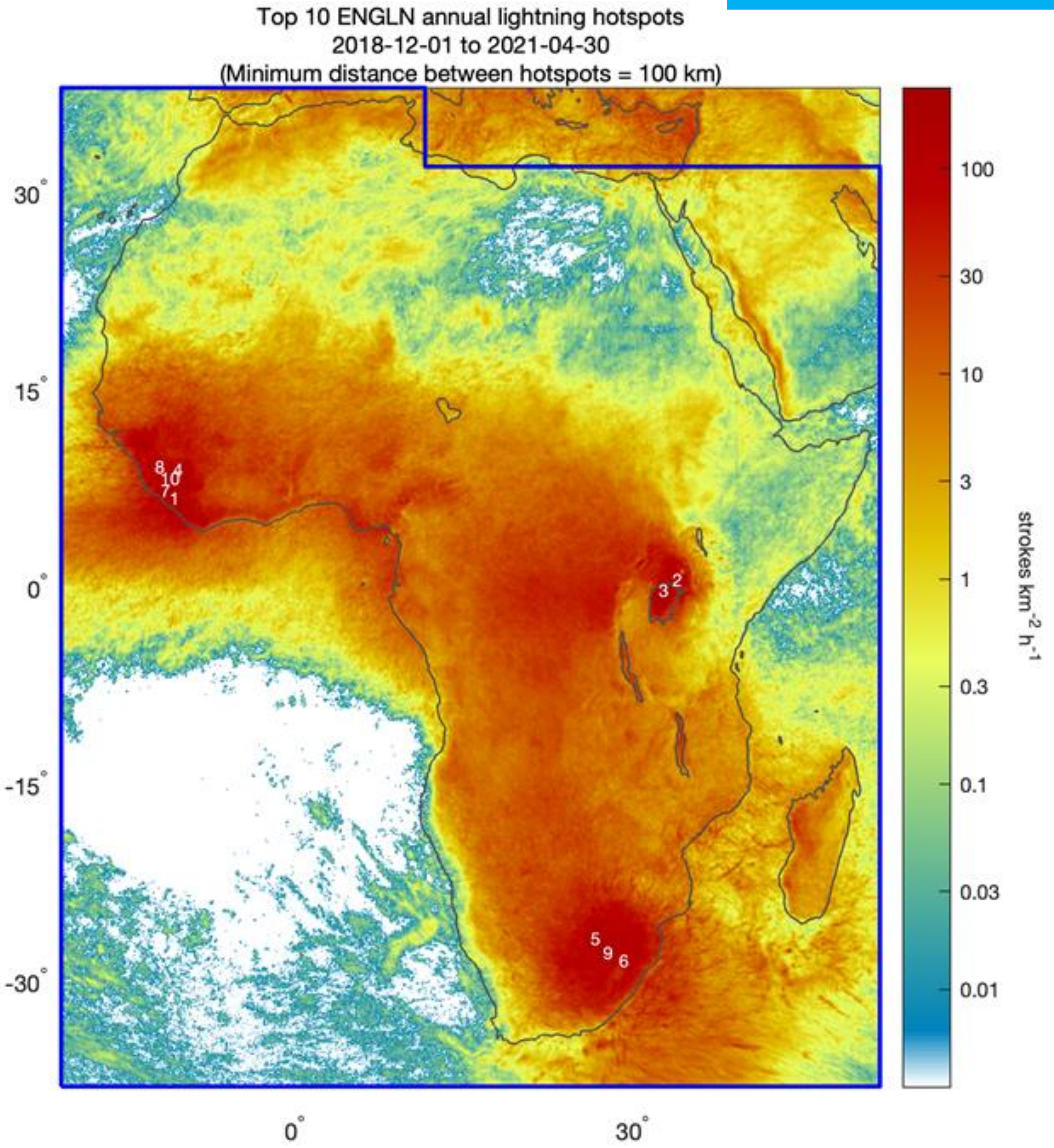

Courtesy of Ryan Said, Vaisala

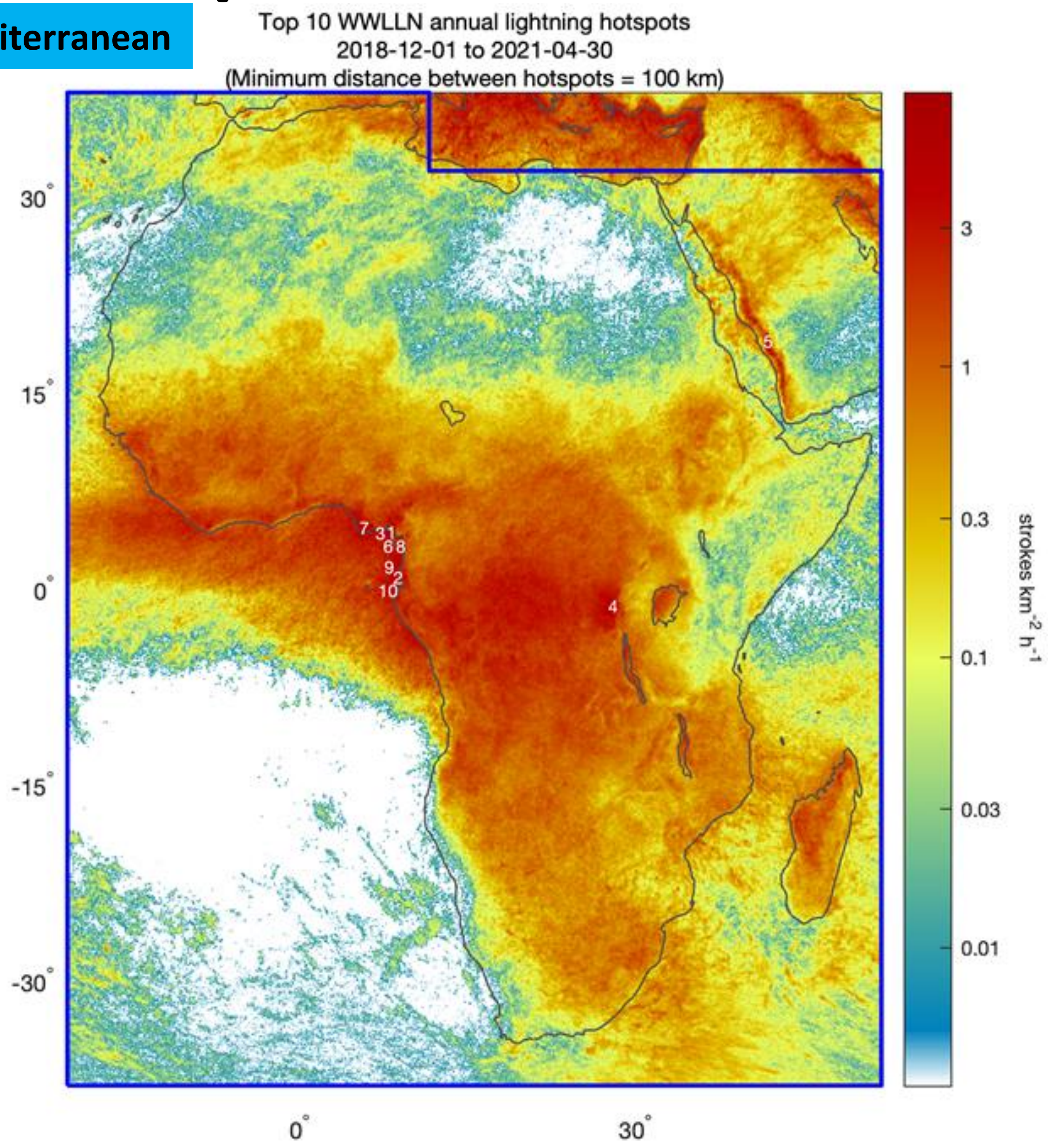
