Planning of LMA campaigns in Africa in the context of the LI Cal/Val activities

Final report

Contract EUM/CO/20/4600002481/BV

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Executive Summary

In support of Meteosat Third Generation (MTG) Lightning Imager (LI) cal/val activities, several scenarios of Lightning Mapping Array (LMA)-based campaigns in Africa have been investigated. First a literature review of past LMA-based campaigns in support of space-based optical lightning sensor validation, combined to a specific survey have provided the actual requirements of the campaigns, the issues faced during the campaigns and the lessons learned for pre- and post-campaign activities and the operations during the campaign. However this evaluation has some significant limits as one should be very careful in drawing conclusions from field campaigns in American countries for a validation campaign in sub-Saharan Africa as local reality is very much different. Interaction with local hosts should help set up plans and mitigation for not only the site survey, but also the deployment, the operation, the security of the equipment and the team, and the dismantlement.

The analysis of the survey responses and of the bibliography reveals that the UT3/UPC (Université Toulouse 3 / Universitat Politècnica de Catalunya) Consortium has faced the same issues when operating their LMAs either in Colombia, Ebro Delta or in Corsica. The UT3 and UPC LMAs have successively demonstrated their capability to measure lightning activity on the stand alone from their bases and remotely. The observations of the two LMA networks have contributed to the International Space Station (ISS) Lightning Imaging Sensor (LIS), the ISS Atmosphere-Space Interactions Monitor (ASIM) and Geostationary Lightning Mapper (GLM) cal/val activities. UT3 and UPC are currently running their networks through national and European projects of more or less short duration. But there will be a need to define a Human Resources strategy for the years to come to keep current personal working on soft money, to get recruitment of new permanent staff, and to define as well a more general UT3-UPC project strategy at national, European and international levels in support to long term operations, including MTG-LI validation in Africa and in Europe.

A multiple-source storm climatology has been built based on 10-year EUMETSAT Spinning Enhanced Visible and InfraRed Imager (SEVIRI), 16-year NASA Tropical Rainfall Measuring Mission (TRMM) LIS and 6-month Vaisala Global Lightning Dataset 360 (GLD360) records. The climatology has been analyzed in terms of location and severity over the whole African continent through seasonal and diurnal cycles of the convection. Three regions – Kenya/Uganda/Lake Victoria, Côte d'Ivoire and South Africa - have then been investigated accordingly to EUMETSAT demand. Geographical distributions of the lightning activity and convection at different (decade, yearly, seasonal, monthly) temporal resolution have been documented. Properties of the lightning activity in terms of flash rate and flash density have also been investigated. For each of the three regions of interest, between three and four scenarios of LMA campaign have been proposed, each scenario corresponding to a specific regional coverage at either the same period of the year (Kenya/Uganda/Lake Victoria; South Africa) or at different times during the year (Côte d'Ivoire).

Interactions with Kenya, Côte d'Ivoire and South Africa National Weather Services (NWSs) help consolidate and at ranking these scenarios according to their feasibility, their scientific relevance and their benefits relative to MTG-LI validation. Based on the exchanges with the Kenya, Côte d'Ivoire and South Africa NWSs and on the main conclusions of the present study on the thunderstorm activity in Africa, the following scenarios are proposed from higher to lower validation/science interests: Scenario #1.2 for the region of Lake Victoria (*annual flash rate [mean annual flash rate] : 3.12-49.78 [24.72] flash/km^2/year; monthly flash rate [mean monthly flash rate] : 0.054-0.155 [0.107]* *flash/km^2/day*); Scenario #3.3 for the region of South Africa (*annual flash rate [mean annual flash rate] : 7.46-46.76 [19.03] flash/km^2/year; monthly flash rate [mean monthly flash rate] : 0.044-0.164 [0.104] flash/km^2/day*); and Scenario #2.1 for the region of Côte d'Ivoire (*annual flash rate [mean annual flash rate] : 0.50-43.44 [11.79] flash/km^2/year; monthly flash rate [mean monthly flash rate] : 0.007-0.141 [0.049] flash/km^2/day*). Note that Scenario #2.1 and Scenario #3.3 might provide observations that would help validate two different LI optical cameras (OC1 & OC2, and OC3 & OC4, respectively) because of possible overlaps of LMA and LI optical camera coverage areas.

The Consortium strongly recommends conducting a site survey with electromagnetic noise level measurements in the LMA Very High Frequency (VHF) band (60-66 MHz) at all potential regions of interest, prior to any decision on the actual location of the LMA-based campaign. Staff of the host institutes could be trained to conduct such field activities, but their travel and subsistence expenses should be covered by EUMETSAT. Note that multiple campaigns could be conducted over several years at the different regions identified in the present study.

It is planned to run the LMA network on a standalone operation (power delivered by solar panels and batteries). There is also the need for efficient mobile phone coverage for remote monitoring of all LMA stations. Between 10 and 12 LMA stations will be deployed, meaning that 10 to 12 sites + 6 backup sites about ~20-30 km distant from each other should be identified and surveyed. **All LMA stations have to be deployed in the same country to avoid border crossing**. The LMA stations must be deployed in quiet electromagnetic areas, so site surveys (electromagnetic noise level, layout) will have to be conducted prior deployment at least 1 year and, for a second time, a few weeks before the actual deployment for verification. All LMA stations should see around at 360° with ideally no obstacles at close range. LMA stations should be deployed in accessible, safe and secured areas (away from floods; thieves). The visit of all stations should be conducted every week for data recovery and maintenance. Local storage, technical and office (with internet) rooms will be needed. Obviously, a referent of the host Institute will have to work closely with the LMA team, to locally keep contact with land owners and to handle paper works and issues with local authority. Finally there is definitively the need of local support for deployment, maintenance (with technical and science training), dismantlement, and logistics in general (including drivers).

It is important to associate well in advance, before the field deployment and the 1st visit, the team of the host Institute through a common training and science plan to contribute to the science and technical objectives of the MTG-LI validation campaign. Such interactions should first rely on pre-campaign exchanges between staffs and scientific studies conducted between all teams, and their costs should be included either in the budget of the campaign or through a dedicated Europe-Africa project focusing simultaneously on science, technology and operational applications. Local African universities should also be invited to join the campaign during its different phases.

Finally the objectives, requirements and milestones of the LMA-based field campaign should be clearly defined. This includes the definition of a science plan in collaboration with the African NWS host, the definition of an observational (and modeling) plan and the definition of a data processing plan. Associated risk analysis should be investigated in order to propose mitigation plans as uncertainties (extreme weather events, sanitary conditions, national and international issues) will be present during the periods before, during and after the campaign. The preparation of the campaign should start as soon as possible and one might need to contact other governmental and international organizations to ease the processes. Finally the campaign should be advertised to the scientific community for additional contribution on self funding and bigger scientific returns.

A preliminary campaign cost has been assessed that includes instrument preparation, shipping, missions (pre-campaign and campaign related), running costs, spares of instrument sub-systems, data processing and first data analysis, and salary of European and African teams. This cost is not given in this report.

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1. Context

Optical lightning detection from space has been successively demonstrated with several past missions like OTD (Optical Transient Detector) and LIS (Lightning Imaging Sensor) on TRMM (Tropical Rainfall Measuring Mission) (e.g. Boccippio et al., 2000; Christian et al., 2003, Rudlosky et al., 2014) and more recently with LIS on the International Space Station (Blakeslee et al., 2016) and GLMs (Geostationary Lightning Mappers) (Goodman et al., 2013). Starting 2023, the European Meteosat Third Generation (MTG) mission will operate the Lightning Imager (LI) from geostationary orbit. LI is a narrow-band camera designed to capture the optical signal radiated by lightning flashes at 777.4 nm at 1000 frames per second. LI instrument will cover Europe, the Mediterranean Sea, Africa, the Atlantic Ocean and part of South America.

