Lightning Applications for Weather and Climate

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Lightning Photo Credit: Marko Korosec/WMO

Acknowledgements

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Anatomy of a Lightning Flash

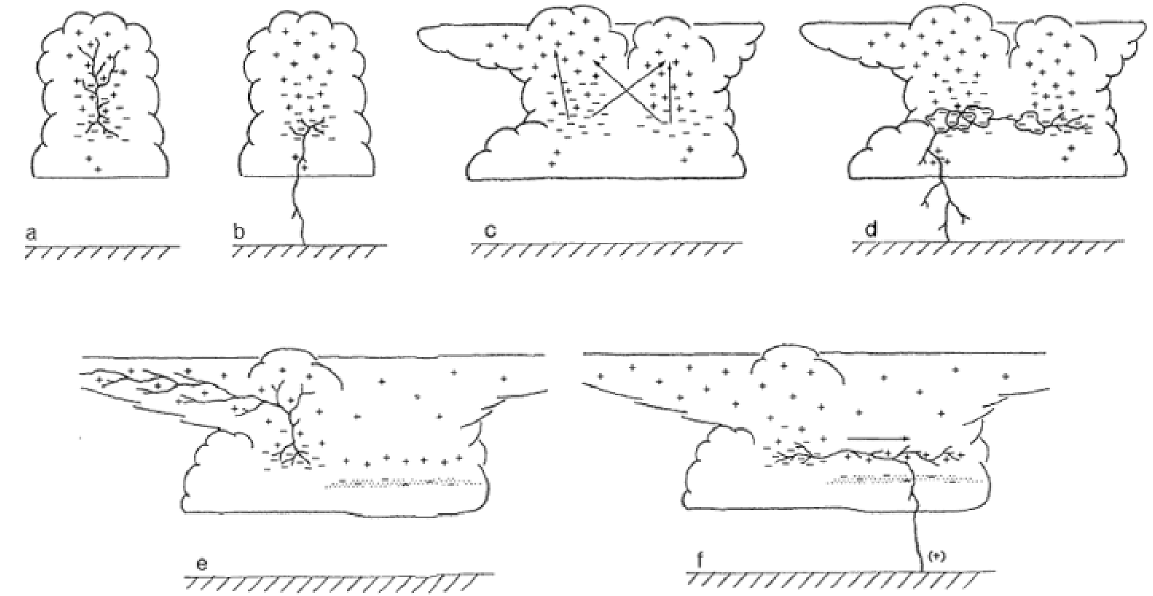
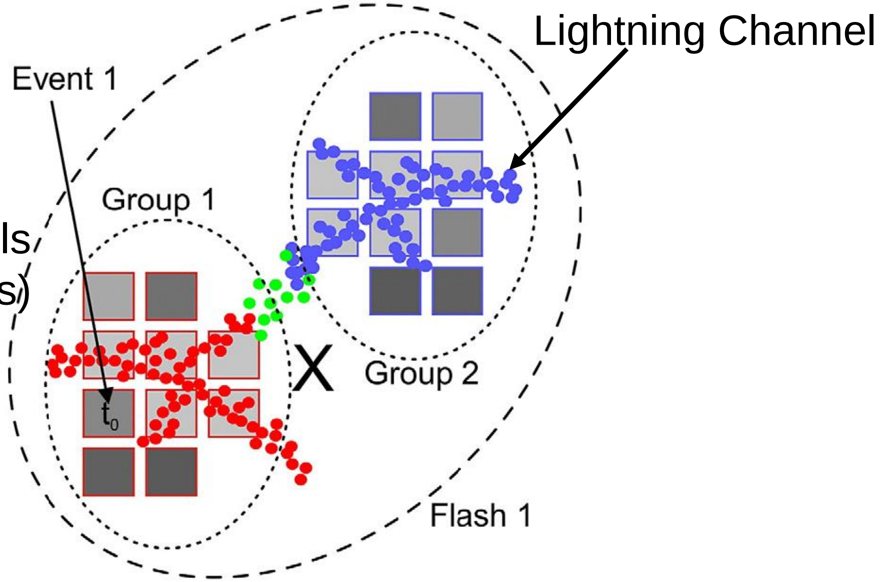


Figure 8.11 The apparent evolution of lightning with time in a thunderstorm, based on a variety of observations in different storms. See text for explanation. The dendritic structure of the lightning has been guessed in all cases except for the multicellular intracloud discharge of part c. The dotted 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)



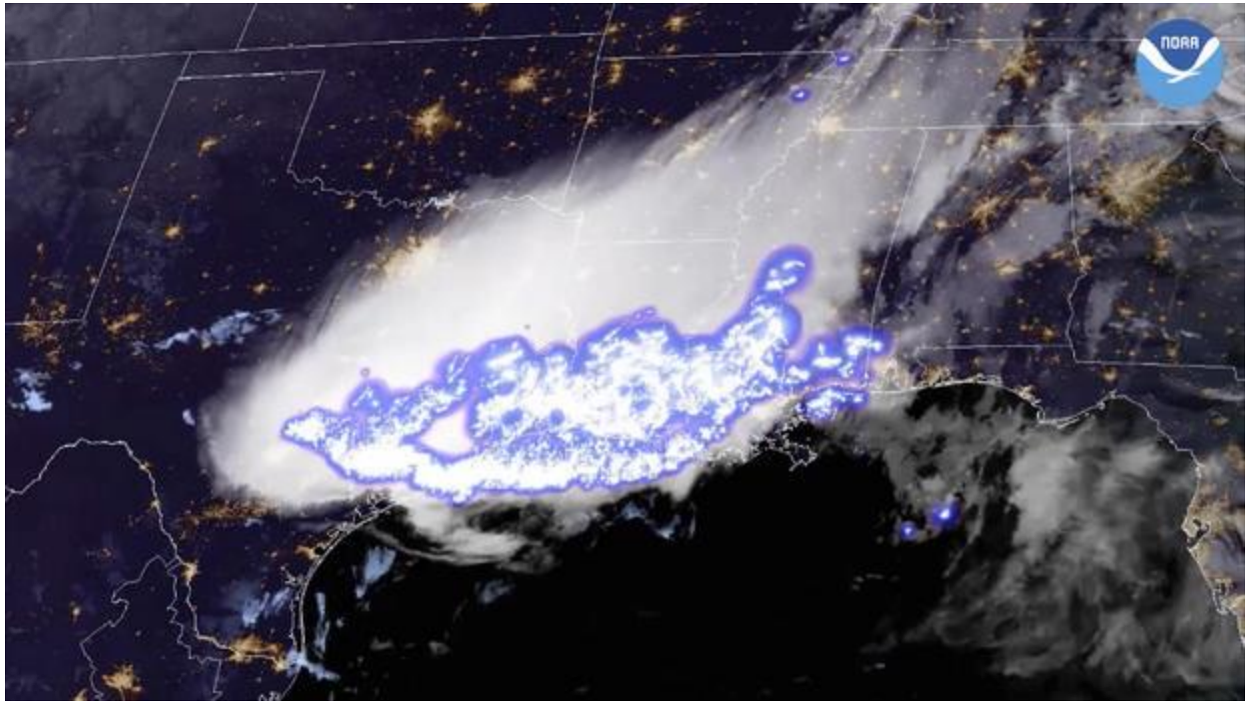
Longest Lightning Flash Ever?

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).



Courtesy of Scott Rudlosky and Michael Peterson

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

Weather Value Proposition for Space-Based Lightning

NOAA Technical Report NESDIS 153

https://doi.org/10.25923/2616-3v73

Geostationary Lightning Mapper Value Assessment

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Premise

Improving Lightning Safety – The GLM improves public safety across broad segments of society, and the socioeconomic benefit continues to grow as access is gained by users traditionally unable to afford lightning data (e.g., emergency managers, event organizers, local athletics officials, and the public).

Improving Severe Thunderstorm and Tornado Warnings – Integrating GLM data into the severe weather warning process promotes earlier warning decisions, better assessment of the areal coverage of hazards, and fewer false alarms, especially during radar outages and in regions of poor radar coverage.

Improving Safety and Effectiveness of Wildfire Response – The GLM benefits the firefighting community through unique identification of continuing current lightning strikes most likely to ignite fires, better pyrocumulonimbus characterization, and thunderstorm tracking in areas lacking robust radar coverage.

Improving Short-term Model Forecasts (Data Assimilation) – Lightning data assimilation (DA) is relatively new, especially GLM DA, but early results indicate many benefits, especially for short-range forecasts of radar reflectivity, accumulated precipitation, and lightning threat in convection-allowing models.

Improving Precipitation Estimation – The GLM observations improve satellite precipitation estimates, benefiting flash flood forecasting in significant portions of the western US, Hawaii, and US territorial islands without adequate radar coverage.

Improving Tropical Cyclone Diagnosis and Warning – The GLM identifies convective tendencies below cloud top in tropical cyclones (TCs) which helps better diagnosis TC structure and evolution and aids forecasts of TC intensity change including rapid intensification.

Improving Climate Applications – GLM data offer unique insights for monitoring climate-scale variability and response in a changing climate, a close link between lightning and convective cloud properties makes it an essential indicator of inter-annual to decadal change and a key variable for validating climate models.

Value of Filling Data Gaps – The GLM's broad spatial coverage and rapid temporal updates complement radar observations over CONUS to support severe weather warning decisions, and rapidly updating GLM observations over vast (often data sparse) regions outside CONUS provide decision makers with information they need to forecast, monitor, and react to thunderstorms, cyclones, and volcanic hazards at a faster cadence than ABI.

Value of Mitigating Aviation Hazards – The GLM observes the complete spatial footprint of total lightning flashes, which helps better characterize the lightning risk and increase confidence/certainty when suspending and resuming ramp operations, leading to enhanced safety, improved efficiency, and cost savings. The GLMs broad coverage and rapid updates provide tremendous cost savings to the aviation industry through improved diagnosis and avoidance of thunderstorm hazards, especially over oceans.

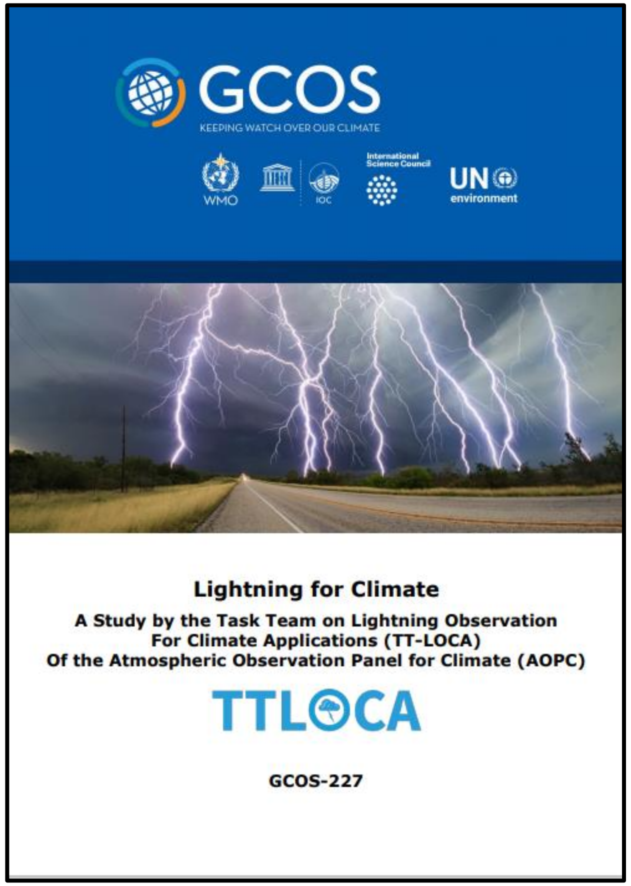
Climate Value Proposition for Space-Based Lightning

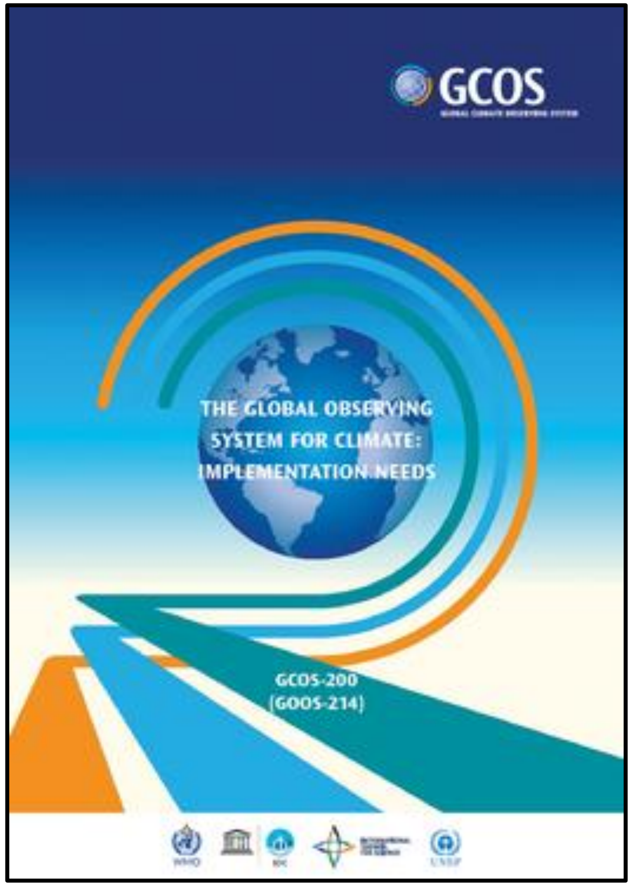
Why Lightning for Climate

An Essential Climate Variable (ECV) is a physical, chemical or biological variable or a 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, to guide mitigation and adaptation measures, to assess risks and enable attribution of climate events to underlying causes, and to underpin climate services.