# Africa Lightning Hot Spots

**ENGLN**

**WWLLN**

Blue border to exclude Mediterranean



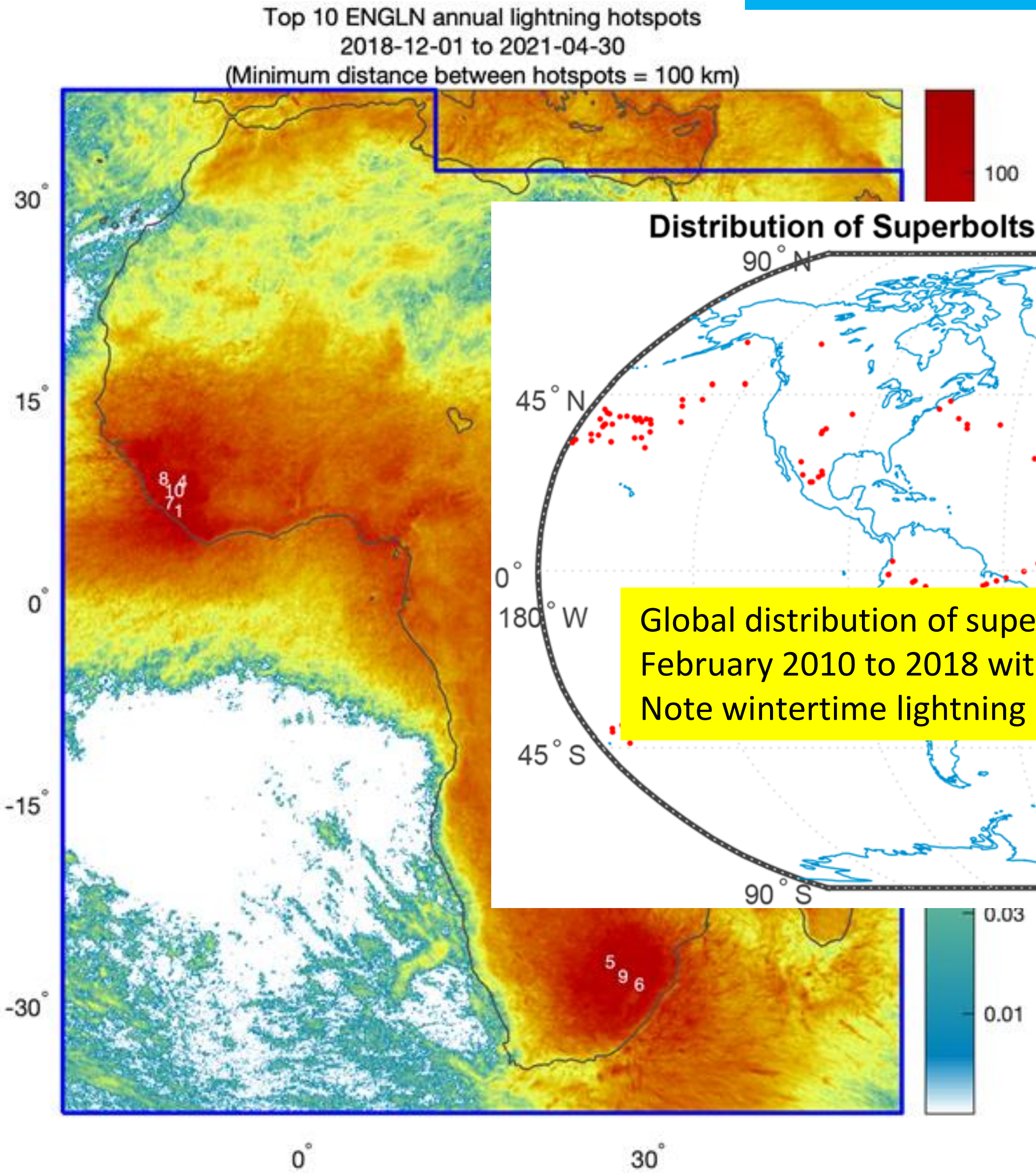