Fig.-1.1 shows the seasonal global distribution of the lightning activity as derived from low orbit LIS and OTD observations (Christian et al., 2003). Lightning activity occurs all year long in continental Africa with, as expected, a latitudinal motion according to the seasons. Africa presents most of Earth's lightning hotspots (Albrecht et al, 2016) with the highest flash rate density. Over the EUMETSAT member countries, the lightning activity is mainly over land during summer and over the Mediterranean Sea during winter. Africa definitively appears as a region of interest for the validation of MTG-LI all year round.

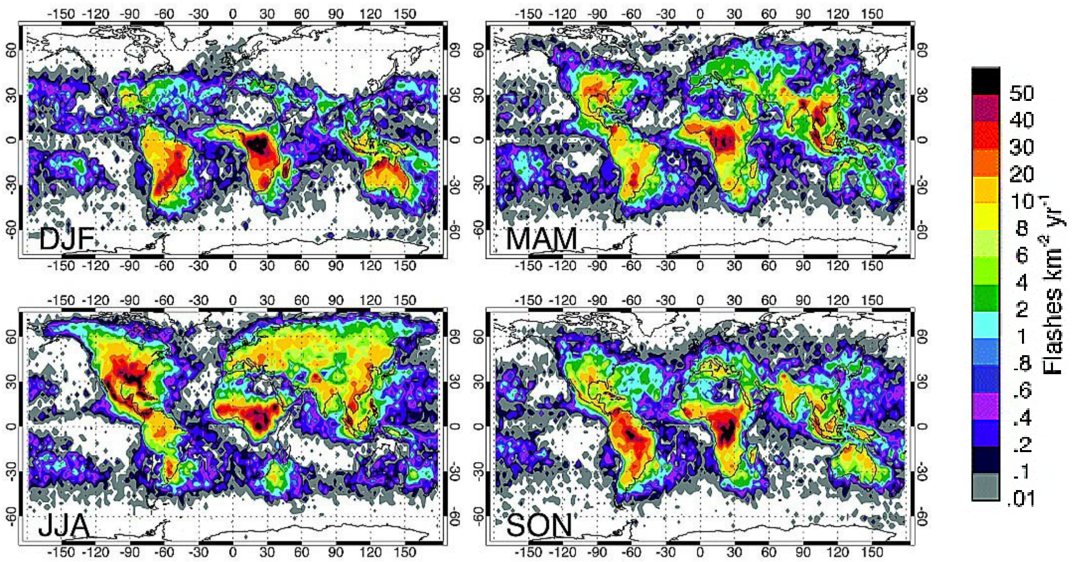

Fig.-1.1. Seasonal lightning distribution as derived from LIS and OTD optical records (Christian et al., 2003).

Defer (2010) provided a first verification and validation strategy for MTG-LI where Lightning Mapping Arrays (LMAs) are among the instrumentation proposed for such cal/val activities. LMAs usually map in 3D the VHF radiation emitted by lightning flashes within a range of a few hundred kilometers (Rison et al., 1999) offering a unique temporal and spatial description of the development and the extension of flashes at flash and storm scales. LMAs have been used recently in different GLM cal/val activities (Zhang and Cummins, 2020; Rutledge et al., 2020) and during inter-comparison with ISS-LIS (e.g. Montanyà et al., 2019; Erdmann et al.; 2020; van der Velde et al., 2020).

2. Description of the Work

The study aims at proposing scenarios of LMA-based LI validation campaigns in Africa. Four main items have to be addressed:

1. Which are the dedicated LMA campaigns run or being run providing data for comparisons against space-borne lightning optical imagers? Which are their key characteristics and results?
2. What type of dedicated campaign(s), with intellectual/human resources needed, could be performed by relocating the European LMA networks, as we know them today?
3. What are the best sites over African territory to run a dedicated LMA campaign? What is the lightning activity in such sites?
4. What are the possible examples of dedicated campaigns that EUMETSAT could consider to run after the launch of LI?

3. Activities

The activities are spread along 4 technical Work Packages (WPs) and a fifth one dealing with the management of the study (Fig.-3.1).

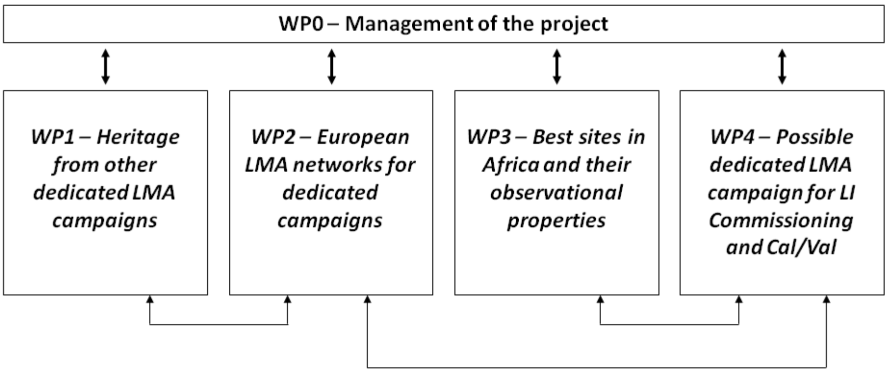

Fig.-3.1. Work breakdown structure

3.1 Work Package WP0 – Management of the project.

Several Consortium meetings have been organized along the study to discuss results, work share and way forward. Seven deliverables (KoM presentation, MR-1 to 8, PM-1 presentation, MTR report, MTR presentation, PM-2 presentation, FR report and PDC) have been delivered to EUMETSAT. The 1st Progress Meeting (PM-1) was held online during the 11th LIMAG meeting on 09 Feb 2021. The 2nd Progress Meeting (PM-1) was held online on 28 April 2021 while the online Mid Term Review (MTR) occurred on 10 March 2021. The final presentation was organized on 09 July 2021. The project has been run according to the schedule despite the sanitary crisis experienced during the entire duration of the contract.

3.2 WP1 – Heritage from other dedicated LMA campaigns.

Two main activities have been conducted in WP1. The first one relies on a literature review on the LMA-based field campaigns that were conducted in support of LIS and GLM cal/val activities. This literature review was extended to scientific contributions that have used LMA records to exploit and then evaluate LIS and/or GLM data. The second activity has designed the content of a survey that has been sent out to the LMA community that has been involved in worldwide field deployment and to scientific teams that have been involved in African campaigns. The different survey items are given in the Annex A. The survey was required as what can be found in the literature mainly provides scientific results but very little information on the issues faced during the field campaigns and on the lessons learned.

3.2.1 Literature review

The literature review mainly explored scientific articles related to field campaigns that used LMA networks to contribute to LIS or/and GLM cal/val activities. The following campaigns have been identified: CHUVA-GLM, GOES-R Post Launch Test airborne science field campaign, RELAMPAGO, and ASIM Colombia. Note also that the investigation has been extended to opportunity comparisons between LIS/GLM and LMA records.

The synthesis of what has been found in the literature is given in a suite of tables in the following (see Table 3.2.1.1 to Table 3.2.1.4 in the following pages). Different topics have been extracted from the literature including among others, a short description of the campaign with its objectives, the main results of the campaign, details on the LMA deployment and operation, the problems faced during the campaign. A list of references (publications, web pages) is also given.

In addition a list of field campaigns is given in Table 3.2.1.5 where LMA networks have been operated. Principal Investigators and LMA operators could then be contacted to provide additional advice in case the information found in the literature and collected through the survey does not appear sufficient.