They are required to support the work of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC).





Global Climate Observing System (GCOS)

Essential Climate Variables

For graphical version click here
What are Essential Climate Variables (ECVs)?

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

Issues Identified in the GCOS 2021 Status Report

Sustainability

Long-term continuity of some satellite observations is not assured. While satellite observations have been a major success, there are gaps:

- No assured continuity for Aeolus (wind profiles), cloud radar and lidar on research satellites. High-inclination altimetry and high-latitude sea-ice thickness monitoring is at risk.

Sustained funding is needed. Most ocean and terrestrial observations are supported through short-term funding with a typical lifetime of a few years leaving the development of long-term records vulnerable.

Many otherwise successful projects have not led to long-term sustained improvements. - most of the projects in developing countries with a component on observations have not led to sustainable long-term improvements in the observational capacity of these countries due to lack of resources and planning.

PARIS 2015

Issues identified in the Status Report

Gaps in Geographical Coverage

In situ observations for almost all ECVs are consistently deficient over certain regions, most notably parts of **Africa, South America, Southeast Asia**, the **Southern Ocean**, and **ice-covered regions**, a situation that has not improved since the GCOS 2015 Status Report.

3 GCOS Regional Workshops have looked at why some regions have problems in making sufficient observations. These issues include:

- For small nations (e.g. Pacific SIDS) the costs of observations may far exceed the resources available nationally;
- Lack of planning or reserves for foreseeable expenses;
- Lack of trained staff and poor staff retention;
- Poor understanding of the national benefits of observations.

Large gaps still exist in ocean observations. Subsurface measurements are critical to monitor and forecast the climate system. continental boundaries, the polar oceans and marginal seas remain an issue

Supporting the Paris Agreement

Adaptation

Current ECVs and ECV products can provide adaptation indicators for for the GST. Developed, at national level to add value to NAPs, through assessment of climate hazards and vulnerabilities, assisting in identification of adaptation options implementation, and in management, monitoring and evaluation

Mitigation

Atmospheric concentrations of GHG can be used to support emission inventories, detect sources, validate national emissions and removals and monitor the complete carbon cycle. Measurements can also support some mitigation efforts, particularly those using forests and land use.

Climate Science

Improving our understanding of climate cycles of carbon, water and energy will improve our projections of future climate

Data Stewardship, Archiving and Access

Satellite data and most ground-based netwroks have well curated data archives with long term support.

This is not true for all ECV. Data Archives are needed for all ECV that

- have sustainable, long-term, adequate funding.
- have clear requirements that will ensure a consistent approach among the data centres.
- should be open and freely available to all users.
- perform quality monitoring and ongoing reprocessing of data when new techniques or observations become available.
- support data rescue that allows data series to be extended into the past and provide open access to this data

gcos.wmo.int @gcos_un 11/2021

Presented at COP26, Glasgow

*AOPC IP 2022: Improving the Climate Observing System - Themes for Lightning

6.3 Theme B: Filling Data Gaps

B3. In-situ cal/val networks (regional to global lightning RF networks agreement to produce a Lightning ECV product)

B4. Improve monitoring of trace gases and aerosols (Lightning-NO_x)

B7. Proposed Earth observing satellite missions (NOAA GeoXO follow-on (LMX follow-on to GLM), Lightning optical/RF CubeSAT missions under study by US (NASA/LANL), CNES (France/Israel), INPE (Brazil/Germany)

B9. Improve ECV observations in polar regions (GeoXO LMX, EUMETSAT MTG LI lightning coverage to 70^0 N/S)

6.4 Theme C: Improving Data Usefulness

C1. Monitoring standards, best practices for ECVs (Lightning ECV Metadata)

C3. ECV specific Data Processing Method Improvements (GOES-R instrument reprocessing, GLM/LIS Enterprise reprocessing with AI/ML methods)

6.5 Theme D: Improving Data Management

D2. Ensure Global Data Centers for all ECVs (NASA ESDIS GHRC DAAC Huntsville offered to provide stewardship for the Lightning ECVs- space and ground-based) – already NASA archive for LIS 25-year data set

D3. Improve access to data in Global Data Centers (before data rescue) – NASA/NOAA satellite data in the cloud (e.g., AWS)

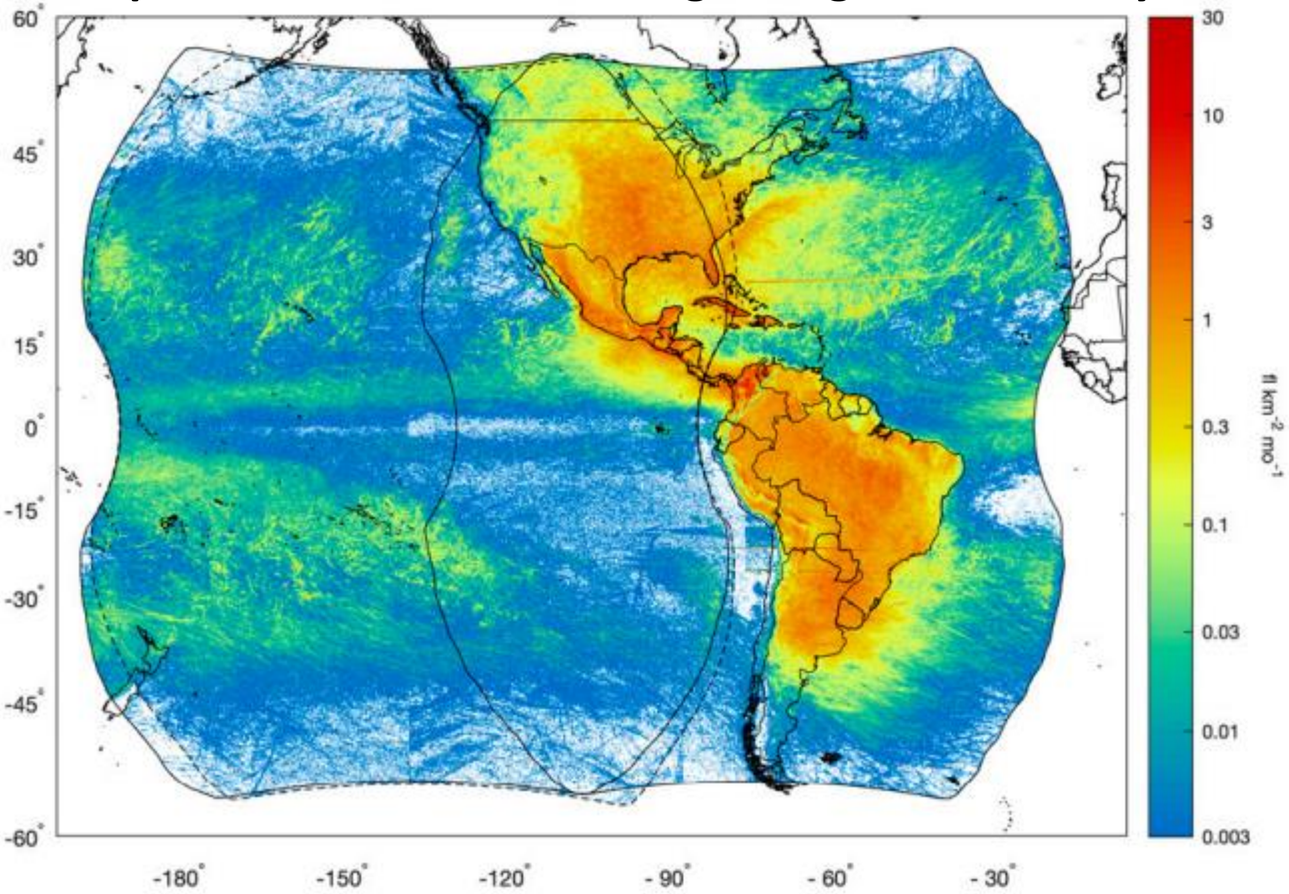
D4. Data rescue – Thunder Day records (cooperation with ECMWF, NCEI - Asheville)

*Atmospheric Observations Panel for Climate: Implementation Plan

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

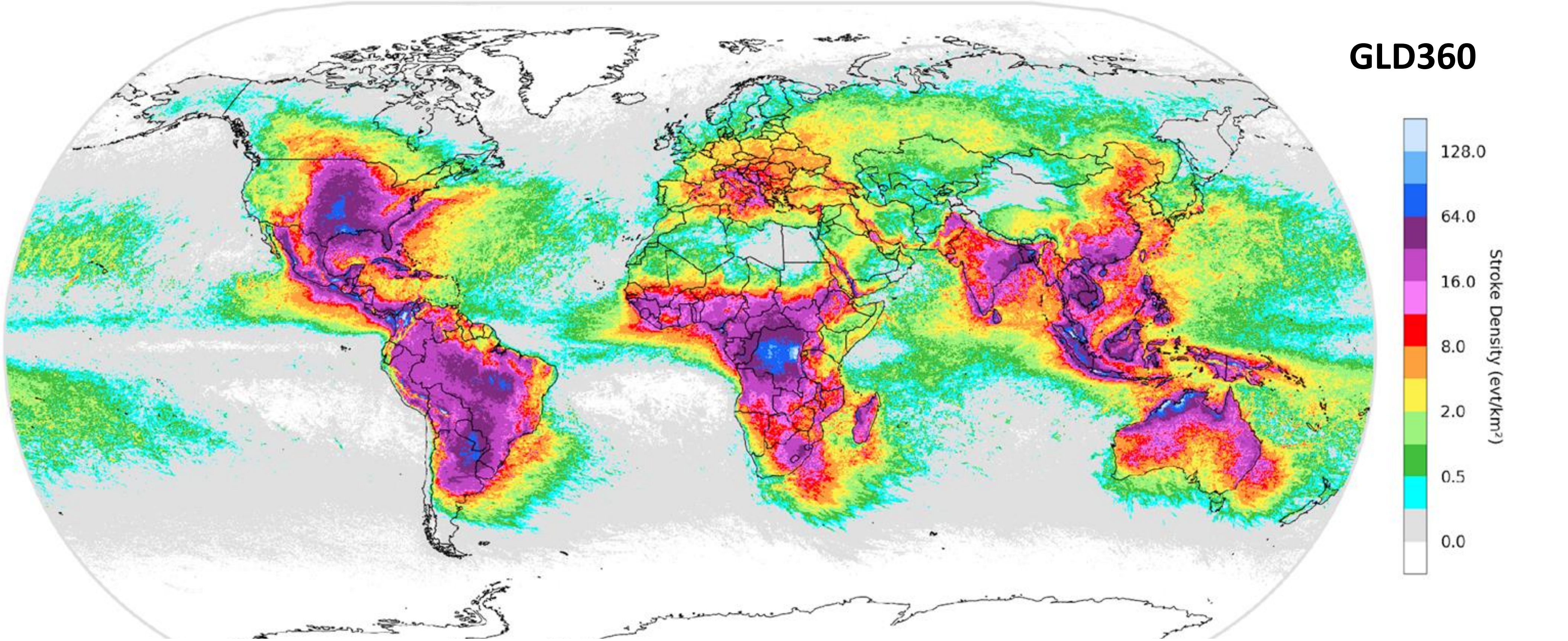
Space-based: GLM Total Lightning Flash Density



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).

