2024 WMO GCOS TTLOCA Final Report Draft

1. Introduction

The Atmospheric Observation Panel for Climate (AOPC) agreed during AOPC-22 (Exeter, UK, March 2017, (GCOS, 2017)) on the creation of a dedicated task-team on lightning observations for climate applications (TTLOCA). The WMO published the report GCOS-227 on the initial findings and recommendations of the task team in 2019 entitled "*Lightning for Climate: A Study by the Task Team on Lightning Observation for Climate Applications (TT-LOCA) of the Atmospheric Observation Panel for Climate (AOPC)*". Due to on-going work, unfinished tasks, and the impacts of COVID-19, the Task Team was extended to complete its work with this final report. Interim progress reports were submitted to the AOPC and annual reports on the state on the state of the climate for lightning were published in the American Meteorological Society Special Supplements on the State of the Climate (Blunden and Boyer, 2022; 2024; Blunden, J., T. Boyer, and E. Bartow-Gillies, 2023). The State of the Climate summaries include the planned lightning ECV quantities and anomalies for the recent La Nina and El Nino events observed by satellite lightning imagers and by ground-based global networks. The current report summarizes the work done by TTLOCA and covers key aspects of lightning observations for climate applications. The report also describes the status of observations and data stewardship, discusses gaps and open research questions and provides recommendations for monitoring requirements for lightning, including metadata requirements.

There is increasing evidence of the link between lightning and the climate system, and the importance of the new ECV definition for lightning. Saha et al. (2023a) have shown the strong link between global and regional lightning activity and **cirrus cloud** formation in the upper troposphere. Cirrus clouds are ice clouds that have a net warming on surface temperatures, since their cloud albedo forcing is a lot smaller than their cloud greenhouse forcing. In other words, cirrus clouds trap in more energy emitted from the Earth than they reflect from the Sun. The net forcing is positive, with more cirrus clouds resulting in a net warming of the Earth's surface, and less cirrus cooling the surface. Lightning observations may have a significant role in understanding cirrus cloud changes in the future.

Price et al. (2024) have extended their early studies that showed the strong link between lightning and upper tropospheric water vapor (UTWV). Thunderstorms act like large vacuum cleaners sucking up water vapor from the boundary layer, processing this water through clouds as drops, ice, and graupel, and depositing large fractions of the sublimated ice crystals as UTWV. Here too, UTWV results in surface warming due to water vapor being a key greenhouse gas. In fact, small changes in water vapor in the upper troposphere have a much larger impact compared with the same changes in the lower atmosphere. Changes in thunderstorm activity (and lightning) will impact the UTWV distributions and amounts, with direct links to the Earth's surface temperature.

Finally, Saha et al. (2023b) has extended these two studies to show that the interannual variability of Arctic Sea Ice extent is likely linked to the increasing lightning activity being observed in the Arctic over the last decade (Holzworth et al., 2021). The increasing lightning in the Arctic is resulting in more UTWV and more cirrus in the Arctic, with positive feedback on surface temperatures, and hence enhanced Sea Ice melting in the late summer and fall. Years with enhanced thunderstorm activity are associated with years of enhanced melting of Arctic Sea ice. Hence, enhanced summer thunderstorms in the Arctic may accelerate sea ice melting in the future.

2. Lightning ECV Quantities

Lightning ECV quantities have been identified. These include lightning flash density and Thunder Hours derived from both space-based optical observations from the satellites operated by space agencies and ground-based observations from global and regional networks of radio frequency receivers operated by researchers and commercial companies that sell their data. The latter have agreed to make their monthly ECV data products publicly available. Monthly lightning quantities will be available at a nominal grid resolution of 0.1 deg x 0.1 deg. Some quantities may be available from the data provider at daily temporal resolution.

The space-based optical data from LEO include the NASA Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS) for the period 1997-2015, International Space Station LIS for the period 2017-2023, and the LIS pathfinder named the Optical Transient Detector (OTD) from 1995-2000. The instruments were developed for NASA's Earth Observing System (EOS). The nominal coverage domain for LIS is 35 deg N/S latitude, ISS-LIS is 54 deg N/S, and OTD is 70 deg N/S. The Geo-Ring optical lightning imagers operated by NOAA, EUMETSAT and the Chinese Meteorological Agency (CMA) are continental in coverage. NOAA's GOES Geostationary Lightning Mapper (GLM) period of record is November 2016-present with GOES-East at 75W and GOES-West at 137W. The CMA FY4a Lightning Mapping Imager (LMI) period of record is December 2016-present at 105E, and the EUMETSAT Meteosat Third Generation imaging satellite (MTG-I1) Lightning Imager launched in 2022 is at 0E and is in the commissioning phase of the mission. The MTG-I2 imaging satellite will be placed at 9.5 deg East providing extended coverage to the Middle East.

2a. Lightning Stroke Density (0.1 x 0.1 deg, strokes/km^2)

Stroke data are provided by the ground-based VLF networks (Earth Networks Total Lightning Network- ENTLN, Vaisala Global Lightning Dataset-GLD360, and the University of Washington World-Wide Lightning Location Network-WWLLN).

2b. Lightning Flash Density (0.1 x 0.1 deg, flashes/km^2)

Space-based Geo optical lightning imagers detect optical pulses from lightning flashes. One or more optical pulses are observed during the lifetime of a lightning flash. The flashes may be localized to an individual thunderstorm or extend over hundreds of kilometers in horizontally extensive mesoscale convective systems that can produce numerous individual strokes to ground. Such flashes have been observed by the GLM in the Southern Great Plains of the US and in the La Plata Basin region of South America.