Table 3.2.1.1. The CHUVA campaign.

Acronym	**CHUVA-Vale do Paraíba Field Campaign**
Full name	Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud-Resolving Modeling and to the Global Precipitation Measurement (GPM)
Location	São José dos Campos City, São Paulo State, Brazil.
Period	01 November 2011 to 31 March 2012.
PI (LMA)	Steve Goodman & Richard Blakeslee. Carlos Morales and Rachel Albrecht.
Funding	NASA.
Amount	Universidade de São Paulo (USP) got 15000 EUR (these are without overheads.....). No money was paid for LINET, ENTLN, Vaisala.
Consortium	NASA, University of São Paulo.
Short description	The CHUVA project was composed of six field campaigns throughout Brazil, with the objective of describing and understanding the cloud processes responsible for precipitation formation in the main precipitating regimes in Brazil (Mattos et al., 2016).
Objectives	• Lightning proxy dataset for the NOAA Geostationary Operational Environmental Satellite (GOES)-R program (Machado et al., 2014). • Evaluation of LIS (TRMM) (Blakeslee et al., 2013).
LMA information	• 10 stations first and later 12 stations. • Real time data. • Base lines: 15-30 km. • Network diameter: 60 km. • Frequency: 11 stations at channel 8 (180-186 MHz) and one station at channel 10 (192-198 MHz). <u>Site survey:</u> C. Morales and R. Albrecht conducted a site survey 2 months before with a TV channel analyzer and with a TV to look for 'pirates'. <u>Installation:</u> Jeff Bailey and Scott Rudlosky and one technician from USP. <u>Operation</u>: Morales' team (3 hired plus C. Morales and R. Albrecht). Stations had internet connection. Real time data. Visit once per week to do maintenance and data collection.
Other systems	• LINET, ENTLN, Rindat, and Vaisala TLS VHF interferometers. • High speed camera.
LMA use	• LMA and TRMM-LIS record comparison. • Nowcasting: lightning jump.
Problems	• Significant TV channel 9 noise. • Other noise only produces small contributions. • Real lightning dominates the noise. • Noise was filtered based on a certain region (TV tower).
Significant results	LMA performance and comparison with LIS by Blakeslee et al. (2013): • Some LIS events not detected. Attributed to reflections by nearby non-electrified clouds or views from the edge of the cloud. • Majority of flashes detected. • LIS do not detect all flashes. • Some singletons correlate with LIS events.
References:	Albrecht et al. (2015) Evaluating lightning detection signatures at different technologies: A contribution to GOES-R and MTG; https://pdfs.semanticscholar.org/a2c8/e9bd3451f4d70c38134cc991ce696c2cba90.pdf Bailey et al. (2014), Sao Paulo Lightning Mapping Array (SP-LMA): Network Assessment and Analyses for Intercomparison Studies and GOES-R Proxy Activities, ICAE 2014 Blakeslee et al. (2013) http://chuvaproject.cptec.inpe.br/portal/workshop/apresentacoes/10/6-01_CHUVAWorkshopSPLMA_RJB_V3.pdf Blakeslee et al. (2013) http://cics.umd.edu/~rachela/Memorial/DOC/DOC_20.3.58-POSTER.pdf Höller et al. (2013), Ground-based and space-borne lightning observations during CHUVA,

	CHUVA Intl. Workshop 2013, Sao Paulo, Brazil, 2013 Machado et al. (2014); https://journals.ametsoc.org/view/journals/bams/95/9/bams-d-13-00084.1.xml Albrecht et al. (2014) ICAE: Using Lightning Mapping Array to evaluate the lightning detection signatures at different technologies Mattos et al. (2016) https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JD025142 Inpe: http://chuvaproject.cptec.inpe.br/soschuva/

Table 3.2.1.2. The RELAMPAGO campaign.

Acronym	**RELAMPAGO**
Full name	Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations
Location	Cordoba province (Argentina).
Period	20181024 – 20190430 (valid operation during 163 day).
PI (LMA)	T. Lang (NASA). NSF ref. 1661785 funding: L. Carey (UAH).
Funding	Primarily funded by GOES-R, deployed by NASA MSFC & partners. Supported NSF/DOE/NASA/NOAA. Argentina/Brazil RELAMPAGO-CACTI field campaign. National Science Foundation (NSF) Award reference: 1661785.
Amount	$579,822.00 (NSF ref. 1661785 funding).
Consortium	NSF, DOE, NOAA, NASA, SMN, MINCyT, INPE, FAPESP.
Short description	RELAMPAGO was a National Science Foundation (NSF) field campaign to understand intense and severe convection in central Argentina, near the Sierras de Cordoba mountain range. In order to address RELAMPAGO science goals, as well as to assist with ground validation of the Geostationary Lightning Mapper (GLM) instrument on the GOES-16/17 satellites, NASA Marshall Space Flight Center (MSFC) installed an 11-station Lightning Mapping Array (LMA) in this region.
Objectives	• The RELAMPAGO campaign aimed at characterizing the atmospheric conditions and terrain effects that facilitate the initiation and growth of intense weather systems in this region of South America. • To assist with ground validation of the Geostationary Lightning Mapper (GLM) instrument.
LMA information	• 11 stations. • Base lines 10-15 km, (>60 km radius). • LMA solar with 3G communications. • Installed in remote areas. • Operating frequency: Channel 3. Site survey: conducted about 1 year before the campaign to identify sites and conduct noise level measurements. Installation: 6 persons involved in the installation, 3 for the dismantlement. Operation: stations visited once every few weeks. LMA runs for six months. Monitoring of the stations remotely.
Other systems	• WWLLN.
LMA use	• LMA and GLM record comparison for GLM performance assessment.
Problems	• Radio frequency interference in one site meant they had to move the station. • Problem with PLCC electronics (LMA board). • Problems with GPS cable. • Power problems. • Elevated noise >-70 dBm. • Insects. • Not very solid mechanics, they used PVC poles. Wind damages. • As a result they had fluctuations of the number of available stations, several days with <7 stations. • Although the fluctuations data was good for 100 km range (7-8 stations) and extending to 150 km for 10-11 stations.

Significant results	https://goes-r.nsstc.nasa.gov/home/sites/default/files/2020-09/200_glm_lang.pdf:
	• For 71 case days:
	  • GLM DE 71% (day), 84 % (night).
	  • Despite favorable bulk statistics, RELAMPAGO LMA provides significant evidence that GLM detection efficiency degrades in intense, high-flash-rate convection, as well as

	anomalous storms. • Allowing 1 GLM flash to correspond to multiple LMA flashes. ***Lang et al. (2020, J. Atmos. Oceanic Technol):*** • Comparisons with GLM on two days: • GLM most successfully detected larger flashes (i.e., more than 100 VHF sources), with detection efficiency (DE) up to 90%. • GLM DE was reduced for flashes that were smaller or that occurred lower in the cloud (e.g., near 6-km altitude). GLM DE also was reduced during a period of overshooting tops electrical discharges. • Overall, GLM DE was a strong function of thunderstorm evolution and the dominant characteristics of the lightning it produced.
References:	T. Lang The RELAMPAGO Lightning Mapping Array: Deployment, quality control, and data products https://ghrc.nsstc.nasa.gov/pub/fieldCampaigns/relampago/lma/doc/RELAMP_LMA_DataPresentation.pdf https://ghrc.nsstc.nasa.gov/pub/fieldCampaigns/relampago/lma/doc/relampagolma_dataset.pdf NSF: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1661785&HistoricalAwards=false Lang, T. J., and Coauthors, The RELAMPAGO Lightning Mapping Array: Overview and initial comparison to the Geostationary Lightning Mapper. J. Atmos. Oceanic Technol., doi: https://doi.org/10.1175/JTECH-D-20-0005.1. Peterson, M. J., Lang, T. J., Bruning, E. C., Albrecht, R., Blakeslee, R. J., Lyons, W. A., et al. (2020). New WMO Certified Megaflash Lightning Extremes for Flash Distance (709 km) and Duration (16.73 seconds) recorded from Space. Geophysical Research Letters, 47, e2020GL088888. https://doi.org/10.1029/2020GL088888 https://goes-r.nsstc.nasa.gov/home/sites/default/files/2020-09/200_glm_lang.pdf

Table 3.2.1.3. The GOES-R PLT campaign.