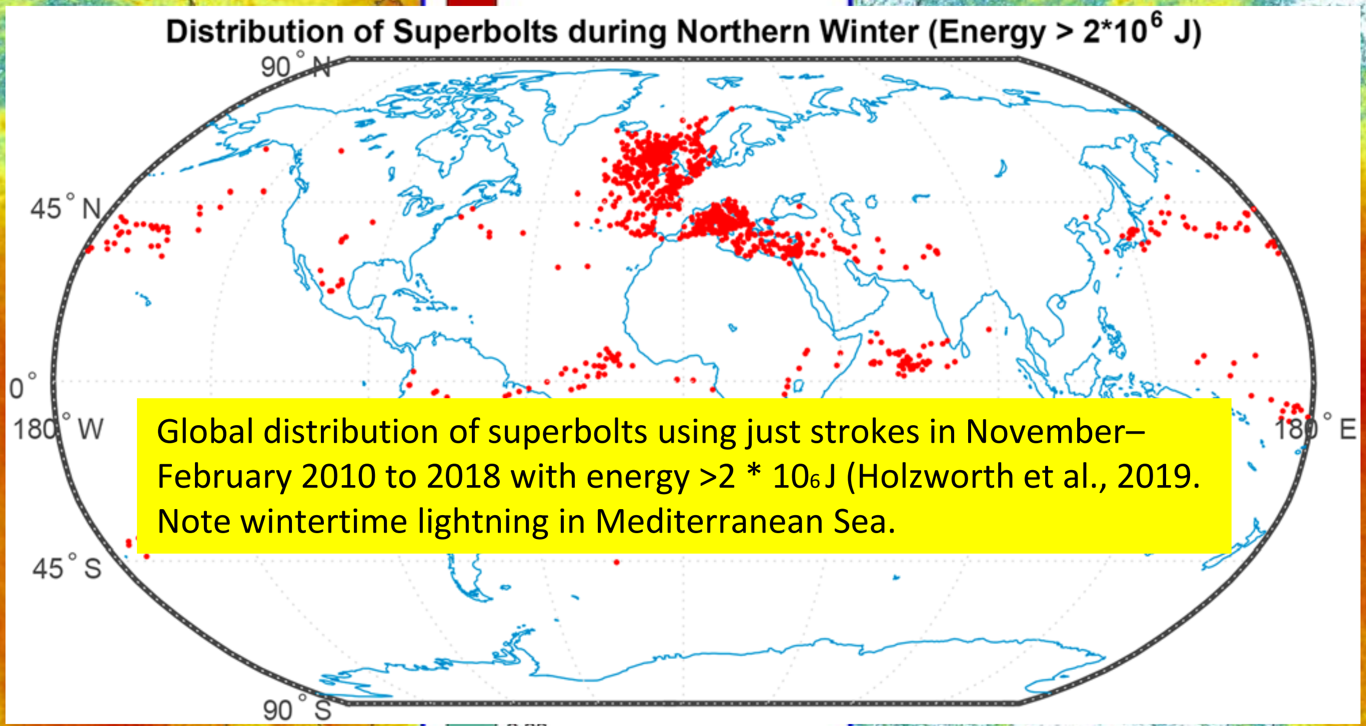
ENGLN

# Africa Lightning Hot Spots

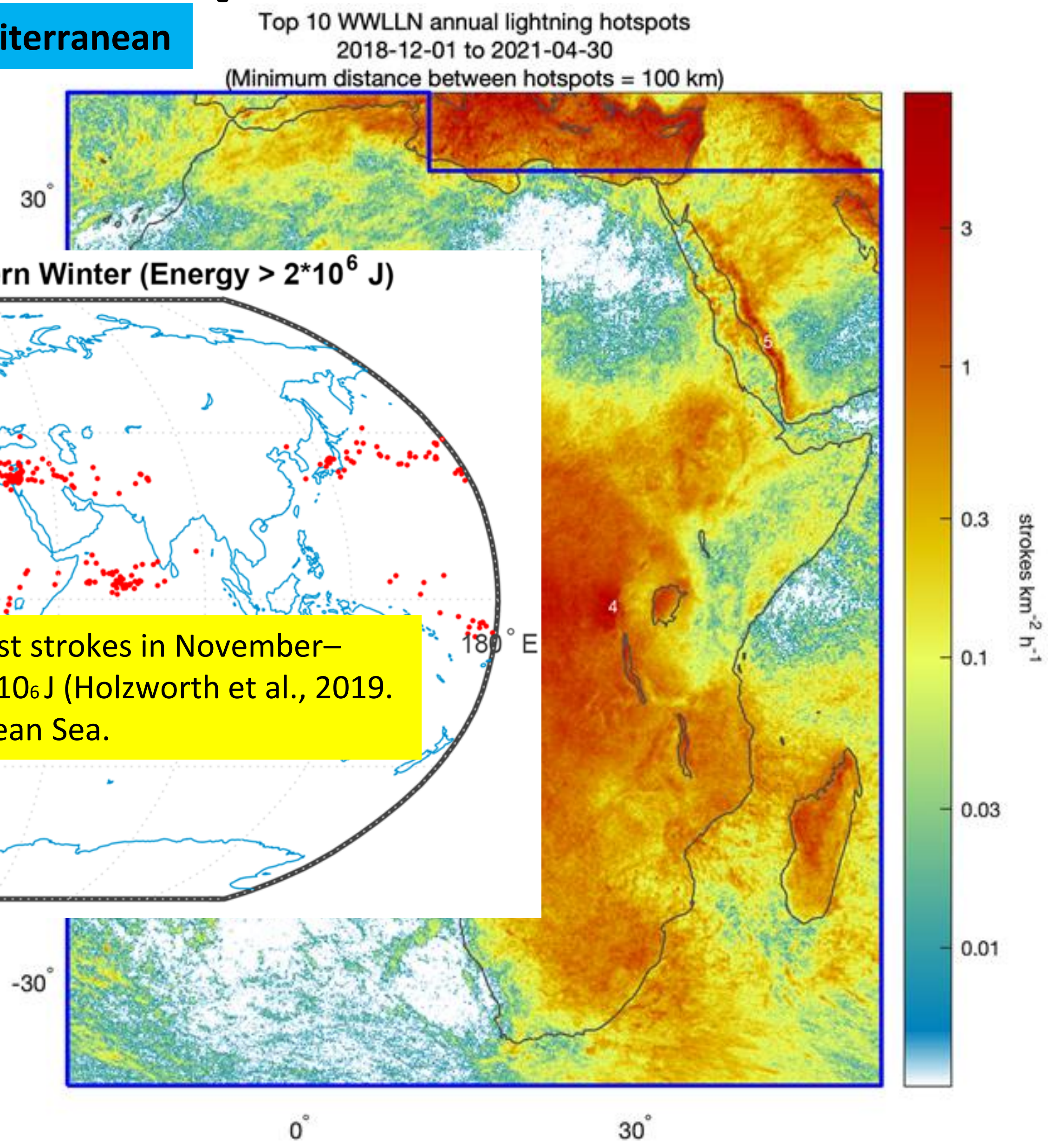
WWLLN