2c. Thunder Hour (TH, # hours)

The 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 or grid point. The mapping of thunder hours enables the characterization of thunderstorm frequencies around the world (DiGangi et al., 2021) that are indicative of high impact weather and lightning hazard (Blunden and Boyer, 2024). Thunder hours can be derived from optical, radio, and sonic remote sensing and result in maps that offer a statistically robust measure of the frequency of deep convection on time scales ranging from hours to decades suitable for climate studies. In Figure 1 the space-based Geostationary Lightning Mapper (GLM) on the GOES satellite and ground-based low frequency lightning networks combined were used to produce maps of the TH anomaly attributed to the 2023 *El Niño* event. The anomaly of up to ~200 additional thunder hours over the eastern tropical Pacific (Fig. 2b) is attributed to increased convection associated with above-average SSTs and El Niño. Above-average numbers of thunder hours and precipitation in southeastern South America has been attributed to a teleconnection between weather patterns in northwestern and southeastern South America in austral spring.

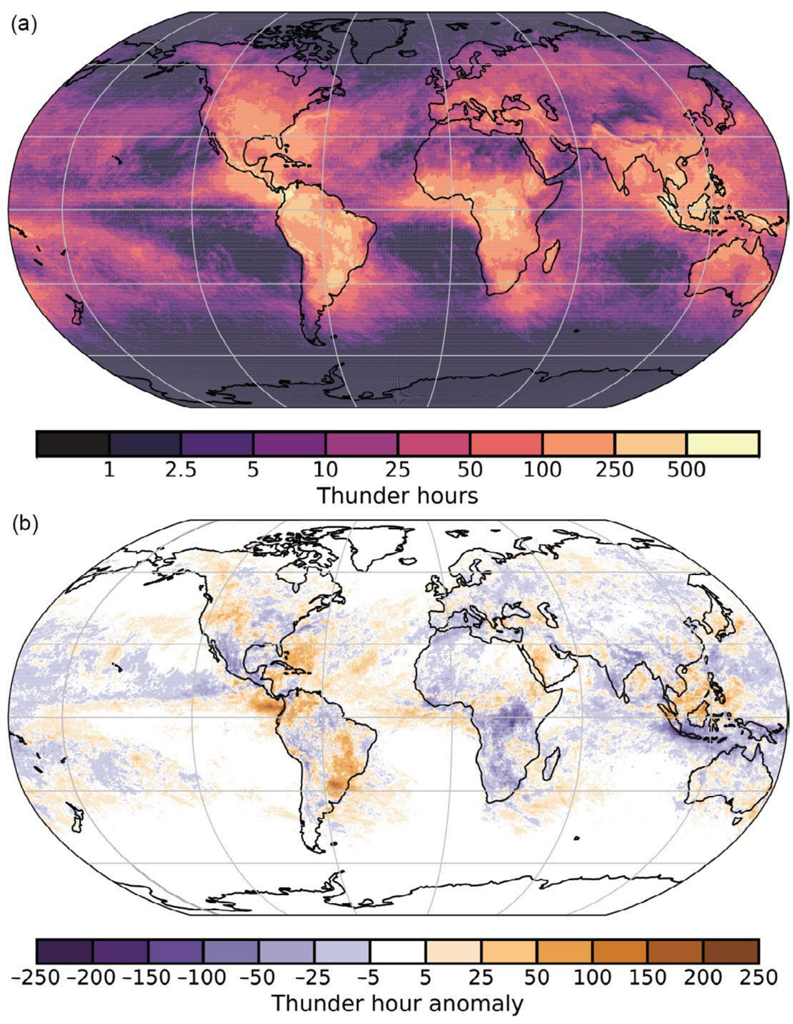


Fig. 1. (a) Total number of thunder hours for 2023 averaged from three ground-based global lightning detection networks (Vaisala Global Lightning Detection Network [GLD360], Advanced Environmental Monitoring Earth Networks Total Lightning Network [AEM ENTLN],

and the University of Washington's World-Wide Lightning Location Network [UW WWLLN]) and (b) thunder hour anomalies for 2023 (base period is 2018–22). Source, Blunden and Boyer, 2024.