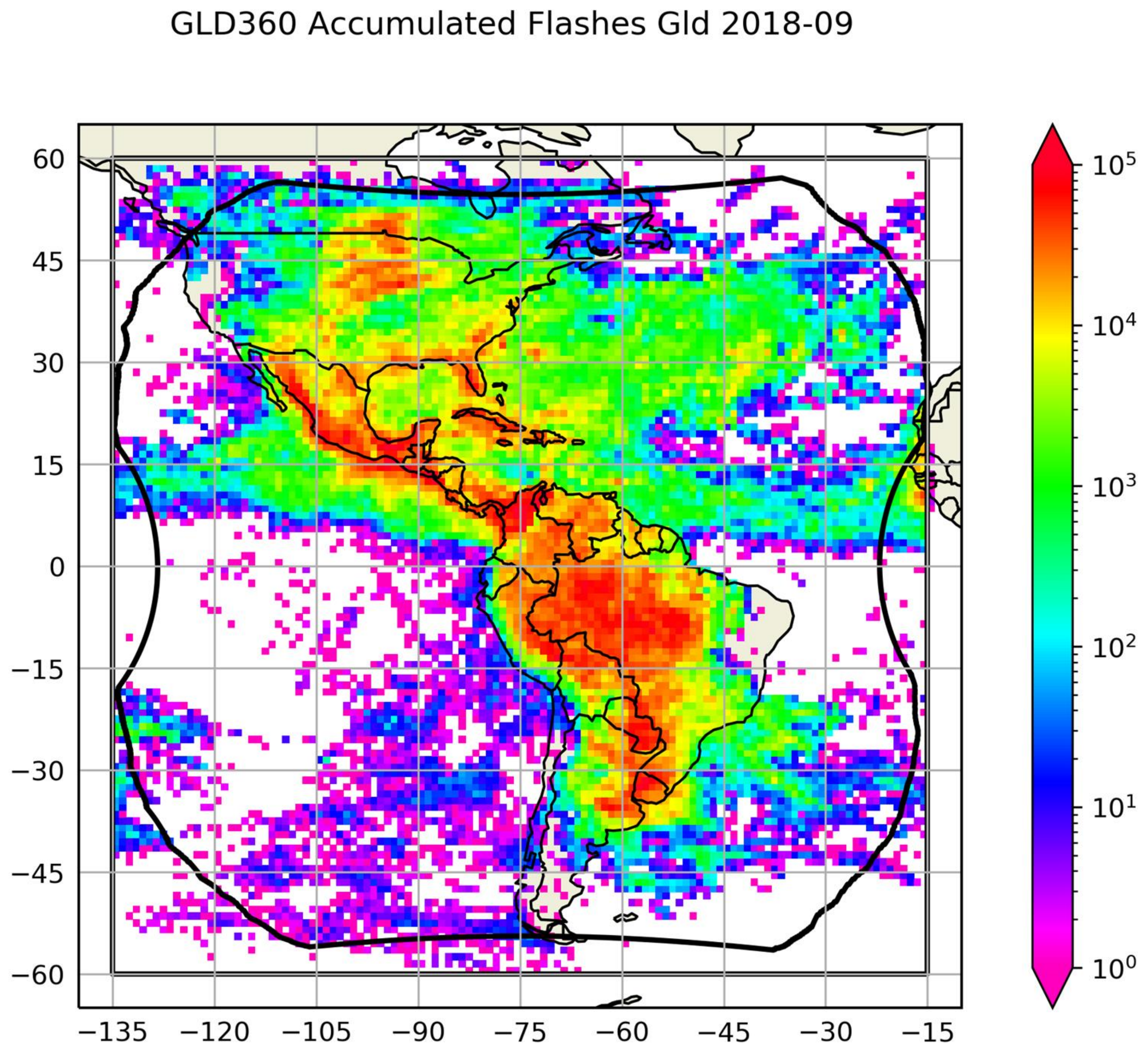
Is Lightning the Most Frequent Natural Hazard on Earth?

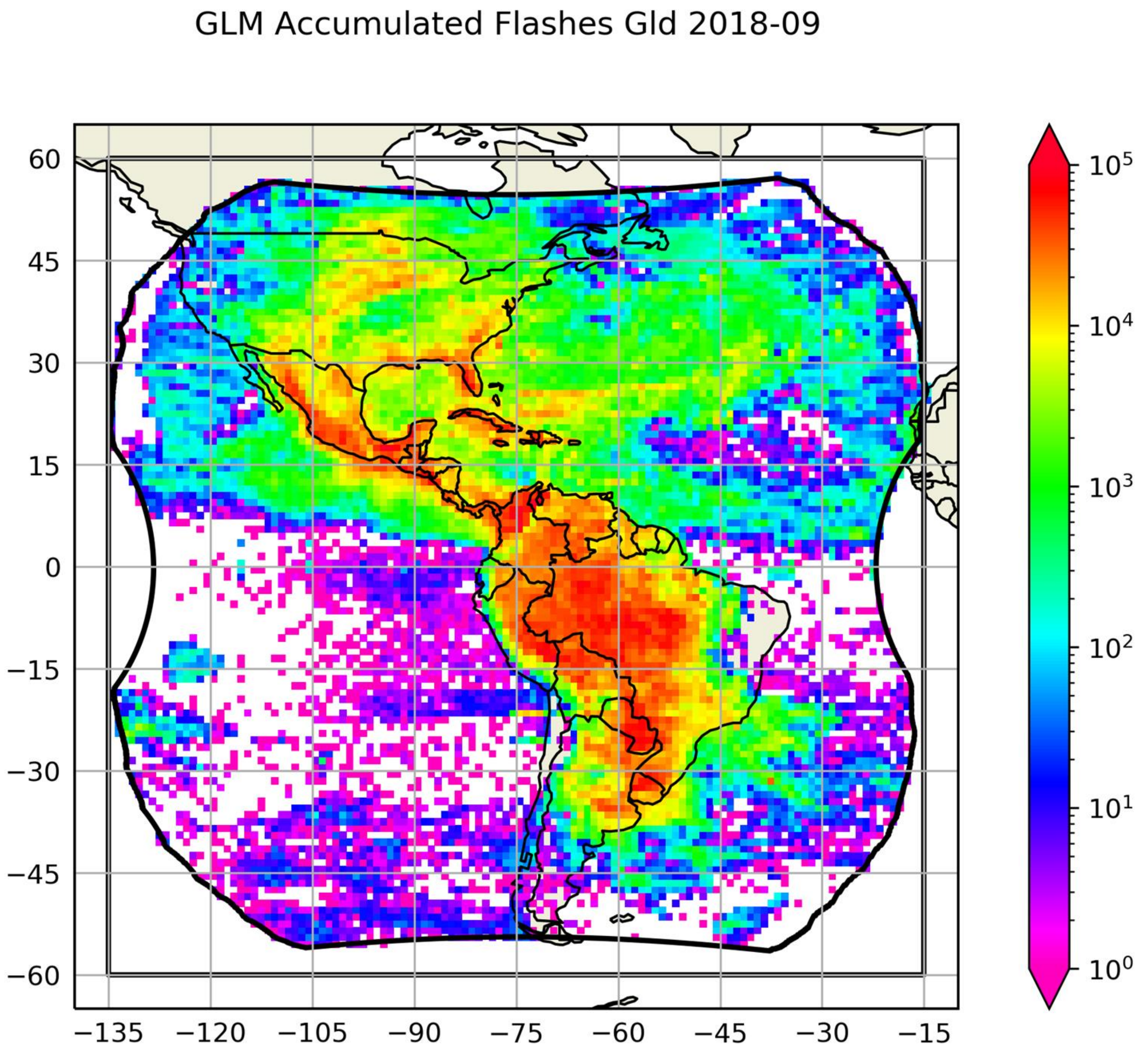
The global flash rate is estimated to be 45 fl/sec (in-cloud and cloud-to-ground)
Asia-Oceania, Europe/Africa, Americas are the 3 main global chimneys for lightning
24,000 people are killed and 240,000 are injured worldwide per year by lightning (Holle, 2016)



Total lightning density 20-km grid, 2016-2020 annual average, Over 10 billion events detected Said, 2017

GLD360 and GLM flash accumulation September 2018





EUMETSAT

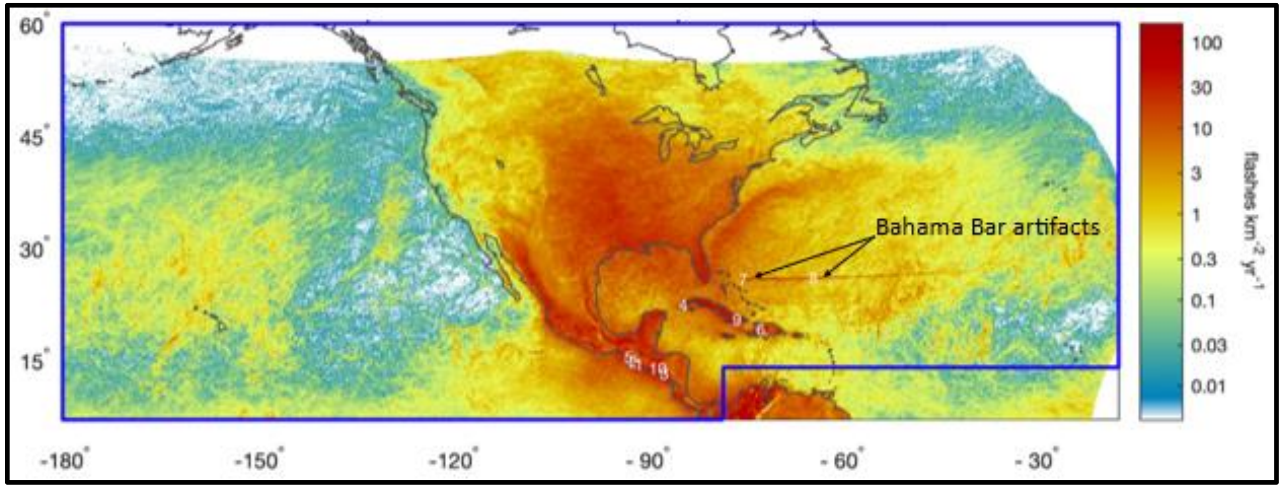
Metadata

- **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.

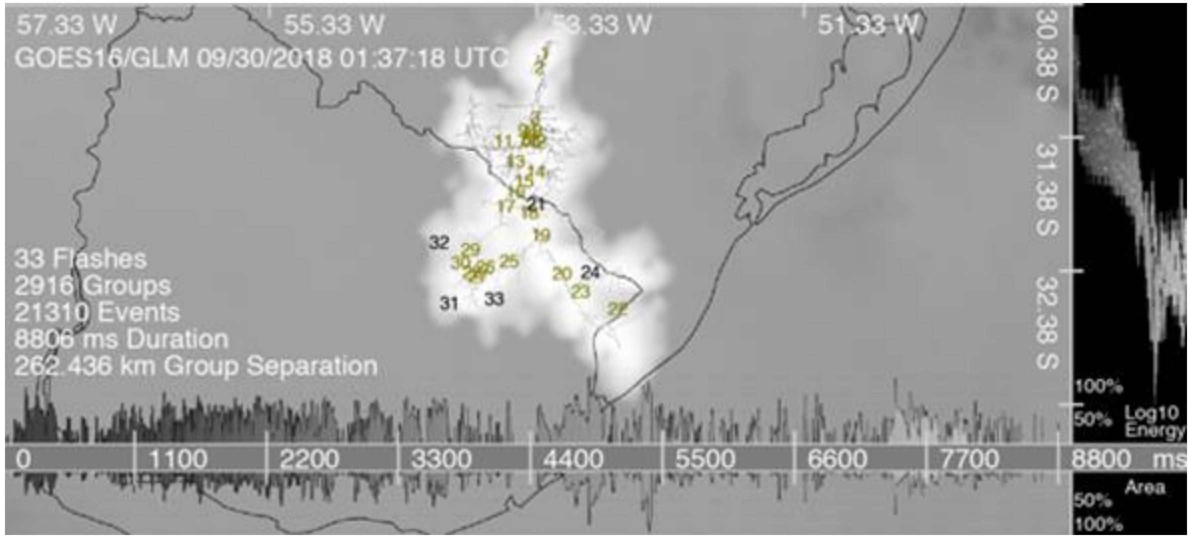
GLM Reprocessing and Removal of Artifacts

GLM for Climate



GLM-16 Top-10 lightning hotspots in North America for the period 12-01-2018 to 04-30-2021.The #7 and #8 maximum flash density hot spots in the western Atlantic are artifacts due to the Bahama Bar (Goodman et al., 2021). Note the blue border to exclude South America.

GLM for Public Safety



A horizontally extensive Megaflash producing multiple strikes to ground that was artificially split by the operational GLM LCFA into 33 flash clusters. Applying a clustering algorithm based on the LCFA without its cluster thresholds results in a single long-duration propagating flash.