Acronym	**GOES-R PLT campaign**
Full name	GOES-R Post Launch Test (PLT) campaign
Location	Multiple (limited-range) areas covered by permanent LMA networks within the US ([N: 43.573, W: -124.625, E: -72.202, S: 26.449]).
Period	21/03/2017-17/05/2017 (duration of 9 weeks).
PI (LMA)	Colorado LMA; Washington D.C. LMA; Kennedy Space Center LMA; North Alabama LMA; Oklahoma LMA; Southern Ontario LMA; West Texas LMA.
Funding	NASA; NOAA.
Amount	Not known.
Consortium	NASA; NOAA, LMA owners/operators.
Short description	Collaborative project to validate the Advanced Baseline Imager (ABI) and Geostationary Lightning Mapper (GLM) instruments aboard the GOES-R, now GOES-16, satellite. The campaign consisted of two phases: the first centered on the U.S. west coast, providing tests primarily for the ABI instrument, and the second focused on the central and eastern U.S. with tests primarily for the GLM instrument. Airborne measurements were taken using NASA's ER-2 aircraft, equipped with spectrometer, radar, lidar, radiometer, and other atmospheric observation instruments to assist with ABI and GLM validation. This campaign provided a blueprint for the operation of future GOES validation projects.
Objectives	The goal of the campaign was to provide a collection of coincident airborne, satellite, ground based, and near surface measurements of surface weather phenomena to test, validate, and improve the accuracy of GOES-R ABI and GLM measurements. The target phenomena for validation observations included land and ocean surfaces, active wildfires, and thunderstorms. The primary objectives of GOES-R PLT field campaign included: • Provide high altitude validation of spectral radiance measurements for all ABI spectral bands • Provide surface and atmospheric geophysical measurements for validation products • Validate GLM lightning flash detection efficiency over land and ocean • Validate the location and time accuracy of GLM flash detection • Focused on validating the 70% flash DE and 5 % false alarm rate.
LMA information	Existing LMA networks: • Washington D.C. LMA • Southern Ontario LMA • Oklahoma LMA • North Alabama LMA • Kennedy Space Center LMA • West Texas LMA • Colorado LMA
Other systems	• Aircraft NASA's ER-2 (105.1 mission flight hours) with Fly's Eye GLM simulator (FEGS) • ISS-LIS
LMA use	• Comparison of FEGS, GLM and LMA records to assess GLM performances.
Problems	• Not known.
Significant results	Over 39.5 hours of airborne lightning observations were collected, including day and night observations of low and high flash rate storms in multiple regions. Samples on the order of 1000 flashes.
References:	https://ghrc.nsstc.nasa.gov/home/micro-articles/goes-r-post-launch-test-plt Rudlosky, S. D., Goodman, S. J., Koshak, W. J., Blakeslee, R. J., Buechler, D. E., Mach, D. M., & Bateman, M. (2017). Characterizing the GOES-R (GOES-16) Geostationary Lightning Mapper (GLM) on-orbit performance. 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). doi:10.1109/igarss.2017.8126949

Table 3.2.1.4. COLOMBIA ASIM SITE.

Acronym	**COLOMBIA ASIM SITE**
Full name	COLOMBIA ASIM validation
Location	Santa Marta and Barrancabermeja
Period	2020/15/06 to 2022.
PI (LMA)	J. Montanyà, Jesús Alberto López (UPC).
Funding	Ministry of Science and Innovation (Spain).
Amount	Travel: 24000 EUR. Salary (8 years) of non permanent person: 192000 EUR. Communications, maintenance, hardware: 24000 EUR. Average: 30000 EUR/year. This includes the minimum costs (e.g. no cost from other UPC members). Overheads not included.
Consortium	UPC, Universidad de Magdalena, Universidad Nacional, Universidad Industrial de Santander, Keraunos, Xagen
Short description	The UPC group provides ground support to ASIM. To do that lightning detection and optical observations were deployed in Spain and Colombia. Colombia was selected because the high lightning activity increases the chances of simultaneous observations.
Objectives	To provide 3D mapping of lightning flashes to ASIM detections. The evaluation of GLM and ISS/LIS is not a primary objective.
LMA information	• 8 stations. • Base lines 6-24 km (55 km network diameter). • 3G communications. • Installed in universities and in oil fields. • Operating frequency: Channel 3. • Site survey: using LMA stations just before installing. In Barrancabermeja, site survey with TV receiver and spectrum analyzer. • Installation: One from UPC and local support. • Operation: Remotely sensor management and periodic data recovery. • Noise level: - 65 dBZ (some -50 dBm but some up to -70 dBm). • Average 6 to 7 sensors from 8 are available. • Detection area diameter of 100 km.
Other systems	• LINET.
LMA use	• Science related to ASIM optical observations and lightning.
Problems	• GPS cable that caused GPS damage. • LMA operating system corrupted due to power failures (only few times because power mains have good quality at oil fields). • In one station a bad GPS location. • Restrictions to access to the stations (oil fields).

Significant results	***Portal (2020):***
	• Evaluation of GLM:
	  • It was found that some GLM flashes had multiple LMA flashes (this did not happen with ISS-LIS).
	  • Flash DE higher than 80 %
	  • Flash DE decays <60 % when flashes do not reach cloud altitudes higher than 50% of the cloud height.
	Montanyà et al. (2021):
	• GLM is able to track leaders involving high currents (return strokes, continuing currents, recoil)
	Van der Velde et al. (2020)
	• GLM detection rate of 14 % of the flash duration observed by ASIM.
	• GLM detected luminosity when the energy was >332 J determined by ASIM photometers.

References:	López J. A., J. Montanyà, O. A. van der Velde, N. Pineda, A. Salvador, D. Romero, D. Aranguren and J. Taborda (2019), Charge structure of two tropical thunderstorms in

	Colombia, Journal of Geophysical Research: Atmospheres, doi.org/10.1029/2018JD029188 van der Velde, O. A., Montanyà, J., Neubert, T., Chanrion, O., Østgaard, N., Goodman, S., et al. (2020). Comparison of high-speed optical observations of a lightning flash from space and the ground. *Earth and* Space Science, 7, e2020EA001249. https://doi.org/10.1029/2020EA001249 Montanyà et al. (expected early 2021), A simultaneous observation of lightning by ASIM, 1 Colombia-Lightning Mapping Array, GLM and ISS-LIS, submitted to JGR-Atmospheres. N. Partal (2020), Tools for validation of the Lightning Imager sensor on the 3rd generation of the METEOSAT weather satellite, UPC Aeronautics MSc. Thesis.

Table 3.2.1.5. Other field campaigns with LMA deployment.