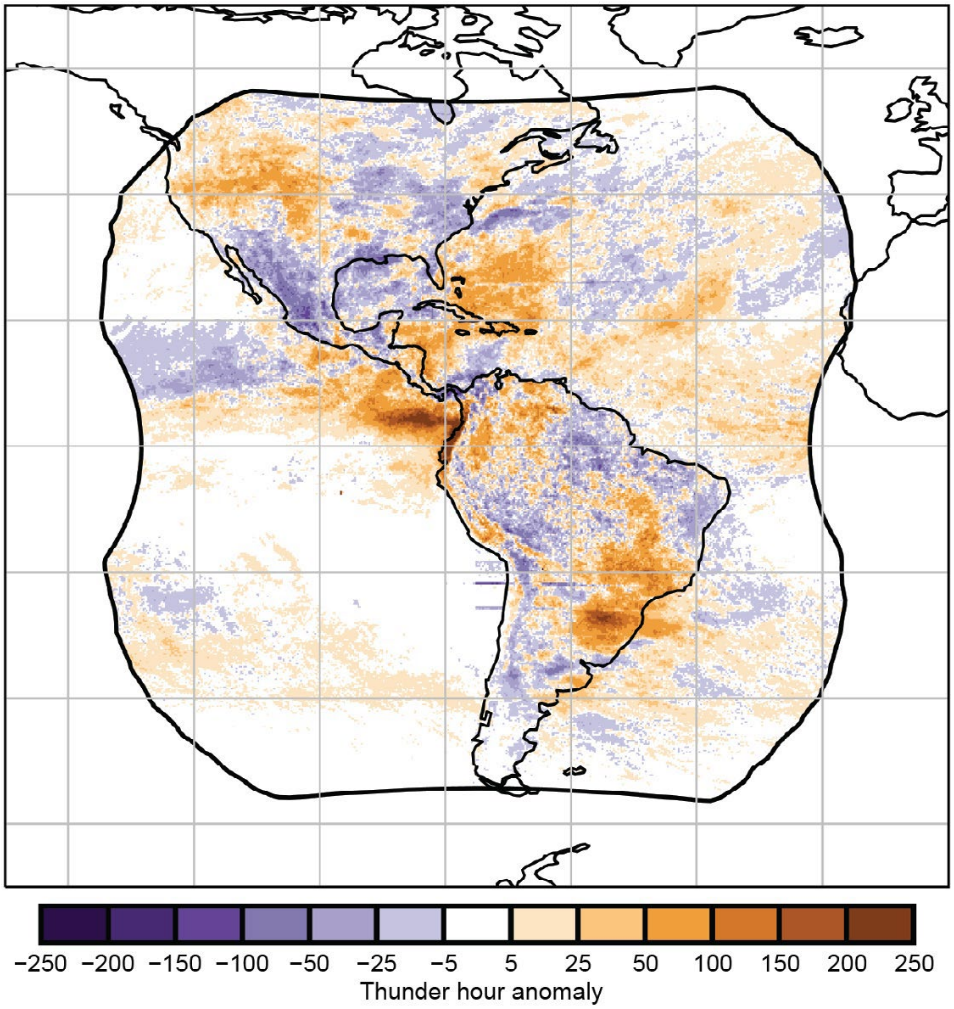


Fig. 2. Thunder hour anomaly for 2023 calculated from NOAA's Geostationary Lightning Mapper on GOES-16. This compares well to the 2023 anomalies calculated from ground-based lightning detection networks. Source, Blunden and Boyer, 2024.

2d. Thunder Day (TD, # days)

A thunderstorm day (Thunder Day) is when thunder is heard by a human observer from an official observing site. Whether thunder is heard once or many hundreds of times during a day, this is recorded as a single Thunder Day. Records are recorded by National Meteorological and Hydrological Services worldwide (WMO, World distribution of thunderstorm days, part 1, *WMO-21,* https://library.wmo.int/idurl/4/37380, 1956). More recently, Lavigne et al. (2019) developed a methodology to extend the thunder day climate record by comparing the Global Surface Summary of the Day (GSOD), a data set of over 9,000 ground-based meteorological stations located worldwide (https://data.nodc.noaa.gov/), with space-based observations of lightning from the Lightning Imaging Sensor aboard the TRMM satellite. This methodology can then be applied to a new and expanded Thunder Day data set being facilitated by the TTLOCA with stewardship and archive supported by the Copernicus Program (https://www.copernicus.eu/en).

Lavigne, T., Liu, C., & Liu, N. (2019). How does the trend in thunder days relate to the variation of lightning flash density? Journal of Geophysical Research: Atmospheres, 124, 4955–4974.https://doi.org/10.1029/2018JD029920

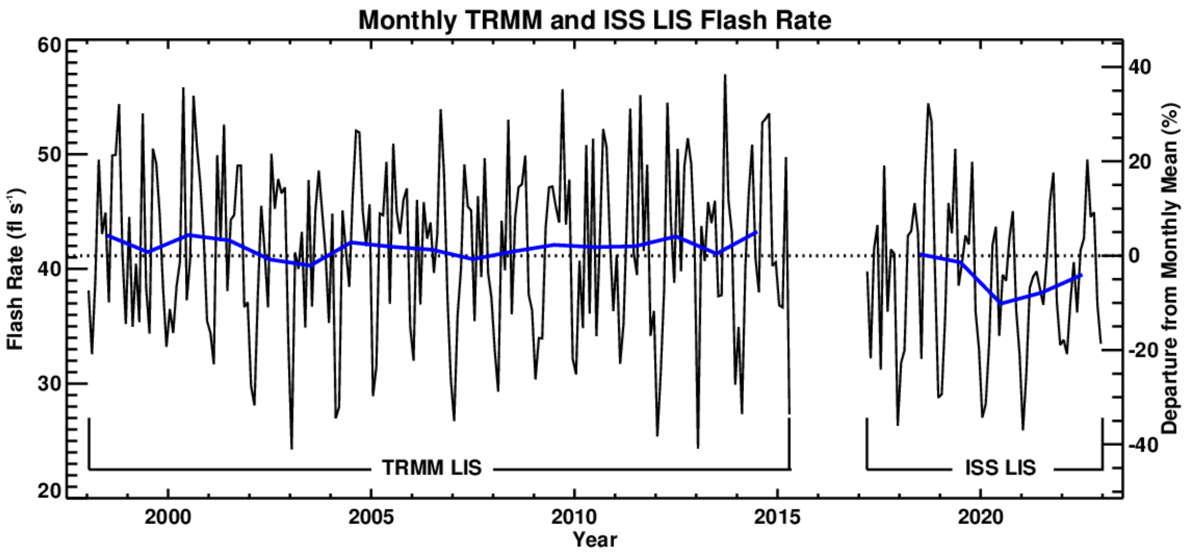
2e. Schumann Resonance (pT, pico Teslas)