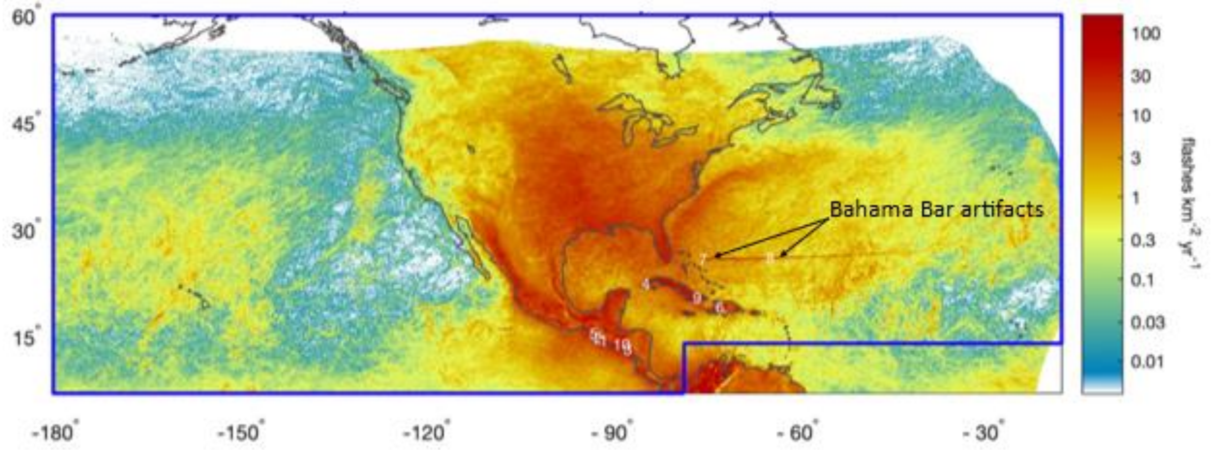
A Common Enterprise Algorithm for Reprocessing Science Data from Space-Based Lightning Sensors (1/2)

- The NOAA/NASA Geostationary Lightning Mapper (GLM) is at the forefront of such observations and is the realization of decades of planning for an optical space-based lightning detection system in geostationary orbit
- GLM is one of several orbital instruments either detecting lightning now or in the future
  - Lightning Imaging Sensor on the International Space Station (ISS-LIS)
  - Chinese Meteorological Agency (CMA) FY4c Lightning Mapping Imager (LMI)
  - GLM follow-on instrument (GEOXO LMX)
  - EUMETSAT Meteosat Third Generation Lightning Imager (MTG-LI)
- However, there are several barriers to utilizing these myriad sensors most effectively to track weather and climate change. Each of the sensors have their own (sometimes changing):
  - Processing code
  - Filters
  - Data formats
  - Output products
  - Artifacts

A Common Enterprise Algorithm for Reprocessing Science Data from Space-Based Lightning Sensors (2/2)

- Example GLM Artifacts
  - Radiation Dots
  - Hot/Cold Pixels
  - Stray Light
  - Sun Glint
  - Solar Intrusion
  - Internal Reflections
  - Subarray Boundary Issues (Bahama Bar)
  - Bolides
  - Cloud Edge Issues (Satellite Movement)
  - Rebound Events
  - Non-Electrified Cloud Illuminations
  - Flash Splitting (Code Limitations)
- A number of these issues have been addressed by code changes
  - They have only been added recently
  - Those artifacts are still in the GLM output prior to the specific filter introduction date

- Other issues in the GLM output include:
  - Changing output data formats
  - Software bugs
- These issues make it difficult to analyze long-term lightning trends for climate change and other studies
- There is a need for a consistent and high data quality Lightning Enterprise Science Algorithm (LESA) that can be applied to all instrument data to provide a common baseline for comparisons and enable weather and climate science studies



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

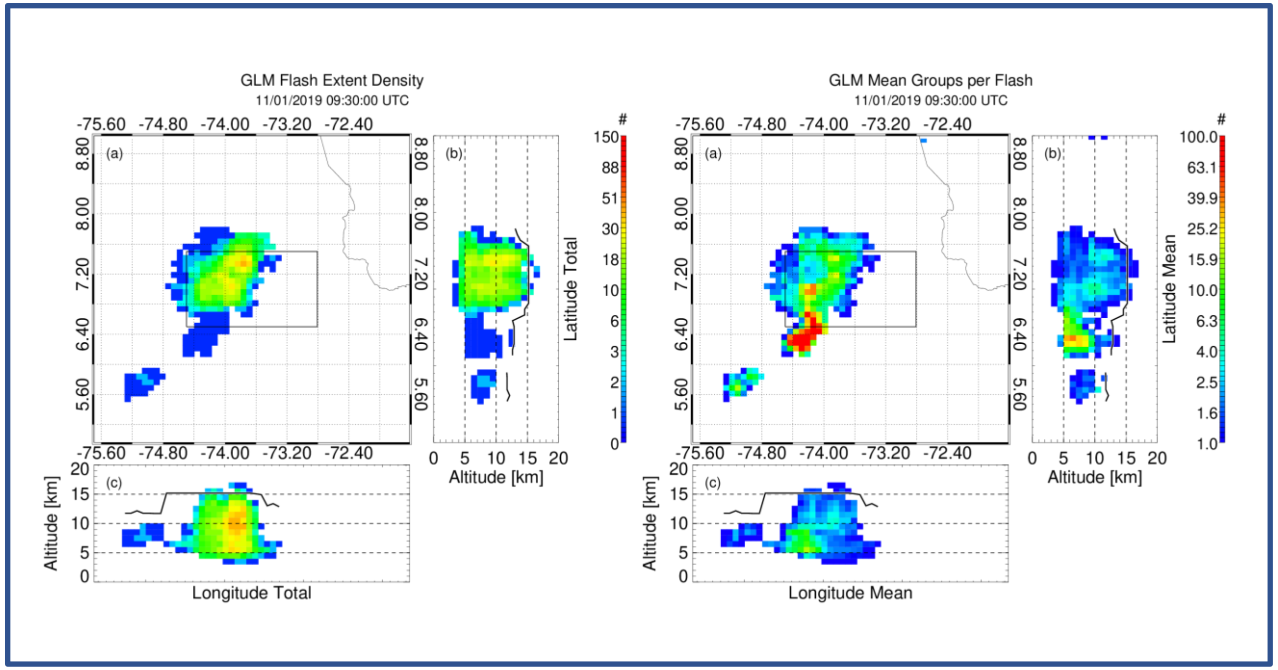
(4) Make the algorithm suite available to the research community (through a cloud service provider)

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.
.

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 identifying Continuing Current and wildfire ignition/forecasting.

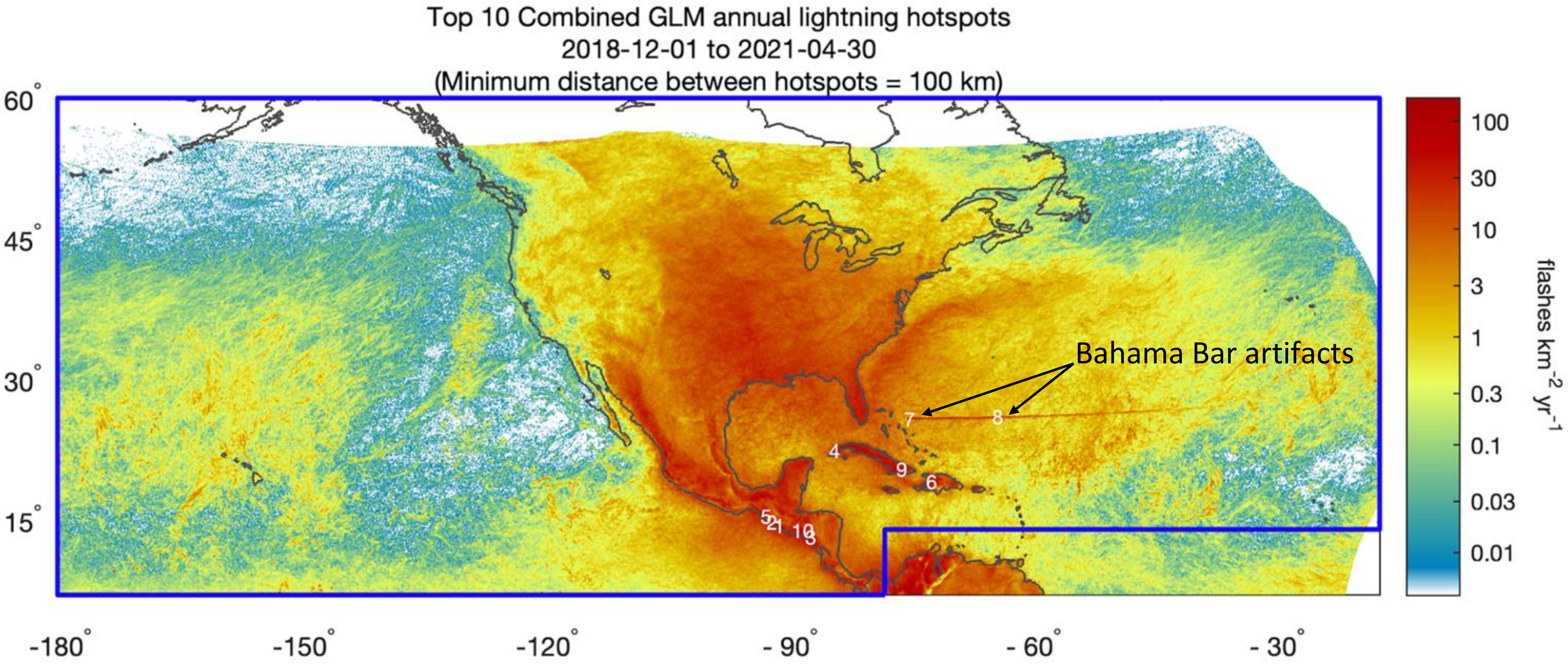
Table 2
Definitions of Geostationary Lightning Mapper (GLM) Flash Characteristics Input as Features Into the Random Forests (RF) Model