**Blue border to exclude Mediterranean**

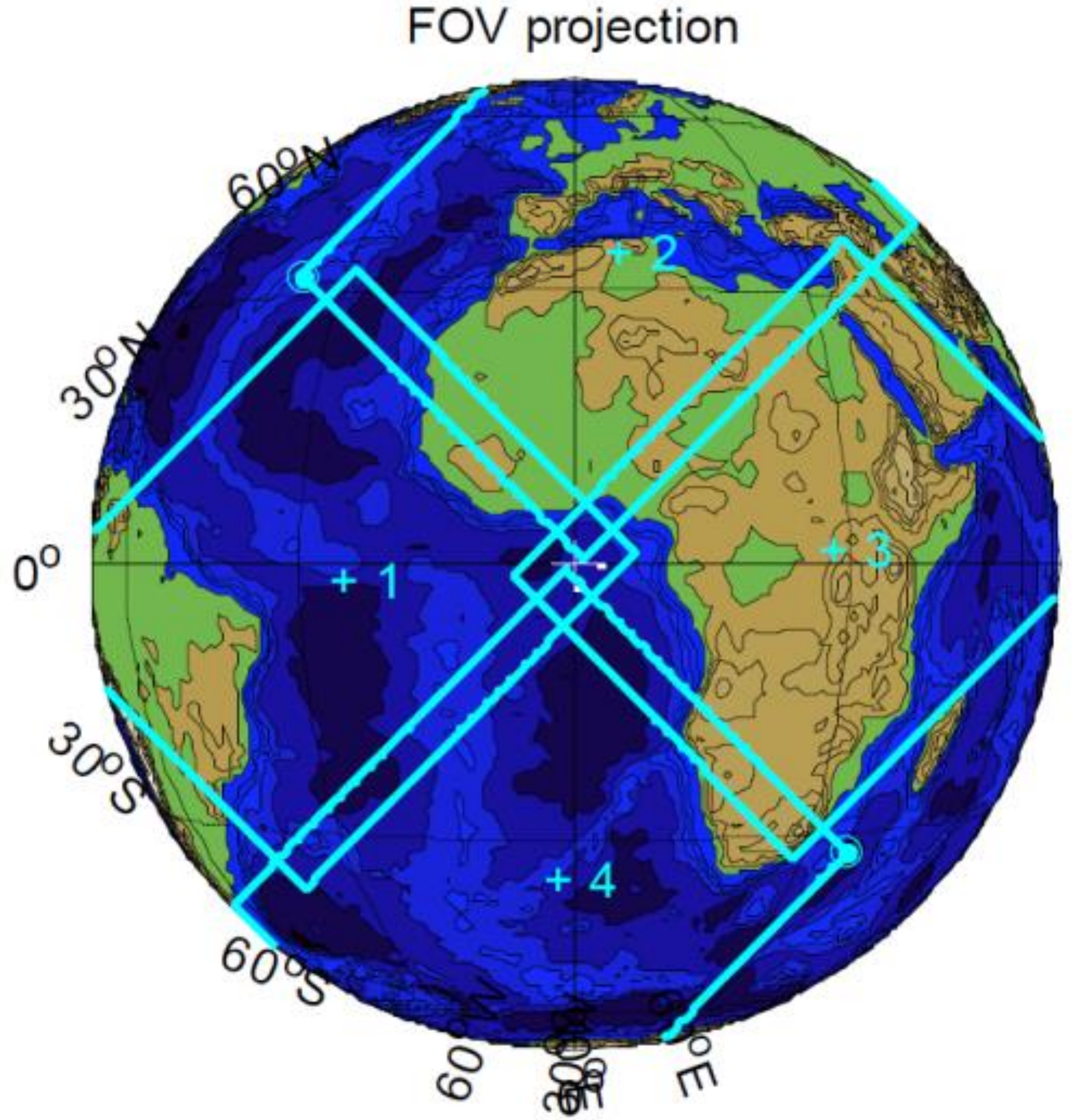



Global distribution of superbolts using just strokes in November–February 2010 to 2018 with energy >2 * $10_{6}$ J (Holzworth et al., 2019. Note wintertime lightning in Mediterranean Sea.