Schumann resonance (SR) is a global phenomenon produced by low frequency (<100 Hz) electromagnetic radiation from worldwide lightning. The SR intensity is computed from the vertical and horizontal magnetic field. In this frequency band there is little attenuation and the radiated signals from lightning can be observed anywhere on Earth. Multi-station observations (a minimum of four research stations) have been used to document the 1997/98 and 2015/2016 El Nino events (Williams et al., 2021).

3. ECV-specific satellite data processing method improvements

3.1 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, 2017-2023).

Status: The LIS/OTD is our baseline data set on global lightning distribution, inter-variability and change. The data set had been updated through December 2022 for the August 2023 Bulletin of the American Meteorological Society 2022 Special Supplement on the State of the Climate (Blunden and Boyer, 2023). Both the ISS LIS and the GLM records are consistent in showing that global lightning totals during the recently ended triple-dip La Niña phase have not returned to the levels of the previous El Niño in 2019. Four TTLOCA Task Team members are co-authors on the report.



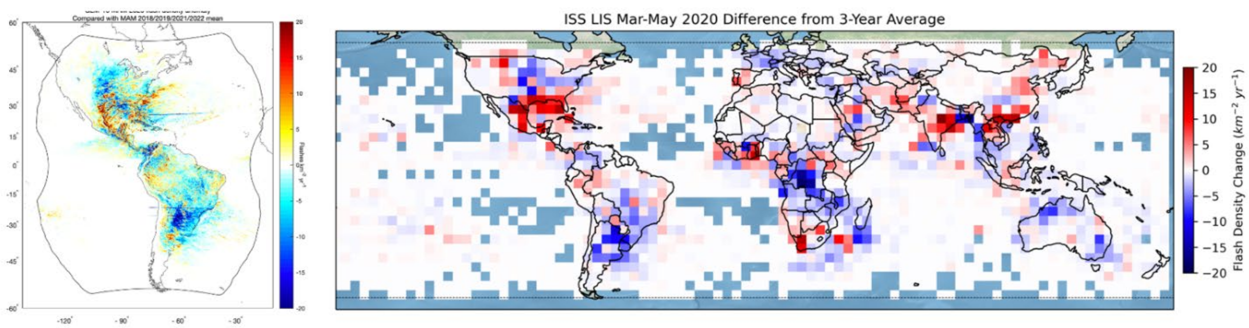


Fig. 3. Seasonal lightning density anomalies for March-May 2020, potentially associated with the reduction of aerosol during the first COVID lockdown. Left – The spatial distribution of anomalies in seasonal lightning density from GLM16. Right – The global distribution of anomalies (relative to MAM 2017-2019) in seasonal lightning density observed from the Lightning Imaging Sensor (LIS) on board the International Space Station (ISS).

LIS Reprocessing: The International Space Station Lightning Imaging Sensor (ISS LIS) mission ended in November 2023 after a nearly 7-year mission. Since then, a data reprocessing and harmonization process has been ongoing. There are two thrusts to this work. One is corrections to and reprocessing of the ISS LIS orbit granules. These corrections include rectifying known errors in the event, group, and flash areas. Calibration updates are also being applied to the ISS LIS data. Errors in ISS LIS timing, flagging, filtering, metadata, and other characteristics are being addressed, and depending on time constraints, similar updates may be made to the Tropical Rainfall Measuring Mission (TRMM; 1998-2015) LIS and Optical Transient Detector (OTD; 1995-2000) datasets.

The second thrust of the effort is harmonization and combination of the OTD plus ISS and TRMM LIS datasets into a global lightning climate data record that spans 1995-2023 with only a two-year gap (2015-2016). This climatology will replace the current TRMM LIS/OTD global climatology and will feature harmonization between the different instrument detection efficiencies and sampling characteristics. This climatology will address many WMO GCOS Essential Climate Variable (ECV) requirements for lightning, though limitations imposed by low-Earth orbit (LEO) sampling may limit the spatial and temporal resolution of the final combined OTD/LIS dataset. Both the updated orbit granules and the final gridded climatology will be released during calendar year 2025.

3.2 Reprocess the GEO Geostationary Lightning Mapper (GLM) on GOES-16/17/18

Status: The Geostationary Lightning Mapper (GLM) on the Geostationary Operational Environmental Satellites (GOES) 16&17 published the first lightning anomaly map covering the Western Hemisphere Americas and adjacent oceans, while the Lightning Imaging Sensor (LIS) on board the International Space Station (ISS LIS) extends the 25+ years of observations of global lightning from previous satellites in low-Earth orbit. GLM science reprocessing was fully funded late in 2022 by the GOES-R Program. Separately the GLM instrument vendor, Lockheed Martin, was funded by the GOES-R Program to reformat the Level 0 instrument data for GOES-16/17 to make it readable by the broader scientific community. This L0 data set will be archived at the NOAA National Centers for Environmental Information (NCEI) and at the NASA Global Hydrometeorology Resource Center (GHRC) Distributed Active Archive Center. The intent of science reprocessing is to use the new L0 data set to create a reprocessed L1B and L2 data set that fixes several known artifacts in the science data. GOES 18 GLM was made operational in January 2023 at 137W to replace GOES 17 which is in storage at 104.7W should it be needed. GOES-19 launched in June 2024 will replace GOES-16 as the operational GOES-E satellite in early 2025.