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

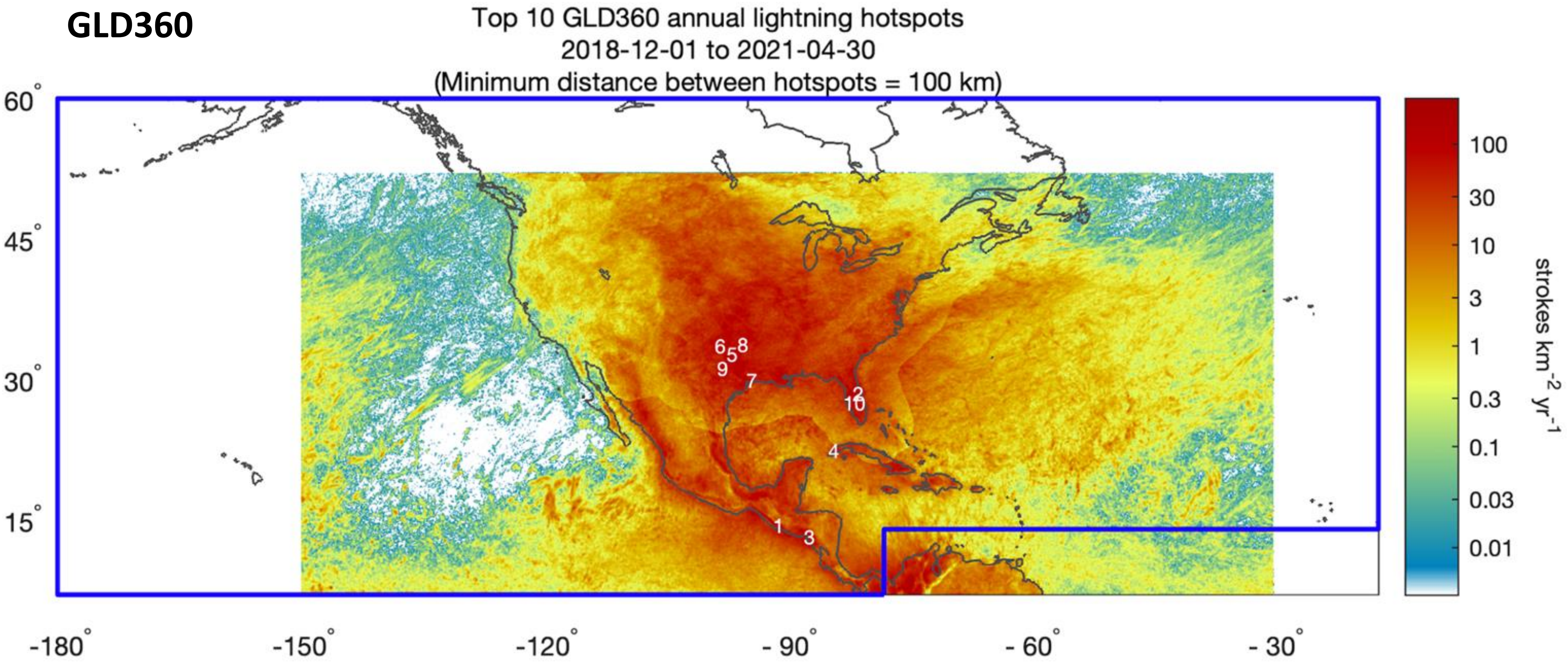
North America Lightning Hot Spots

Compare space-based optical to ground-based RF



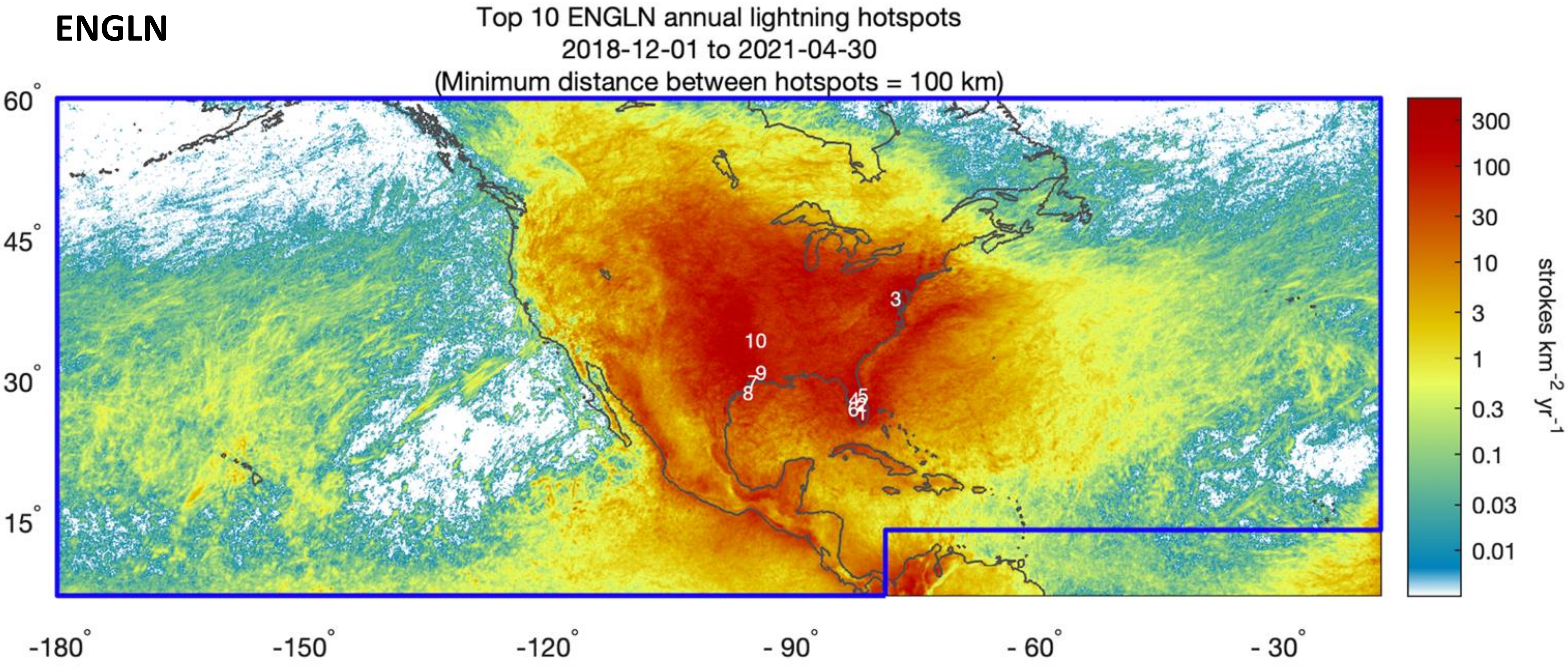
Blue border to exclude South America

GLD360



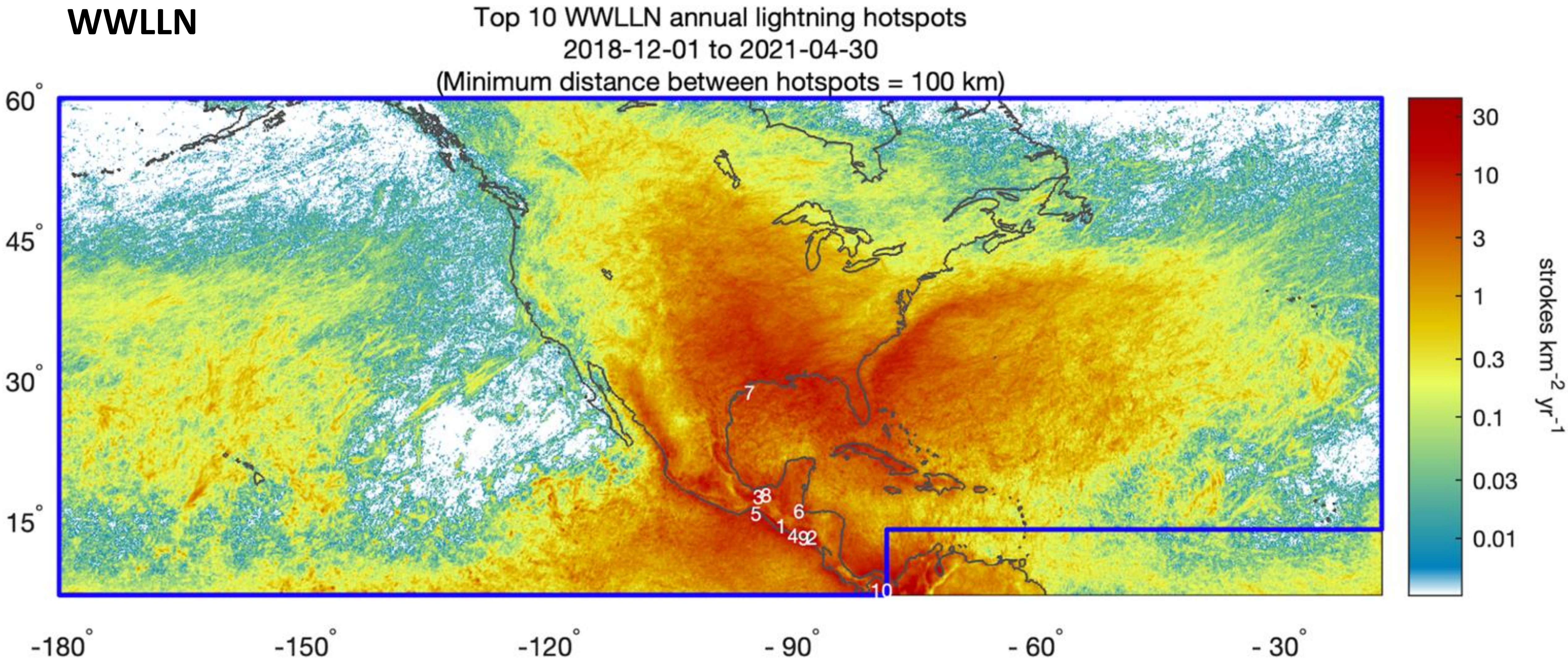
Blue border to exclude South America

ENGLN



Blue border to exclude South America