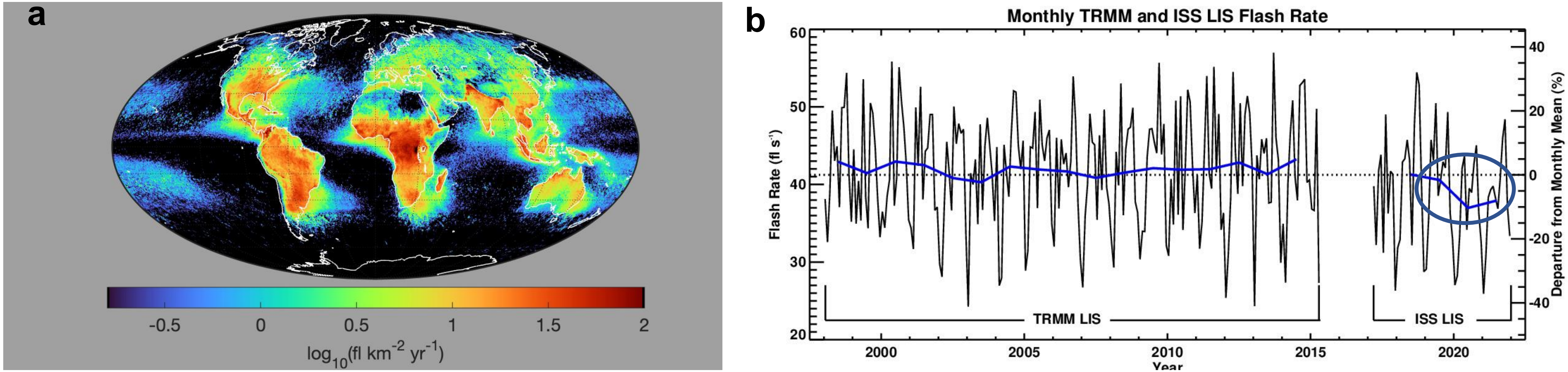


# MTG Lightning Imager Coverage



# Attribution : Is the 2019-2020 reduction of lightning linked to aerosols and COVID reduction of industrial activity?

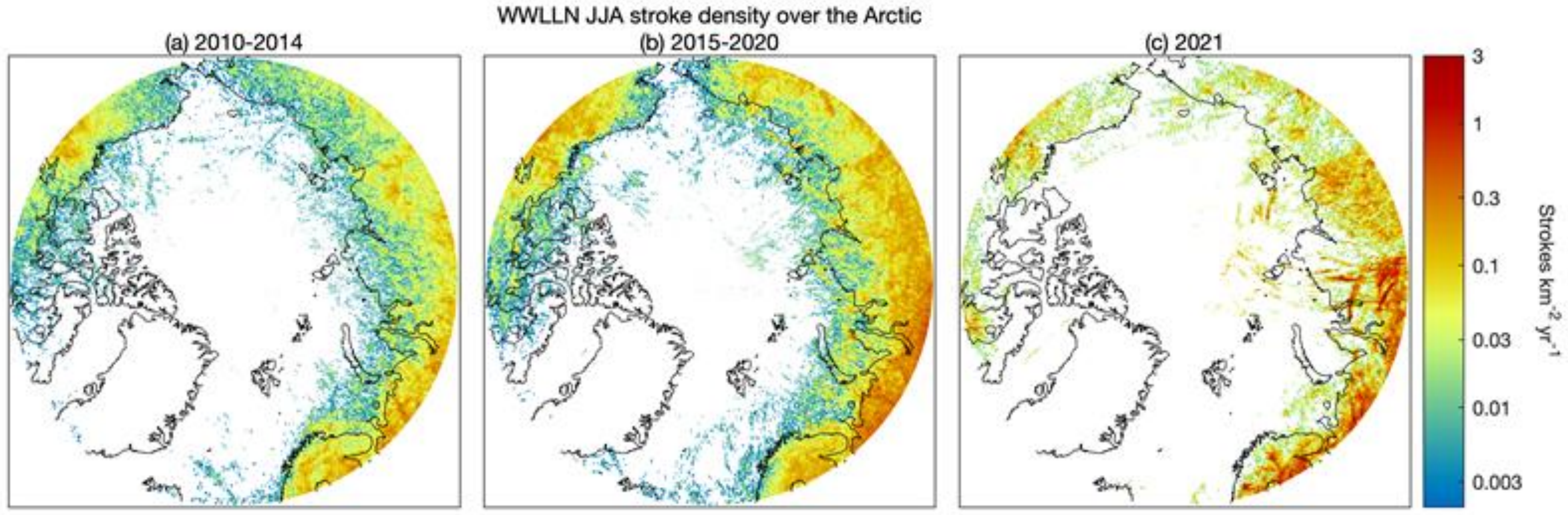
**LIS/OTD 1995-2021**




Lightning observations from space. Left - Global distribution of lightning flash rate density (fl $km^{-2}$ $s^{-1}$) for the period of record 1995-2021 from NASA's low earth orbit lightning imagers OTD (Optical Transient Detector, May 1995- April 2000), TRMM LIS (Lightning Imaging Sensor, January 1998 – December 2014) and ISS LIS (February 2017 – December 2021). Global lightning is dominant over the continental tropical belt. Right – Monthly (solid black) and annual (blue) mean lightning flash rates (fl $s^{-1}$) observed by the TRMM and ISS LIS instruments within the $\pm 38°$ latitudinal