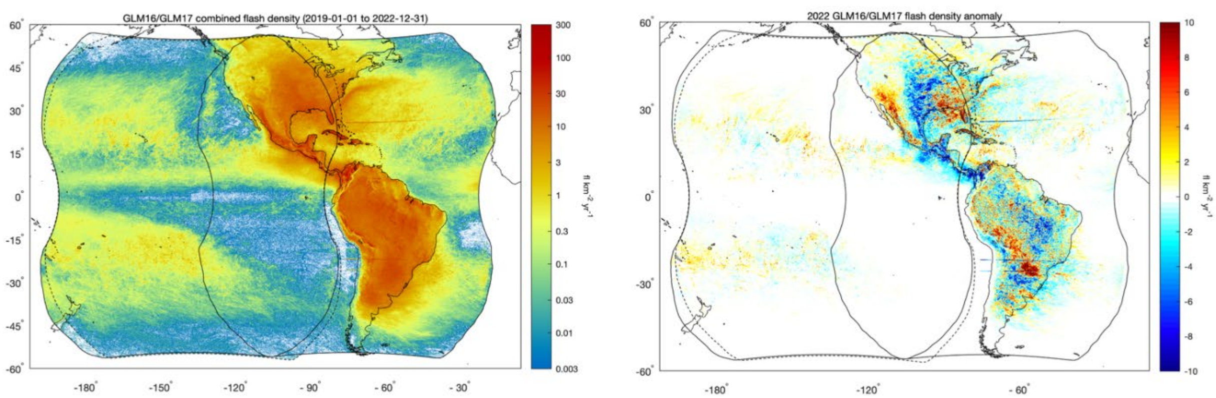


Fig. 4. Left - Lightning flash rate density (fl km^{-2} yr^{-1}) for the period 2019-2022 from NOAA's Geostationary Lightning Mapper (GLM) on the Geostationary Operational Environmental Satellites (GOES) 16&17. Black outline indicates the nominal GLM field of view for each satellite. Right - Western Hemisphere anomalies in lightning density for 2022 that are calculated relative to the 2019-2021 mean.

<u>GLM Reprocessing</u>:

A code set (in Matlab) was developed to process the GLM data from the raw L0 files to the L2 lightning event, group, flash science data, and background scenes. The code is derived from the pseudocode included with the vendor delivered documents. The Matlab code is being converted to C code with improvements to the data processing algorithms that will improve false event filtering and geolocation. The code conversion and improvements are on track to be completed by the end of 2024.

4. Data Stewardship

A landing page for the space-based and ground-based Lightning ECV quantities is in development in partnership with the GHRC. Examples are shown in Figures 5 and 6. It's an automated landing page that develops once the data are formally published. The public will access the landing page via the NASA Earthdata portal CMR Search - Landing Pages for GHRC_DAAC EOSDIS Collections (nasa.gov). The GHRC will coordinate with each data producer to ensure accurate representation of the data, provide full credit to them, and include DOI links to their home web pages.

The GLM space-based lightning metadata descriptions are documented in the GOES-R Product User Guide (PUG). For the Vaisala GLD360, Earth Networks ENTLN, and WWLLN World-Wide Lightning ground-based global RF networks, the data providers developed a Version 0 metadata description document for review by the Task Team at the end of March 2023. Final modifications will be provided to the GHRC Project Scientist. Sample gridded products at the 0.1 x 0.1 deg desired resolution and gridded Thunder Hour grids have been created and the intent is that these will also be in the metadata description at the GHRC landing page.

This component of the lightning essential climate quantity underwent a scientific and content review by NASA's Earth Science Data and Information System (ESDIS). This review confirmed that this dataset is an appropriate contribution to the Global Hydrometeorology Resource Center (GHRC) Distributed Active Archive Center (DAAC); one of NASA's twelve DAACs to archive NASA Earth science data. The GHRC DAAC is known as NASA's lightning DAAC.

The GHRC Science Advisory Committee recommended the gridded products from the commercial ground-based global data providers be archived at the GHRC in case they are not available from the data set owners at some point in the future. Otherwise, the data portal will point the user to the home page of the individual data providers to access the data sets being made publicly available.

The L0-L2 GLM data are available to the community via NASA and NOAA cloud service providers. GLM Level 3 gridded lightning quantities including flash density and Thunder Hour will be publicly available through the NASA Earth Science Data portal. Some of the advantages of this dataset being accepted to a NASA DAAC are

- Cloud-based archive to enable easier access, processing in the cloud, and access to other archived lightning data
- Long-term storage: This is more than a web page on a single server. The DAACs provide free access for years to come, complete with redundant backups
- GHRC DAAC, through a user working group is developing visualization and analysis tools to support science use

The Meteosat Third Generation satellite hosting a sixteen channel Flexible Combined Imager (FCI) and Lightning Imager (LI) is undergoing commissioning. The MTG-LI lightning data plan is for the data to be publicly available following commissioning as the newest contribution to the lightning GEO-Ring. The CMA FY4a LMI 1-minute lightning data files are available from the Fengyun Satellite Data Center portal.