WWLLN

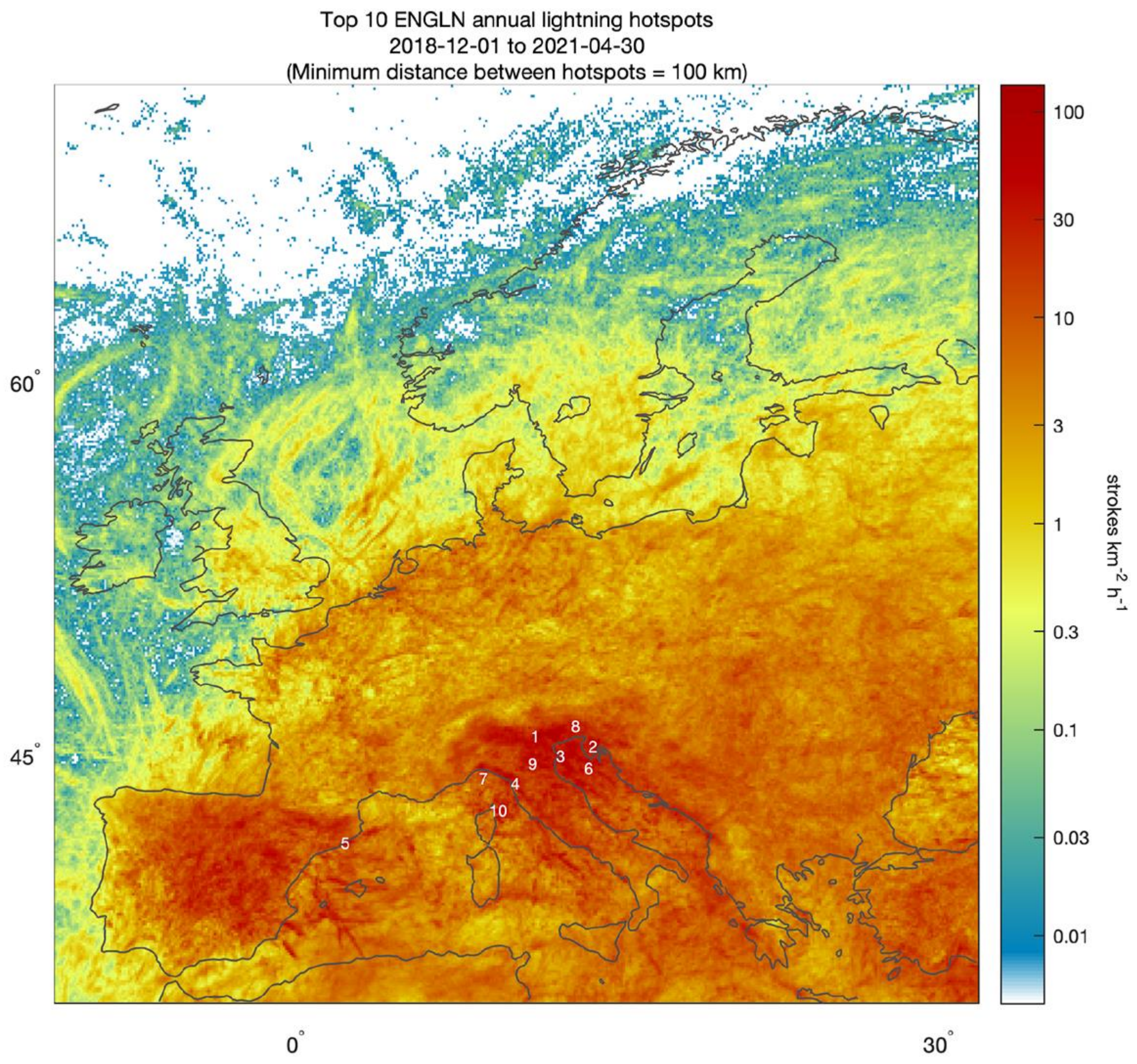


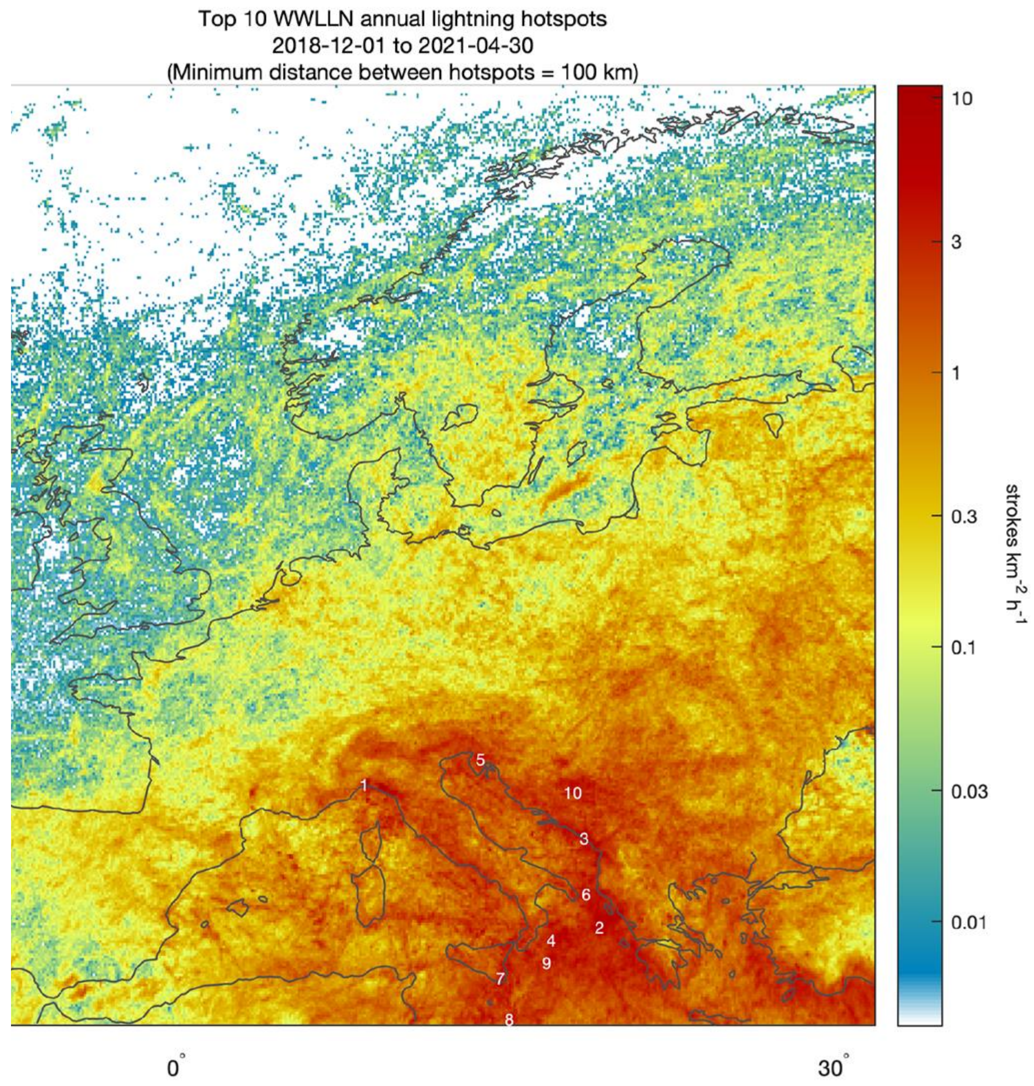
Blue border to exclude South America

Europe Lightning Hot Spots

ENGLN

WWLLN



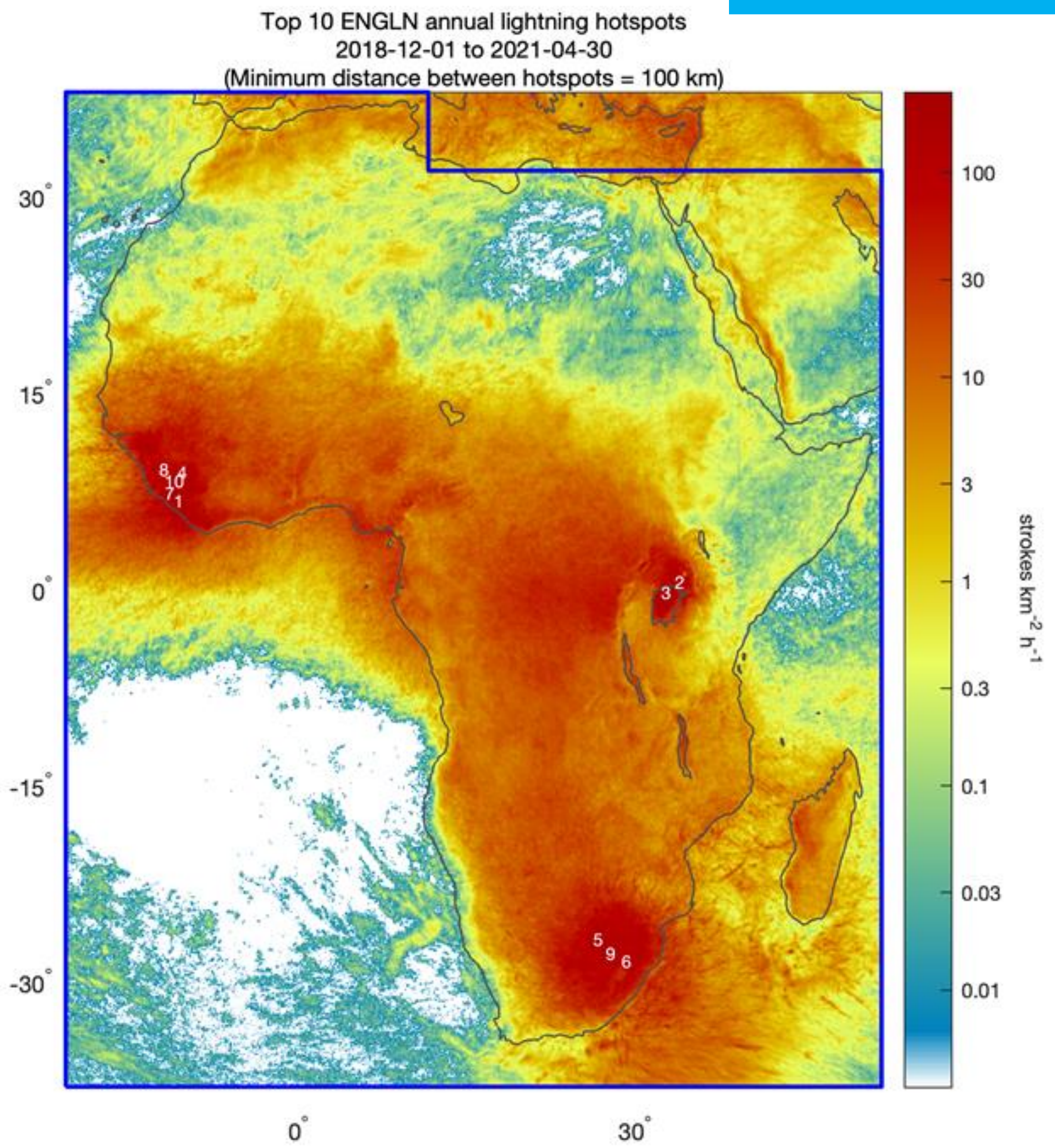


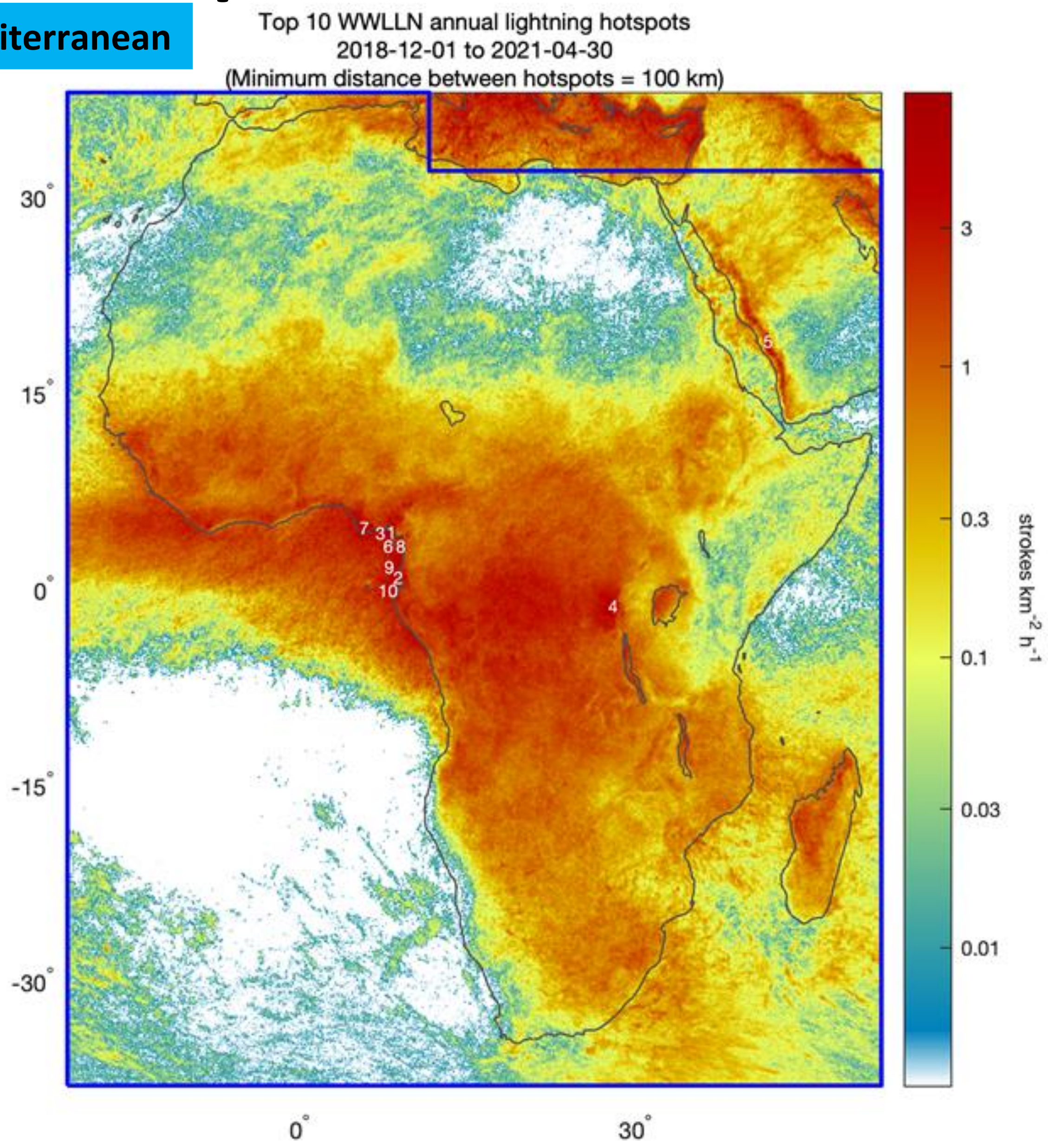
Africa Lightning Hot Spots

ENGLN

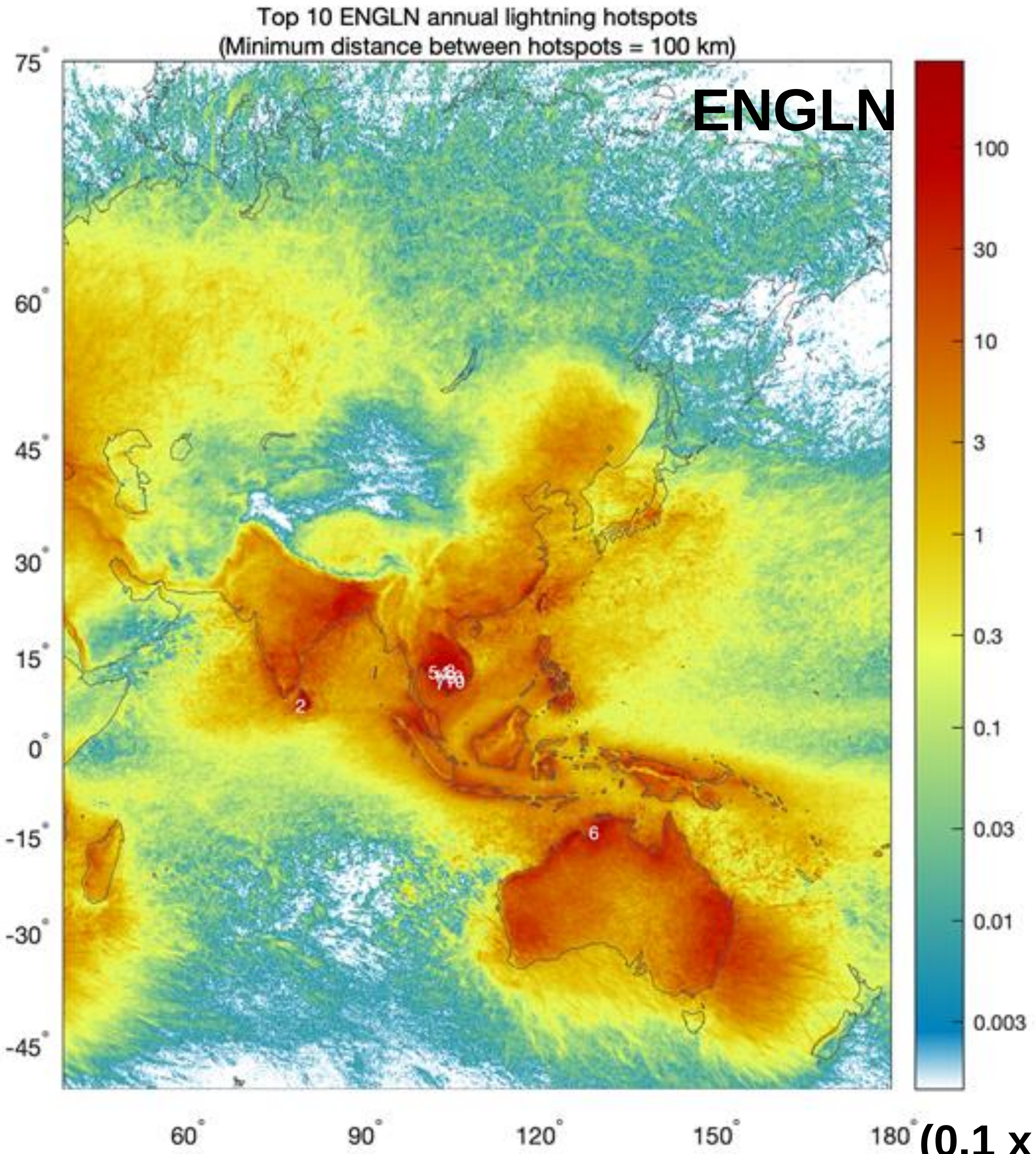
WWLLN

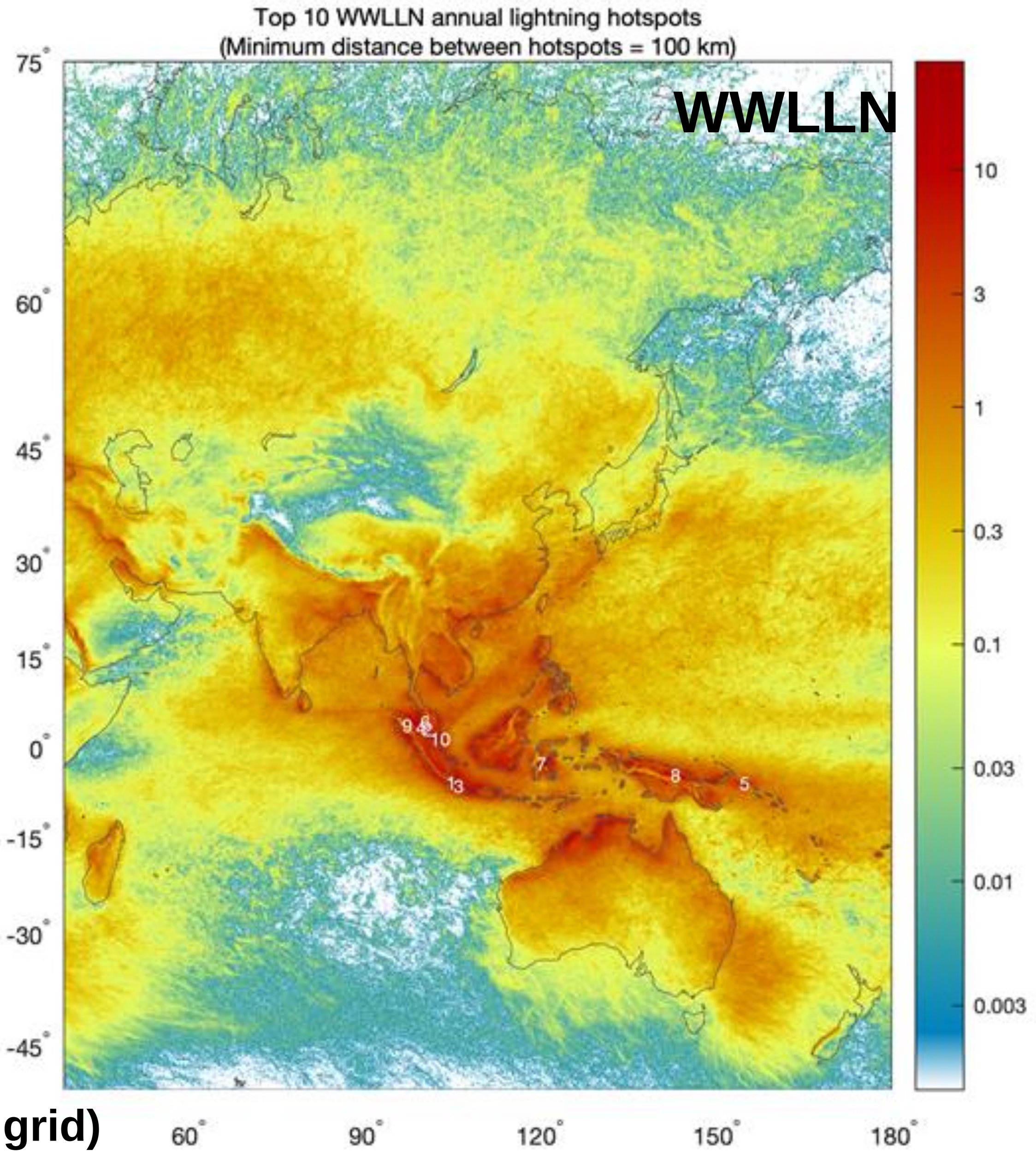