Campaign	Year	Operator	Objective	LMA location	LMA stations	Other
MCS Electrification and Polarimetric Radar Studies (MeaPRS)	1998	NMT	Mesoscale Convective Systems	NW of Oklahoma CIty	10 in 60 km	
Severe Thunderstorm Electrification and Precipitation Study (STEPS)	2000	NMT	Inverted polarity thunderstorms	W Kansas	13 in 80 km	Lang et al. 2004 https://doi.org/10.1175/BAMS-85-8-1107
Thunderstorm Electrification and Lightning Experiment (TELEX)	2003 2004	NSSL NMT	Inverted Polarity, MCS stratiform region	W/SW of Oklahoma City	10-11	MacGorman et al. 2008 https://doi.org/10.1175/2007BAMS2352.1
Deep Convective Clouds and Chemistry Project (DC3)	2012	CSU NSSL TTU GHRC	Interactions storm, chemicals, stratosphere	N Colorado C+SW Oklah. W Texas N Alabama	15 in 100 km 11+7 11 11+2	Barth et al 2015 https://doi.org/10.1175/BAMS-D-13-00290.1
Projet en Electricité Atmosphérique pour la Campagne HyMeX (PEACH)	2012	LA/CNRS NMT	Precipitation-lightning relation, lightning physics, modeling, climatology	NW of Nimes, France	12	Defer et al, 2015 https://doi.org/10.5194/amt-8-649-2015

Table 3.2.1.5. Other field campaigns with LMA deployment (continued).

Campaign	Year	Operator	Objective	LMA location	LMA stations	Other
Kansas Wind-farm 2013 Field Program	2013	UA NMT	Wind turbine corona and lightning discharges	Kansas, 39.4N, -79.7E	10 in 25 km	Cummins et al. https://www.vaisala.com/sites/default/files/documents/Cummins%20et%20al-Overview%20of%20the%20Kansas%20Windfarm2012-2013-ILDC-ILMC.pdf https://doi.org/10.1049/ic.2015.0195
Upward Lightning Triggering Study (UPLIGHTS)	2014	NMT	Upward lightning from tall objects	Rapid City, South Dakota	10	Schumann et al. 20 https://doi.org/10.1038/s41598-019-46122-x
NMT volcano LMA campaigns	2006 2009 2010 2011 2014	NMT	Relating types of discharges and volcanic processes	Augustine, Redoubt, Alaska Chaiten, Chile Eyjafjallajokull, Iceland Sakurajima Japan	2 4 4 6 9	e.g. Behnke et al 2018 https://doi.org/10.1002/2017JD027990 Proposal by McNutt: https://www.usf.edu/arts-sciences/research-scholarship/proposal-tools/stephen-mcnutt-nsf-geo.pdf
Säntis Tower experiment	2017	UPC+Meteocat, EPFL	Analysis of upward lightning and meteorological conditions	Santis tower, Swiss Alps	6	Sunjerga et al. 2018 https://doi.org/10.1016/j.epsr.2019.106067
Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast (VORTEX-SE)	2016 2017	TTU	Tornado dynamics, relation lightning and severe weather	Extension of N Alabama LMA	3	
EXploiting new Atmospheric Electricity Data for Research and the Environment	2018	LA/CNRS	Storm observation and modeling, airborne campaign, lightning physics	Corsica	12	www.hymex.org/exaedre

Table 3.2.1.5. Other field campaigns with LMA deployment (continued).

Campaign	Year	Operator	Objective	LMA location	LMA stations	Other
NMT Broadband VHF Interferometer Field Campaign	2018 present	NMT	High energy emissions from lightning (TGF) and GLM comparisons using VHF broadband interferometers	Delta, Utah near a gamma-ray telescope array	-	Mark Stanley https://goes-r.nsstc.nasa.gov/home/sites/default/files/2019-09/Stanley_GLM19_INTF-GLM.pdf
Space-based Optical Lightning Detection (SOLID)	2015-2022	LA/CNRS	Lightning physics based on multiple lightning detection instruments (LMA, Meteorage, ISS-LIS, BLESKA, SDA-2)	Corsica	12	

3.2.2 Specific survey

A specific survey has been sent out to the scientific community who has been involved in LMA-based studies related to LIS and GLM performance assessments and/or LIS/GLM-LMA analysis. This survey aimed at collecting additional information not usually detailed in scientific publications. The survey form is given in Annex A.

Table 3.2.2.1 lists the recipients of the survey and the replies received by the community. Note that the survey was also sent to other research lightning groups that have been involved in several abroad field campaigns. In addition some specific teams used to conduct measurements in Africa have also been contacted. The replies received are summarized in Table 3.2.2.2.

Table 3.2.2.1. List of the recipients of the survey. Note that T. Lang provided two sets of answers, one for the RELAMPAGO campaign (R6), the second one (R7) for North Alabama Lightning Mapping Array (NALMA).

Name	***Institute***	***Expertise***	***Date of reply***
S. Rutledge	CSU (USA)	Storm, radar and lightning	18/02/21 (R1)
K. Cummins	University of Arizona (USA)	Lightning physics and detection	18/02/21 (R2)
D. Rodeheffer	LMA Technologies, LLC (USA)	LMA maker	19/02/21 (R3)
T. Lang	NASA (USA)	Storm, radar and lightning	01/03/21 (R6)
			01/03/21 (R7)
R. Albrecht C. Morales	USP (BR)	Storm and lightning	03/03/21 (R9)
SAETTA Team	UT3/LA (FR)	Lightning physics and detection	26/02/21 (R5)
Ebro LMA Team	UPC/LRG (SP)	Lightning physics and detection	26/02/21 (R8)
IPA Team	DLR (DE)	Lightning and radar	22/02/21 (R4)
LEETCHIE Team	LA (FR)	Pollution & emissions in Africa	Mid-March through two online meetings

Table 3.2.2.2. Synthesis of the survey replies.

Item	***Answers***
1. Team	R1: NMT in charge. Location: North Colorado, USA.
	R2: has not been directly involved in the LMA campaigns. Has studied GLM data for KSC launch support, TRMM-LIS data, GLM vs GLD360 vs KSCLMA. Principal Investigatot of 6-month LMA campaign in a wind farm in Kansas in 2013 (his answers to the survey is based on that experiment). He recommends: 1 overall field coordinator, 2-person installation teams (possibly more than 1 team), 1 person monitoring the sites while the installation team is still in the field. Location: Kansas and Florida, USA.
	R3: He is in charge of building, deploying and relocating LMA sensors. Typically 4 to 6 individuals are in the field for deployment and dismantlement. Small number of personnel in the field will lead to a longer deployment time. Most of the required on site maintenance occurs within the first month. Data retrieval might be unnecessary with