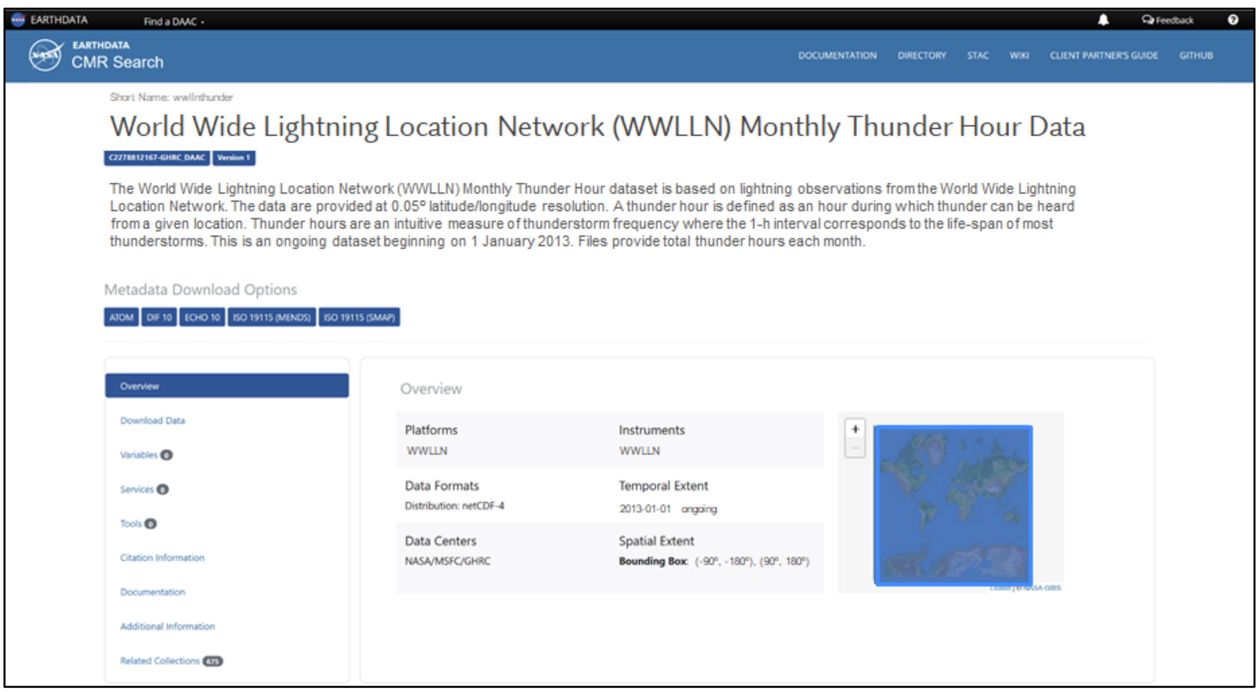


Fig. 5. NASA Earth Science Data portal web page for WWLLN monthly data sets.