coverage of the TRMM orbit. The black dotted line is the combined mean monthly global flash rate (41.2 fl $s^{-1}$). The mean monthly flash rate varies from ~24-57 fl $s^{-1}$. The seasonal variations are due to the annual cycle of lightning activity linked to the larger land area of the northern hemisphere. (Courtesy of the NASA Lightning Imaging Sensor Science Team).

BAMS Special Issue on Climate, 2022

# 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

# Attribution : Interannual Variability and Lightning Teleconnections - ENSO

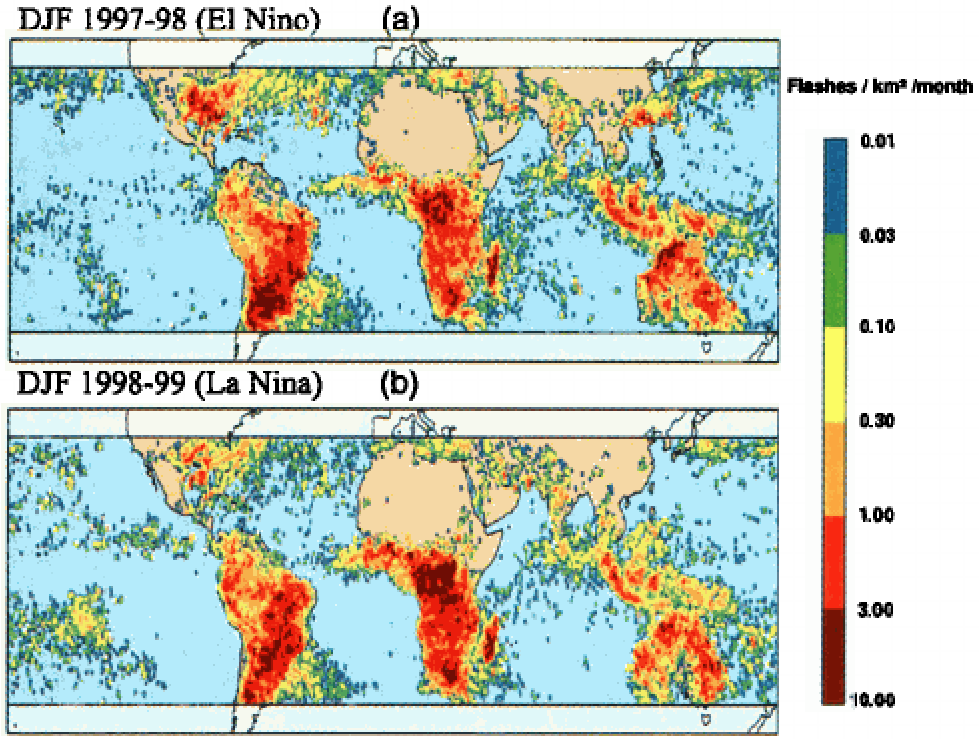



**Figure 1.** Seasonal distribution of lightning during the 1997-98 ENSO winter period December 1997-February 1998 (top panel) and the 1998-99 LaNina winter period December 1998-February 1999 (bottom panel) derived from observations made by the NASA Lightning Imaging Sensor (LIS).