Blue border to exclude Mediterranean





Asia-Oceania Climatology (2015-2020): Top Ten Hot Spots

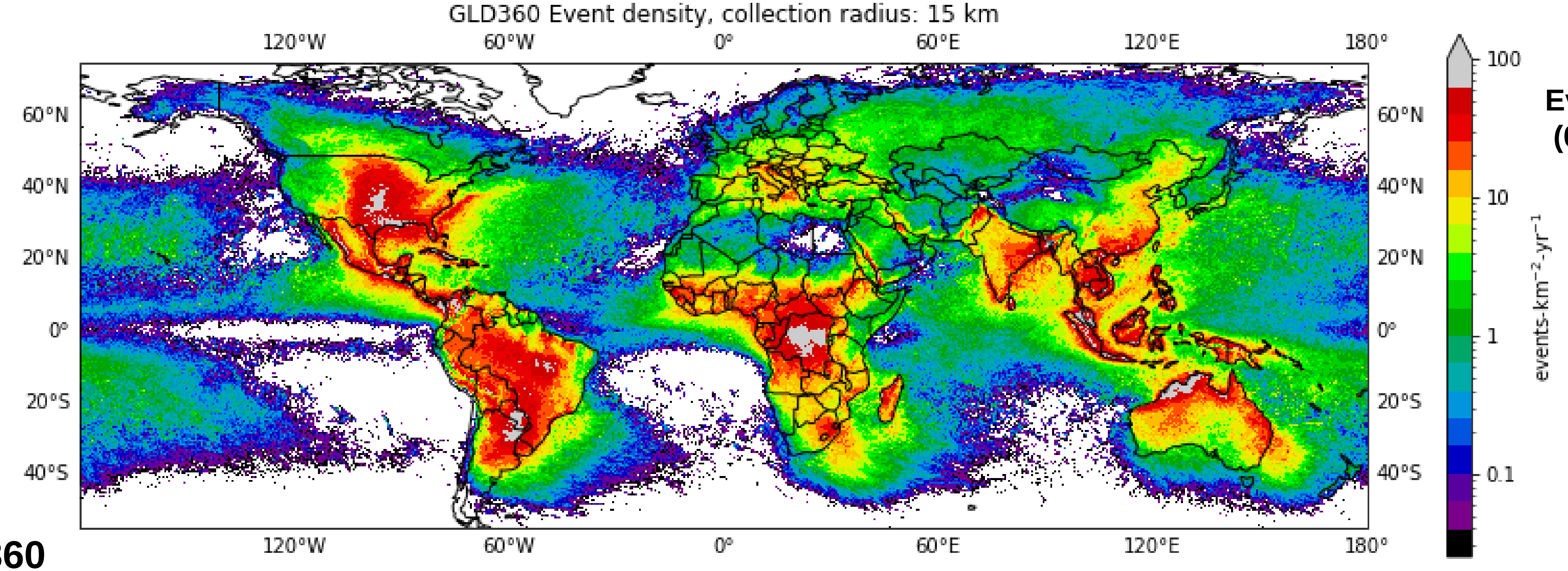




(0.1 x 0.1 deg grid)

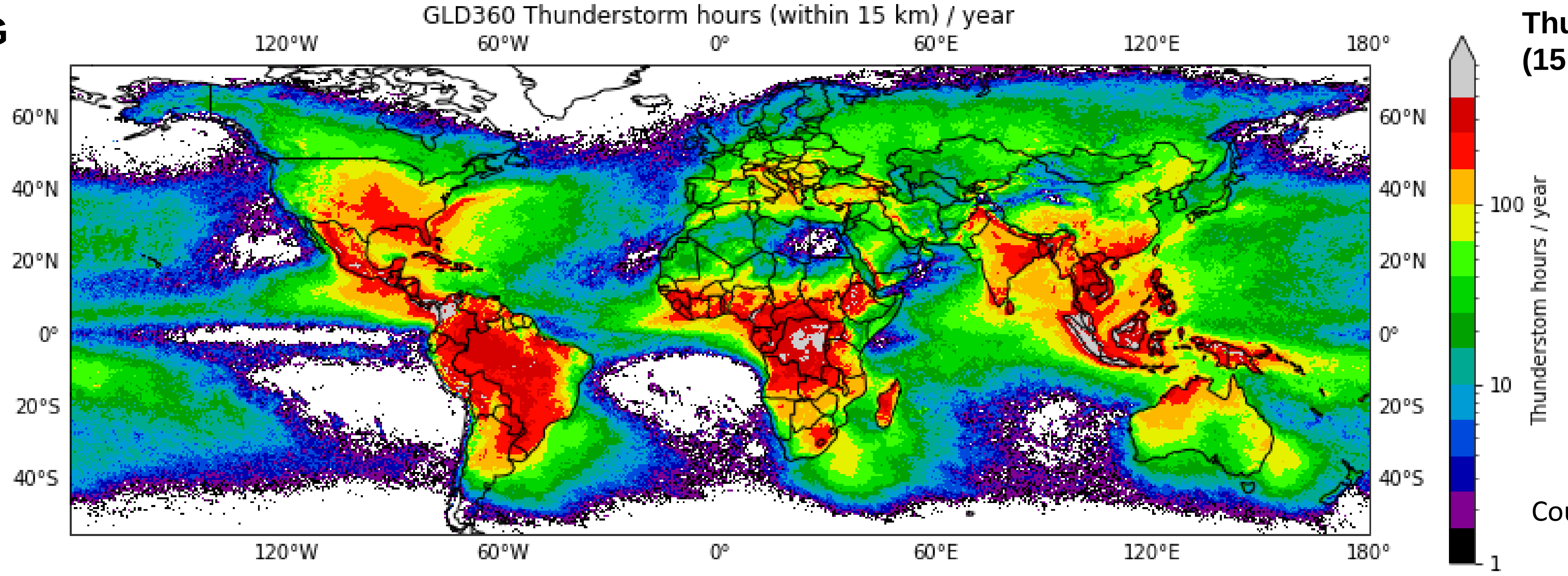
Thunder Hours

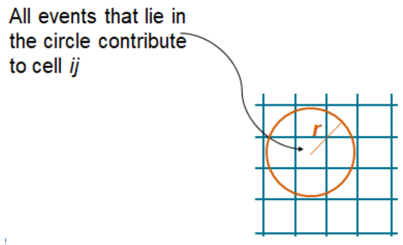
Event Density 2015-2019 (0.1 deg grid)



GLD360 IC+CG

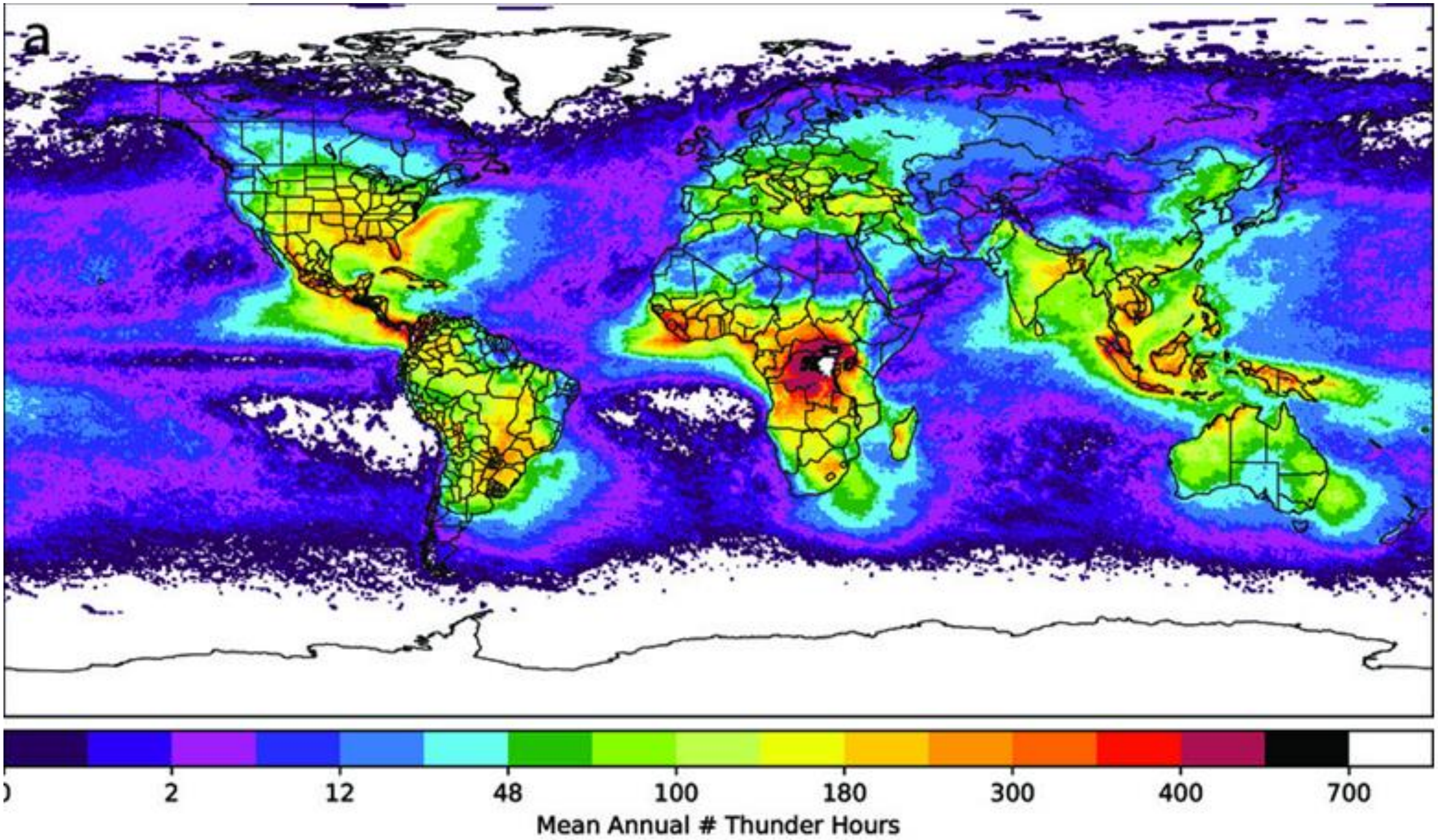
Thunder Hours 2015-2019 (15 km radius)