	good internet connections (50 Gbytes of allowed data per month). Need of hiring local staff if equipment has to be set up on a roof for example. Location: numerous regions in the USA.
	R4: no information provided. Location: Germany, Brazil, Australia, Benin.
	R5: The research group is made up of 8 people: 6 researchers and 2 technicians. Our LMA stations have been designed to be set up by two people, but for reasons of comfort, due to the problems of transporting particularly heavy or bulky items to the site (trunk, batteries, solar panels) doubling the installation team is recommended. During the campaign, the stations are autonomous. Whether or not to maintain a team of two people on site for maintenance operations will depend on the ease of access to the sites and the financial cost involved. One person is dedicated to the operational monitoring of the network: control of the dashboard of each station, control of the smooth running of real-time processing chains. One person is in charge of data processing. To reduce the execution time, having adequate digital resources to parallelize this task (a processor for a slice of 3 hours of data to process) is an asset. At least one person is responsible for quality control while the data analysis is done by scientists. Based on the experience gained during the past years, it is recommended to have maintenance personnel on site for rapid intervention (such as changing a broken antenna or a malfunctioning solar panel, etc.), having these tasks subcontracted locally would be a plus. Location: France.
	R6 (RELAMPAGO): 15 people were involved in total with 6 people were involved for LMA installation, 7 people were involved for LMA operation in the field, 2 involved for LMA operation at NASA premises, 3 persons involved for LMA dismantlement, 2 persons involved in data processing, 1 in the quality control, and 2 data analysis. Hired 3 additional personnel: 2 undergraduate students to assist with station preparations before shipping to Argentina, also brought in an undergraduate intern to assist with RELAMPAGO data processing. Otherwise, the projects used existing personnel. Location: Argentina.
	R7: no information provided. Location: Alabama, USA.
	R8: Colombia LMA team is composed of 4 members of the UPC including PhD students and postdoc plus two local persons for technical and maintenance support. Locations: Spain, Colombia.
	R9. About 10 people (10 for installation, 5 for the LMA operation in the field with 4 of them from local hosts; 2 involved in dismantlement, 2 in data processing, 4 in quality control, 6 in the data analysis including students). No personnel hired. Location: Brazil.
2. Sensors	R1: 17 stations.
	R2: 10 NMT sensors. He recommends: real-time command-and-control communications; slow frame-rate internet camera to monitor the site and local weather.
	R3: Most networks are composed of 10 to 15 sensors. 6 to 8 sensors would work on a smaller area but with little to no redundancy. Networks can use mixed sensors, however I recommend Rev4 and Rev5 LMA boards inside the RF tight enclosures for greater reliability, especially if the network is in a remote location. These sensors are more reliable and do not typically require as much on-site attention. If Rev3 boards are used, I would definitely recommend plenty of solar panels and batteries for remote sensors, as these boards are most reliable when they remain powered up and warm. If they power down in cold and/or humid areas, thermal and moisture failures can occur more often.
	R4: no information provided.
	R5: The network deployed in Corsica is the property of our laboratory. We currently have 12 stations. The 12 stations were purchased in 2013/2014 from New Mexico Tech. The 12 stations are operated on FPGA version v3. The 12 LMA stations are 7 years old

	R6: NASA owns the network of 11 sensors used in RELAMPAGO. The NASA team borrowed some LMA boards (Version 3 LMA board chips) from LMA Technologies due to board failures during RELAMPAGO. Stations about 10 years old.
	R7: NASA owns the NALMA network which operates 11 sensors. Stations about 10 years old.
	R8: Currently 8 stations. Initially 6 stations were taken from the Ebro LMA. Two additional sensors were installed in 2019.
	R9. 12 sensors owned by NASA Marshall Space Flight Center were operated (old version in cooler boxes; ~5-year old).
3. Before shipping and installation	R1: Driving around the Plains of North Colorado. Talked to landowners. Set up other stations at various remote CSU sites. One week for the pre-survey; several days for the survey.
	R2: Survey conducted by NMT before the campaign by first looking at potential sites and accompanied later by a noise survey and communication signal survey.
	R3: If solar powered sensors are deployed at ground level, site surveys are not normally required. Sites should be avoided that are near power transformers and buildings with networking equipment within. If ground level sites can be found that are 100 meters away from structures and transformers, and those sensors can be powered via solar and connected to the internet via cellular, they are almost certain to work well. If the sites are picked with these criteria in mind, it should be sufficient to have a couple of extra sites ready in the event that one of them turns out to be noisy. When that happens, solar powered sensors can be easily relocated to one of the extra sites. I f the above is not possible, it is usually best to have an RF tight sensor taken to the sites and deployed temporarily, using battery power. One of these sensors can be deployed using a small tripod for the antennas, and if the site is noisy, you will see that almost immediately by looking at the operational threshold level on the LMA sensor. If the site looks clean, but you wanted to be more certain, it would probably be sufficient to allow it to run at the location for 24 hours. You can then check the threshold levels over that time period in the log files. Any threshold under 3F is best, but anything under 68 should be operational.
	R4: no information provided.
	R5: So far 2 stations have been removed: one because of a 12 V / 220V converter operating at less than 5 meters, the second one because of vegetation masks limiting the photovoltaic production. With hindsight, a good site is: • a place far from human activities, for which a spectral analysis carried out on site does not show any particular emission in the 60-66 MHz band → RIGOL spectrum analyzer tools; • a place without masks for maximum photovoltaic production → Photovoltaic Geographical Information System (PVGIS) tools; • a place well covered by mobile phone networks → tools 2G / 3G / 4G network tester Sniper-graphyte SIRETTA; • an easily accessible place → IGN portal tools.
	R6: Approximately 1 year before campaign, we sent a technician to the field to work with 2 others in country to identify potential sites. Noise levels were tested at most potential sites using hand-carried key components of an LMA station. The survey took about a week. About 16 candidate sites among 20 sites identified were surveyed. No site truly rejected, but we only ended up using 11 sites.
	R7: no answer provided.
	R8: About one year before we verified that TV Ch3 was not used in the target area. Local help using spectrum analyzer and a TV receives were used to site survey only at the center of the network. Host sensor sites were arranged before basically from local contacts.
	R9: First, we contacted our National Telecommunications Agency and asked for the location and transmission information (frequency and power) of all VHF TV stations in the state of São Paulo. With this information, we mapped the possible unused channels around the

	Metropolitan Region of São Paulo. The unused channels were: 3, 6, 8 and 10. We decided to avoid the areas nearby the surrounding channels (-/+ 1 channel) TV antennas. Then, we started by surveying the most convenient sites for us: USP main campus (IAG - the LMA Server and C. Morales were hosted here), USP weather station (PCT) and USP east campus (ULE). From these locations, we identified potential sites with 15 to 20 km of distance and did a first preliminary site survey for the basic infrastructure. The potential sites were, in general, public institutions (e.g., municipal facilities, schools, universities, research institutions), two private universities and a private cemetery. A few places we knew someone that worked there, others we sent an email explaining the project and asked for a meeting, and others we simply knocked on their doors. We found that this in person encounter (meeting or knocking door) was essential to speed up the process. They were all excited to be able to help such an exciting research project, and most of the places we knocked on the door were immediately prone to get the instrument installed right away. At the site we considered several aspects from a list provided by Jeff Bailey/NASA. For example, we did use a small 14 inches VHF TV with a small antenna, to make sure that channels 3, 6, 8 and 10 were not used. In this basic process, we found that channels 3 and 6 are used by "pirate radio stations" (non-authorized stations). Pirate stations usually have low transmission power, so they were not "heard" in all sites by the TV, but the LMA did pick them in most of the sites inside São Paulo city. We defined on this first survey that channels 8 and 10 were the only candidates. A second and technical survey on the sites with suitable basic infrastructure was then conducted using a LMA station (the same we used in the deployment). Jeff Bailey/NASA provided us with a document with site testing checklist (see files "Portable_LMA_site_testing_checklist.doc" and "DC_checklist.pdf"). With an LMA station (box and antenna) we collected preliminary data from channels 8 and 10. For each channel survey, we changed the VHF filter by the appropriate channel. We collected data for at least one hour, preferably during different times of the day: morning, afternoon, evening, and overnight. During the data collection, we turned on a drill near the antenna and checked if the sensor could capture its noise and increase the trigger rate. We also collected data with the antenna unplugged to check for indoor noise. We started identifying the potential sites a year and a half before, but the actual 10 months 18 sites were surveyed, 6 rejected. We did not have problems with indoor noise for LMA, but for LINET (LF/VLF) we have a huge problem in Brazil with the actual sensor electrical power. Several industries do not use the appropriate convertors and they insert spurious frequencies in the power network.
4. Shipping	R1: not applicable in Colorado.
	R2: done by NMT.
	R3: If the structures and equipment (solar panels, batteries, etc.) are purchased locally, the sensor electronics can many times be carried as luggage with the persons deploying the network. This may not be allowed in some countries, depending on customs requirements. If the structures are being transported, as well as the electronics, it is best to have them shipped to a local receiver so that customs clearances are completed before the deployment team arrives. If one is unsure of customs requirements for the sensor electronics, he would recommend shipping ahead of time as well rather than risking confiscation from any luggage during the flight to the location. He uses a local freight company that is able to fill out and arrange customs paperwork for me ahead of time. Although there is some expense involved in this, there is nothing better than having all of the equipment shipped, having cleared customs, and awaiting his arrival, with nothing for him to worry about but his own personal luggage. To that end, he also recommends shipping the structures needed, so that all you need to purchase on site would be solar panels and batteries (if going solar), and in that case, he would also have them purchased and awaiting your arrival at the same location as the sensors. If not, weeks can be spent trying to find parts to cobble together a structure that may or may not be well built.