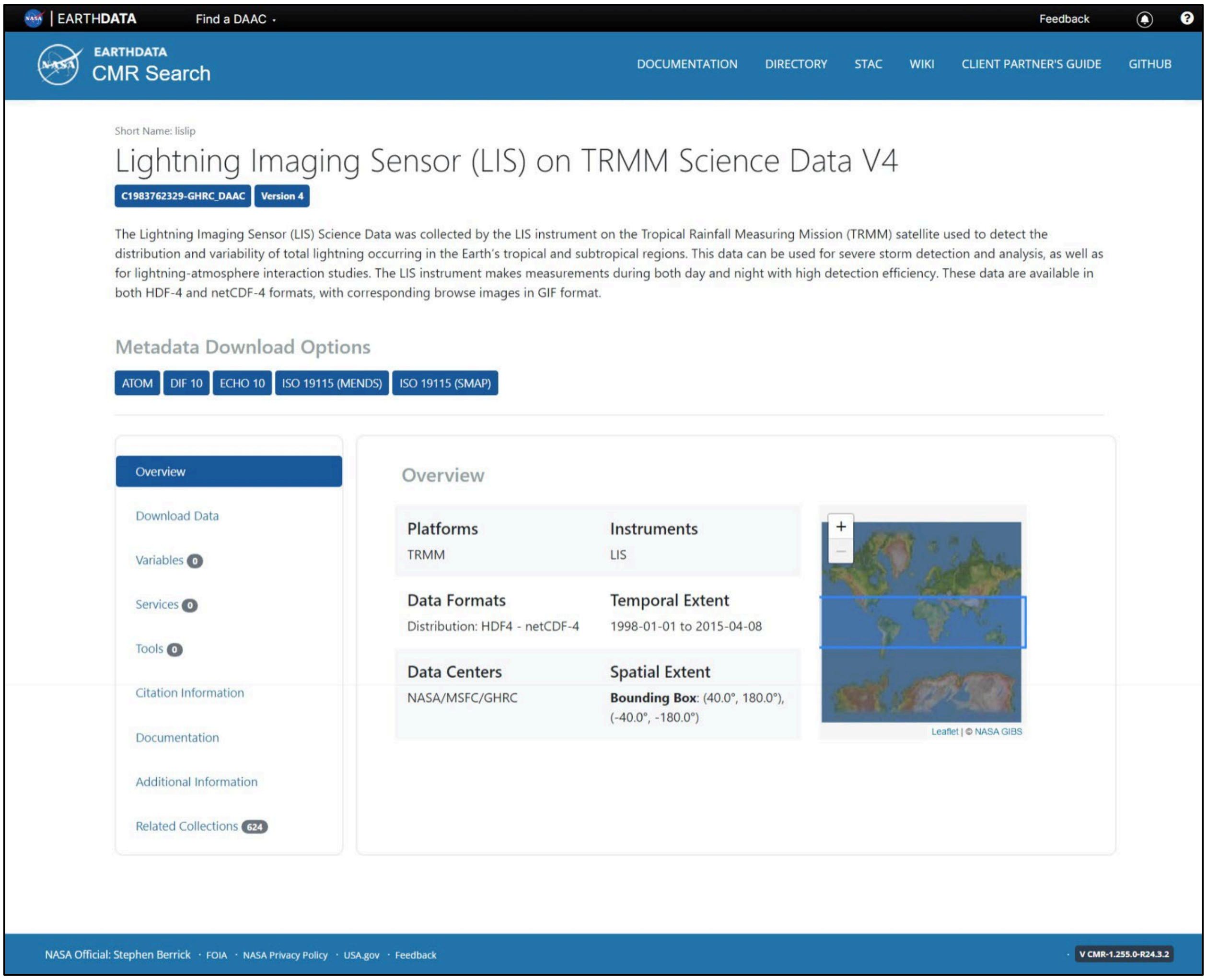


Fig. 6. NASA Earth Science Data portal web page for LIS monthly data sets.

5. Thunder Day Records

<u>Status:</u> Recovery and access to Thunder Day records continues. These datasets are especially valuable for climate studies because of their exceptional length (often many decades). The data will be archived at Copernicus. TTLOCA reached out to a number of contacts to provide the data with the assistance of the WMO / GCOS Project in obtaining missing Thunder Day records from the worldwide NMHS.

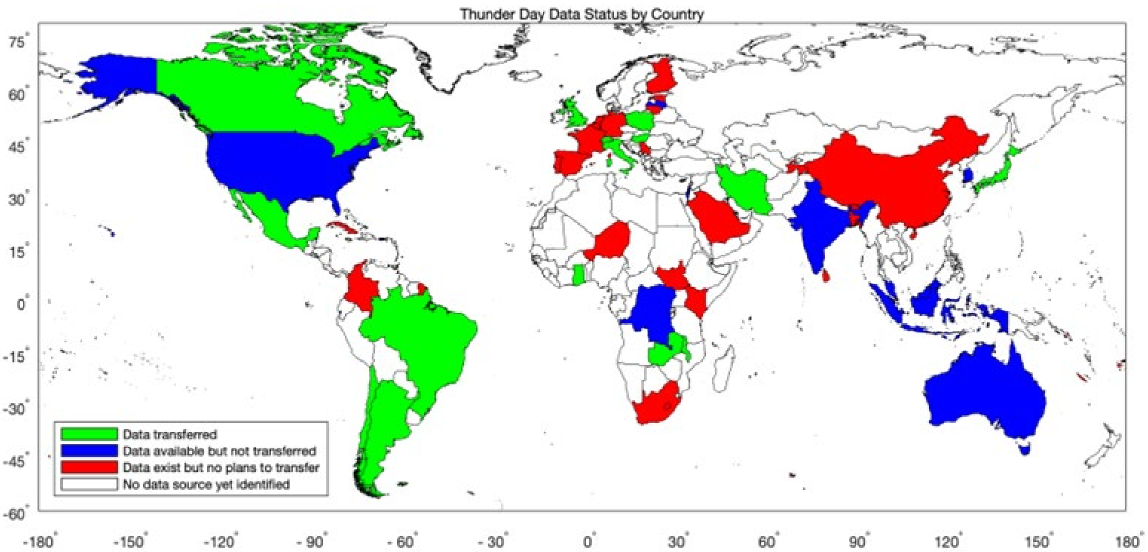


Fig. 7. Thunder Day records retrieved from NMHS through 2024 and provided to Copernicus for data stewardship.

6. Global Lightning via Schumann Resonances

Status: The Earth is surrounded by a continuously variable electromagnetic field known as Schumann resonances. The Earth-ionosphere cavity that bounds the resistive troposphere serves as a waveguide for these resonances that are continuously maintained by global lightning activity. One dominant waveguide mode present in the lower ELF (Extremely Low Frequency) frequency range (3-50 Hz) consists of a horizontal magnetic field and a vertical electric field. The fundamental waveguide mode near 8 Hz has a wavelength equal to the Earth's circumference.

Given the evidence that lightning activity is responsive to both thermodynamic and aerosol effects (Williams, 2020; Fullekrug et al. 2022), the access to global lightning via Schumann resonances provides a natural framework for monitoring global climate change (Williams, 1992; Price, 2000; Williams, 2020; Fullekrug et al., 2022). Two distinct manifestations of SR are accessible in either the electric or the magnetic field measurements: (1) the "background" SR consisting of the superposition of overlapped pulses of individual lightning strokes from global convective scale thunderstorms, ad (2) the "transient" SR consisting of individual excitations of the Earth-ionosphere cavity by intense mesoscale lightning flashes (in mesoscale convective systems) whose ELF amplitudes can be ten times greater than the background amplitude. The signal-to-noise ratio for these exceptional lightning flashes (with the background SR the noise floor) is sufficiently large to enable their geolocation on the basis of single-station ELF measurements (Kemp and Jones, 1971; Price et al., 2004), and global maps have been prepared (Hobara et al, 2006).