Courtesy of Ryan Said, Vaisala

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.

Attribution : Interannual Variability and Lightning Teleconnections - ENSO

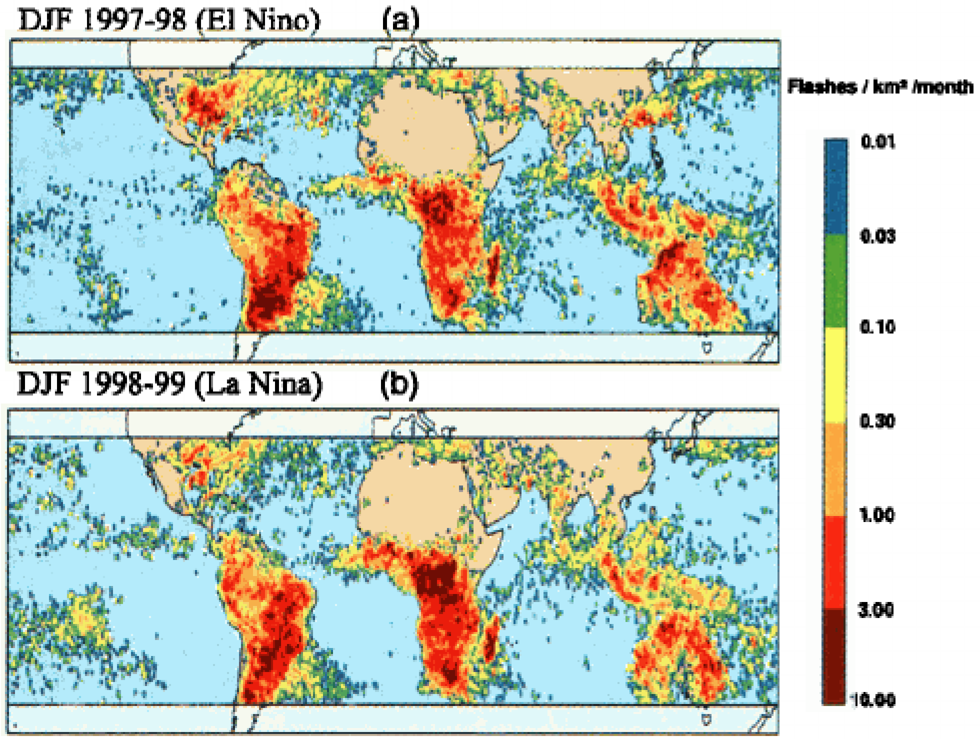


Figure 1. Seasonal distribution of lightning during the 1997-98 ENSO winter period December 1997-February 1998 (top panel) and the 1998-99 LaNina winter period December 1998-February 1999 (bottom panel) derived from observations made by the NASA Lightning Imaging Sensor (LIS).

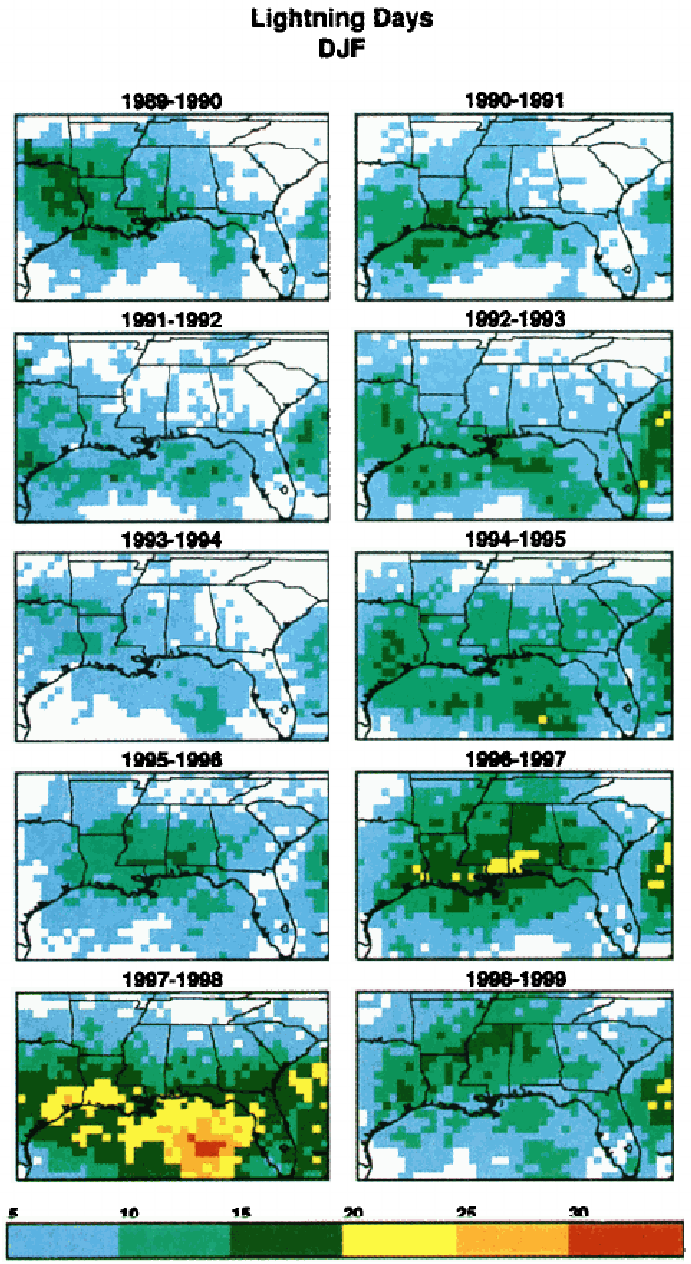
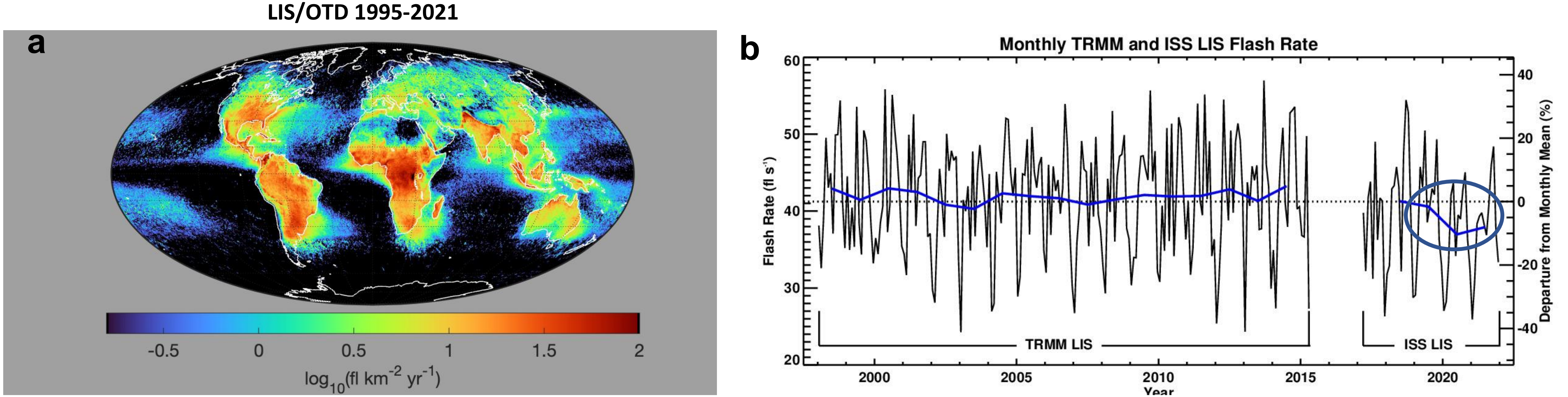


Figure 2. Number of cloud-to-ground lightning days per 0.5° × 0.5° grid box during winter (DJF) 1989-1999.

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.

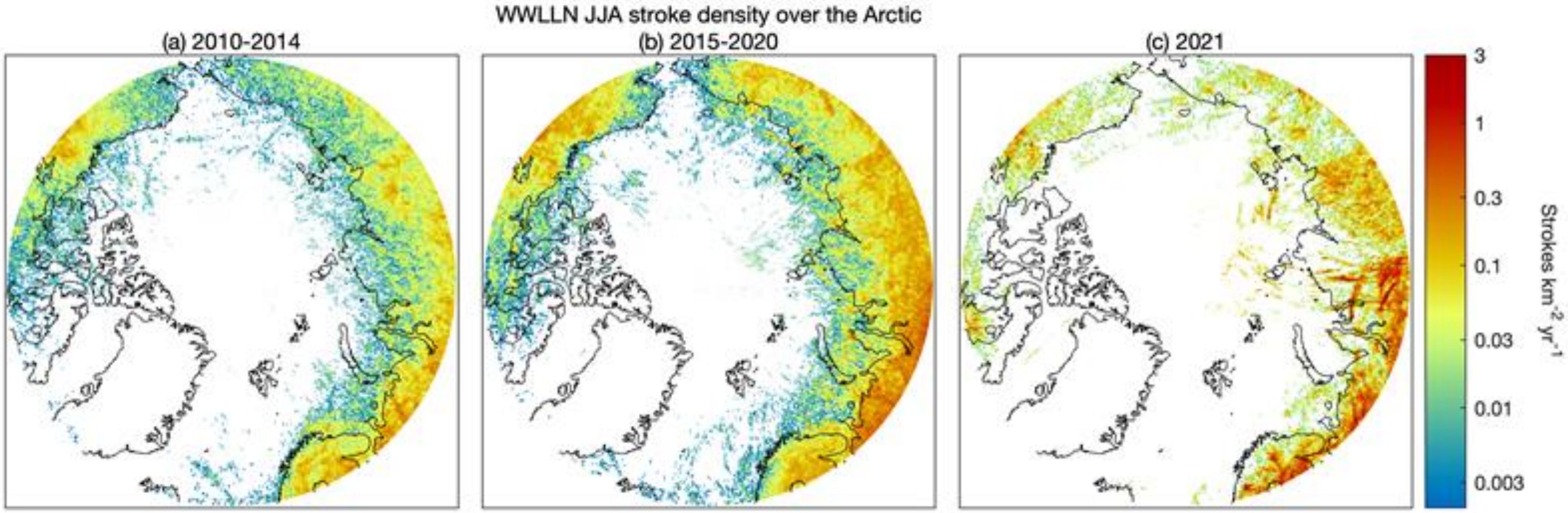
Attribution : Is the 2019-2020 reduction of lightning linked to aerosols and COVID reduction of industrial activity?



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 $\pm 38^{\circ}$ 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).

Fullekrug et al., 2022 – BAMS Special Issue on Climate

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.

Fullekrug et al., 2022 – BAMS Special Issue on Climate

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)

- **How might a lightning ECV be associated with other variables**, such as clouds, precipitation, composition, NOx, and surface observations (e.g., temperature, severe weather reports), ENSO, MJO, Upper Level humidity (see Notes page).

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