	If the project is of a temporary nature, many countries allow customs entry with minimal to no fees. If the network is to remain, the resale value should be used for the customs paperwork, not the value of the sensors when purchased (unless newly purchased sensors are to be used). This value can be significantly less and will save much in customs fees and taxes. If these taxes are required for temporary deployment as well, use a reasonable rental fee for the network over the time it will be deployed in calculating the taxes and fees, not the resale value of the equipment. Return shipping is not usually a problem when the equipment is returned to the country of origin or the country of original purchase, as customs fees do not typically apply. He recommends shipping the sensor electronics, antennas, cables, and structure (including the frame, battery, and electronics enclosures). The only items he would purchase on site would be the solar panels and batteries, if the sensors are to be powered via solar. Arrangement of the shipping (paperwork and scheduling) typically takes two or three weeks. The shipment itself typically takes two to five days via air freight and customs clearances can take another day or two.
	R4: no information provided.
	R5: The LMA stations have been shipped by road and boat with rented trucks and the vehicle of the laboratory. No paper forms to fill as the shipping was done within France. The duration of the shipping was two days. The team recommends using Ulysses CNRS services for network transport, to benefit from their expertise in import / export operations and to benefit from insurance during transport and throughout the entire campaign.
	R6: the LMA stations were shipped to the destination with UPS Air. There were customs brokers attached to the overall RELAMPAGO field campaign. They facilitated entry/exit for multiple instruments, not just the LMA. Fairly minimal custom fees, if any. Customs brokers were majority of the expense. Bringing in and out of the country was just a slow process. NASA self-insures its instruments. List of the equipment shipped: 11 full stations, including LMA boxes, antennas and other RF equipment, station frames, solar panels, and basic tools. Batteries were purchased in the country. Took about a month to arrive.
	R7: no answer provided.
	R8: Sensors were shipped as part of luggage. We did temporal export customs forms. We did not have any problems at the customs of the airport. From the experience in Cape Verde it was very important the role of the host institution to clear customs.
	R9: Sensors were air shipped under temporal export. No custom fees paid because of a US-Brazil agreement on science exchange. The shipping lasted less than 2 weeks (transit + customs clearance).
5. LMA sites	R1: public and private lands. 1 single lease ($900 per year). LMA run on solar and batteries. Communication by phone ($10k per year for CoLMA).
	R2: no information provided.
	R3: He recommends installation at ground level when possible. He has found that airports, farmers, ranchers, schools, and local governments tend to allow deployment of equipment, as well as have open property that is sometimes protected by fencing, etc., and in some cases, these entities enjoy cooperating with scientific projects. Solar power is recommended. These types of sensors are easily placed away from noise sources and easily moved when necessary. The only downside would be risk of theft in some local areas (usually solar panels and/or batteries). Cellular connections are the easiest to set up and maintain. They also tend to be very reliable. If using 3G or better, you will be able to fully utilize the sensor, meaning real-time data and full data sets can be transferred via the connection. 2G speeds can be used as well, however full data transfer may not keep up at all times, depending on the size of the data files. Wifi / ethernet can be used as well; however the weak point in these connections is usually the local network administration. He has found that routers get moved, unplugged, firewalls are installed, addresses changed, and all of these can happen without the local administrator remembering that your equipment is connected

	to the network as well. If ethernet is used, be aware that either the LMA antenna will need to be located far from the sensor, or you will need to use fiber to connect the LMA using fiber to ethernet adapters, as the Ethernet cabling is a source of interference for the LMA. A basic arrangement of the network should be first considered. He then uses Google Earth to find locations, the types of which were suggested earlier, which are in the areas he needs to place the sensors. It is then best to have either a local contact and/or yourself go to the locations to speak with the owner/manager of the location. Take photos of the equipment one plans to deploy and try to ask for a location that is not going to be problematic or a nuisance for the host. If one is going solar, this should be a bit simpler as the site one will want is usually at the edge of the property and out of the way. One needs to keep in mind that one would like to be able to drive up to the site. If it is possible, one can usually have the entire sensor assembled and loaded into a truck or trailer. Then one simply backs up to the site and unloads it. If deployments are planned this way, he has been able to deploy 12 sensors in three days using only one truck, himself, and one other person (and this was around a major metropolitan area where traffic was the most time consuming part of the deployment). If the sites are of the type mentioned before, fees are not usually required. In many cases, the hosts would like to see what the equipment does, so if you have a fully connected network, one can give the hosts the address of the realtime web pages. They usually enjoy watching the storms roll in knowing that they are helping to create that image. Some locations, such as airports, can have access security. However, if your visits are scheduled ahead of time, and extra hour of time is usually plenty.
	R4: no information provided.
	R5: 11 stations are deployed in public domain; one on private land. Each station is powered by two 80 Ah batteries under 12V. The batteries are recharged by the energy input of a 135 W solar panel. At the end of 7 years of network activity, we see that the solar contribution of a single solar panel does not offer enough power for winter months, a doubling of the solar panel surface is planned. 11 stations are equipped with mobile communications (4G router), the last station is in the blind zone. For this, a communication by satellite link was considered but abandoned because of the lack of available energy with a single solar panel. Contact with either the owner or the legal representative of the site. Usually a hosting agreement is put in place which stipulates the conditions of use and for all the restoration of the site to its initial state at the end of its operation. No financial transaction at any of the 12 sites. 5 stations are deployed in the mountains (altitude of 1338, 1706, 1294, 2001, 1800 meters) and 7 stations along the coast (altitude of 60, 92, 400, 875, 162 and 415 meters). North / South distribution imbalance because of the geometry of Corsica Island with a very strong impact of mountains on the calculation of locations of the VHF sources. A judicious choice of location of LMA stations is a key element in order to minimize the number of stations to be deployed.
	R6: the 11 LMA stations were deployed in both private and public areas. The LMA stations were standalone (solar only). Communications: 3G cell modems with 1 GB/month bandwidth. Used only for network status updates and occasional processing of a few minutes of data to ensure functionality. RELAMPAGO hosts were contacted through our partners. No fees charged by the station hosts. Some sites have more security/restrictions than others. These details were worked out for individual sites in advance. Some RELAMPAGO stations were placed in high elevation, and/or building rooftops. The RELAMPAGO network reflected compromises between distance, altitude, and logistical priorities.
	R7: NALMA is operated on a mix of solar power and commercial power. Communications: fast cell modems and some ethernet, with greater bandwidth that facilitates near real-time processing. NASA contacted NALMA hosts directly. NALMA network reflects compromises between distance, altitude, and logistical priorities.
	R8: First network was installed in Santa Marta (Caribbean coast of Colombia) we used host