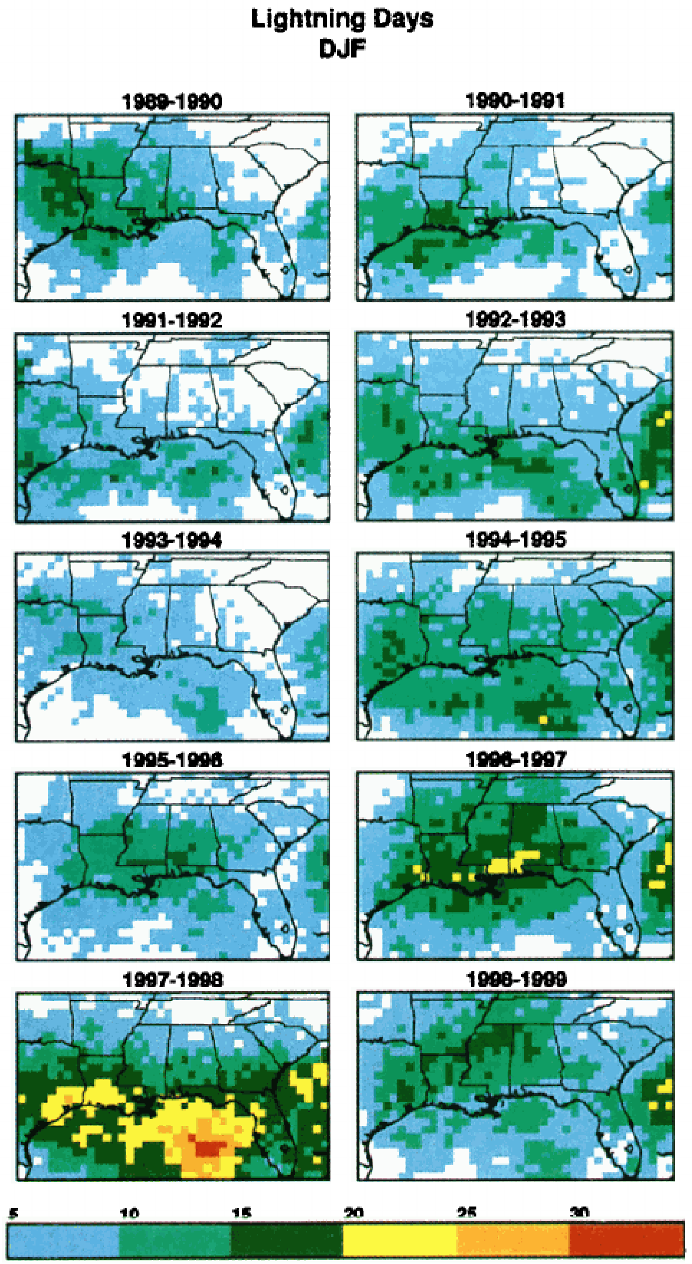



**Figure 2.** Number of cloud-to-ground lightning days per 0.5° × 0.5° grid box during winter (DJF) 1989-1999.

Goodman et al.,(2000), The 1997-98 El Nino events and related wintertime lightning variations in the Southeastern United States, GRL, vol.27, NO.4,541-544.

# Summary

- **Lightning is a global Natural Hazard** of great importance and interest

- **Exemplary datasets –** evaluating candidate data sets (satellite – Ground-Based RF)
  - Thunder Hour (ENGLN, GLD360, GLM)
  - Gridded at 0.1 x 0.1 deg (GLD360, WWLLN, GLM, MTG-LI, Regional Networks)
  - Developing input to the GCOS 5 – year Implementation Plan
  - Archive and Stewardship in the cloud supported by the NASA GHRC Hydrometeorology DAAC (Distributed Active Archive Center)

- **Explore how a lightning ECV may be associated with other variables**, such as aerosols, temperature, clouds, precipitation, composition, NOx, and surface observations (e.g., surface station thunder, severe weather reports), ENSO, MJO, Upper Level humidity.

- **Raise lightning safety awareness** – collaborate with WHO, WMO Disaster Risk Reduction (Natural Hazards) Programme