Simultaneous multi-station SR measurements can be used (via geophysical inversion methods) if made available by the data owners to infer the global lightning activity with a source strength not in strokes or flashes per second, but in units of coulomb^{2}km^2/sec (Heckman et al., 1998; Williams and Mareev, 2014; Pracser et al., 2019). Every lightning stroke contributes to this integrated measure because all thunderstorm discharges involve a vertical (i.e., gravity-aligned) component. Roughly 25-30 ELF stations are now in operation worldwide, in Antarctica, Argentina, Canada, Cape Verde, China, Greenland, Hungary, India, Israel, Japan, Lithuania, Mexico, New Zealand, Poland, Russia, Saudi Arabia, Scotland, Spain, Spitzbergen, Sweden, Tahiti, Ukraine and the United States. One hopes that these many stations can eventually be networked so that all observations may be processed simultaneously.

A valuable shortcut to the multi-station inversion methods discussed above was discovered and verified during a 3-month visit to Hungary late last year to work with the Schumann resonance group in Sopron. This shortcut amounts to a new capability to measure the AC global circuit from a single ELF station, so long as the station is at polar latitudes and is equipped with an orthogonal pair of induction coils. Only two of the many stations considered above are in the polar region. They are Hornsund (in the Arctic and operated by Poland) and Maitri (in the Antarctic and operated by India). The intercomparison of time series records at the fundamental Schumann frequency of 8 Hz from these two stations separated by more than 15 Mm show three-chimney lightning activity every day and a highly correlated behavior (cc=0.94), demonstrating globally representative behavior at each station.

How is this global representativeness achieved? The three major lightning "chimneys" are fortuitously separated by 90 degrees in longitude. One induction coil in the polar region situated on, and perpendicular to, the meridian for Africa will record the African lightning (with the exclusion of the other chimney sources), and an orthogonal coil at the same location will record the SE Asia/Maritime Continent early in the UT day (8 UT) and the American lightning late in the UT day (20 UT), and with only modest overlap due to the rough 12-hour separation. Since the three near-equatorial lightning sources are all roughly 90 degrees from the polar receiver, the non-linear distance dependence in the normal mode equations drops out, and the calibrated magnetic intensity is directly translatable to the respective chimney source strength in absolute units (coul^{2}km^2/sec). Exact 90-degree separation is not necessary because the magnetic intensity at 8 Hz is flat with distance for a source-receiver separation of 90 degrees (10 Mm).

7. Two-station Measurements of the Ionospheric Potential with GRUAN

Status: The ionospheric potential is the voltage difference between the conductive Earth and the conductive upper atmosphere. Begun pre-COVID, the prototype balloon-borne E-field instrument built by Quasar was ready for field testing with collaborators in August 2024. Tests with tethered balloon and ultimately with free balloon sounding are planned if things work well. If successful, E. Williams and collaborators will go to the two GRUAN sites on islands (Graciosa in Atlantic and southern Island of New Zealand, Lauder site, in Pacific) to train people there to make simultaneous soundings with the new equipment.

A second collaboration with electrometer experts at Analog Devices Inc is also underway. The plans are to build an inexpensive electrometer circuit for making E-field soundings (a voltage measurement rather than the Quasar E-field measurement). This method depends on polonium probes. This method was forbidden at Graciosa but has been allowed in New Zealand, and so we are pushing through to have comparative measurements eventually.

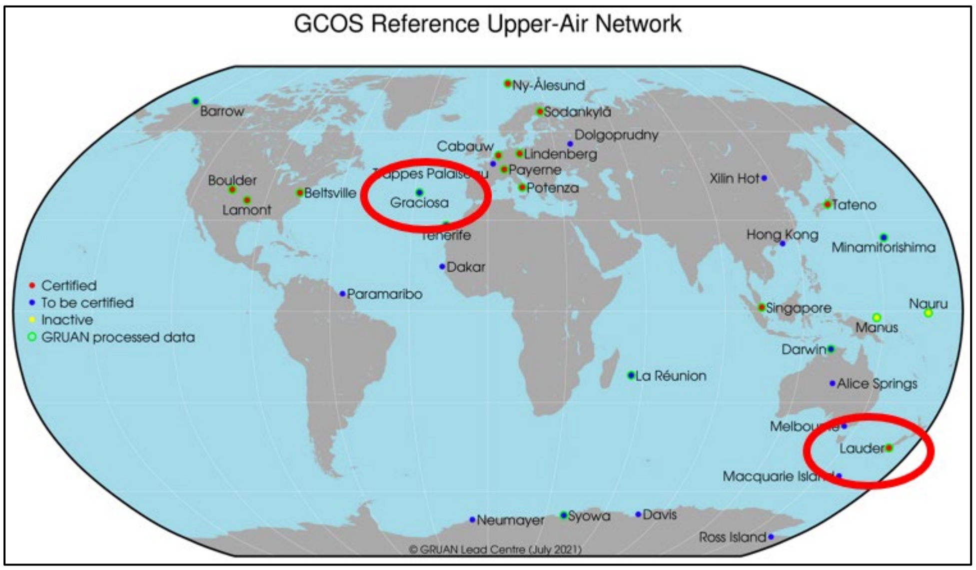


Fig. 8. GCOS GRUAN Upper Air Reference Network with Ionospheric Potential sites encircled in red.

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