	sites such as the University of Magdalena, hotels, private houses and traffic toll sites. Currently, in Barrancabermeja we use two university locations and the rest are owned by an oil company.
	R9: The LMA stations were installed in private properties or public areas, but public were prioritized. All LMA stations were powered on the grid with swap batteries for power failures. The communication went through wi-fi and ethernet (most stations). No fees paid to the LMA station hosts. Access was promptly released by identification at the gates. The stations were deployed in a very urbanized area. São Paulo is located in a plateau between two mountains, to the north and south. Sao Paulo Lightning Mapping Array (SPLMA) deployment was part of GLM Cal/Val activities planned in 2009. We started the survey in 2010 and by that time CHUVA Project was planning a field experiment (CHUVA-Vale do Paraíba) in the region and we decided to conduct the SPLMA GLM Cal/Val activities at the same time as CHUVA. Because of logistics, CHUVA-Vale XPOL radar was deployed in São José dos Campos. We decided to keep the LMA in São Paulo because the infrastructure (mainly internet) was better and we were far into the site's survey (there would not be time to do new surveys around the XPOL radar), and SPLMA covered the XPOL radar. We decided for a shorter baseline (15-20 km) to have better detection efficiency (DE) and location accuracy. However, that may not be the case. In one of the GLM Science Meetings, Bill Koshak showed several simulations with his Monte Carlo algorithm and found that closer baselines do not necessarily increase DE and/or LA. If I recall correctly, 20 to 30 km baselines were the optimum and stations in elevated areas can contribute to the LA in height.
6. Installation	R1: NMT installed the CoLMA.
	R2: no information provided.
	R3: For solar/cellular installations, drive up sites can be deployed in three hours if the equipment is assembled on site. If it is assembled ahead of time, you can deploy in less than an hour. For rooftop sites or similar, plan on about four or five hours per site, as you will have to carry the equipment to the location and assemble it afterwards. For AC powered units, the time required to deploy will depend greatly on how long it will take to run the VHF coax for the LMA sensor, as well as any ethernet, power cables, and/or GPS cable. These installations can easily take one or two days each, if complicated. Help carrying equipment may be required for rooftop or installations in areas to which one cannot drive. He suggests purchasing solar panels and batteries locally and perhaps the mast pipes and battery enclosures as well. If staged ahead of time, most problems can be avoided. When using cellular, he always has the sim cards inserted and makes sure the sensors connect to the network before driving to the deployment site. He also assembles as much of the structure as possible ahead of time. When using cooler boxes and connecting to local Ethernet connections, running the cables is always the biggest headache. The biggest unexpected and expensive cost is not planning for enough time. Extra nights at hotels and having to change air travel plans can happen easily if things go sideways. If properly chosen, the most common extra thing to install is fencing to protect from cattle, etc. If fencing is needed, t-posts and 8 foot cattle panels are quick and work well in the USA. If something similar is available locally, they are highly recommended as they can be deployed in about 30 minutes. If local theft is the issue, a rooftop site may be necessary. Padlocks and fences don't work well in an area where theft is typical. His solar structures are staked to the ground, and the weight of the batteries helps as well. In some cases (near airport runways), he was required to bolt the structure to a concrete pad using anchors. If a flash flood were to occur and the sensor is in moving water rather than standing water, only having the unit bolted down is likely to keep it in place. High spots are recommended for flooding as even the RF tight sensor is not completely watertight. After the water receded, it did come back online for several days, but eventually corrosion within the sensor caused it to fail.

	R4: no information provided.
	R5: the SAETTA team set up the stations with at least four persons together in the field to set up a station. The stations have been deployed since May 2014, i.e. 7 years ago. The stations operate in standalone mode (power : batteries + solar panels; communication : 4G). Concerning bills, no operating cost for energy except the regular renewal of the batteries (~5 years). The operating cost of communications includes 12 4G subscriptions with actual costs based on the volumes transmitted. The maximum expected cost is 75 € / month / station in Corsica. The structures of the SAETTA stations were designed in the laboratory; all the parts necessary for assembly have been shipped. Initially the structure was based on a system built from metal angles screwed together. This system turned out to be too sensitive to corrosion, not easy to dismantle; it has been replaced by a structure based on galvanized tubes (antenna mast) and assembled by flanges. Each station was installed successively because only one person from our team mastered the entire installation process. All the materials necessary for the installation were purchased before installation and delivered to the laboratory. But in the case of an operational deployment in Africa, the transport of batteries, for example, can prove to be extremely complicated and expensive so there is a crucial need to conduct a thorough analysis of what can be bought locally or not for logistical, operational and economical reasons. A station is set up in half a day, excluding the delivery of equipment on site. The atmospheric conditions present during the day of installation can adversely affect the maximum efficiency of the workers (for example installation in heavy rain or with a thunderstorm in the vicinity). The difficulty of access to 3 of the 12 SAETTA sites for the transport of heavy equipment (trunk, batteries) has required the use of a helicopter. Most of the stations have their site fenced, within a square of 4-m side, to prevent the intrusion of animals such as sheep or goats. The security of the equipment against theft or damage is ensured by placing the sensitive elements in a metal box, waterproof and tamper-proof. No specific lightning protection, the whole forming a conductive mass linked to the ground. In 7 years we have had two lightning strikes, without major consequences on the installation.
	R6: NASA contractor led the installation. The LMA network was deployed during 6 months and was run standalone. NASA pays all costs. Stations built prior to installation. RELAMPAGO in particular reused older stations. For RELAMPAGO we designed a new PVC-based structure too. Marine deep cycle batteries (2 per station) were purchased locally. i Average time required to install each station : 0.5-1 work day per station. Minor problems related to the installation: wind damage, insect infestations, vegetation growth. Rev 3 LMA boards had significant issues with chips needing to be replaced/reseated. Fencing was used to secure certain farm sites.
	R7: The LMA network is permanent. It runs on a mix of stations operated standalone or hooked to the power grid.
	R8: Installations were made at least by two persons. Always one from our research group (but Colombia native) and a second one. The second one was sometimes another research group member or a collaborator from local partners in Colombia. It is very important for the local contact to keep contacts with the hosts in order to access the stations regularly. We also hired a local electrician, in particular to access higher places such as roofs. In addition, a local driver must be hired in Colombia.
	R9: The team that installed the LMA network was composed of 10 persons. The LMA network was deployed for a period of almost 4 months. The LMA stations were hooked on the power grid, and a mixture of internet by cable, cell phone and radio was used for the communication. All sites had power and we used it for free. Most of the sites had wired internet. Just 2-3 we bought a cell phone modem or hired a local radio internet (project paid). The LMA stations were all built by Jeff Bailey at MSFC/NASA. The batteries were all bought in Brazil and a few occasional replacement items. We had two teams working simultaneously, but one deploying LMA stations and another deploying LINET stations.

	So, the LMA stations had to be set up successively. Batteries, coaxial and ethernet cables, different screws, screw drivers were locally bought. We completed the installation in one day at most of the sites. But that required more than regular business hours. The main challenge was to accommodate the agenda of the local help (e.g., IT) of all 12 sites in only 4 weeks. In a few sites we had to go back to finish setting up the internet. Several of the sites did not have the internet accessible for us during the installation, mainly because of security regions (firewalls, etc) All LMA stations were installed in already secured areas. The LMA electronic boxes were placed inside buildings to secure them against flash floods.
7. Operation	R1: NMT operates the CoLMA.
	R2: no information provided.
	R3: If the sensors are online, real-time data is generated and allows you to know how the network is functioning. If the sensors are not online, it will be necessary to keep a close eye on them for the first several weeks. After the bugs (if any) are worked out, it would be safe to visit once every couple of months. The RF tight sensors are reliable in most conditions. They should not be exposed directly to the elements, but temperature extremes are not normally an issue. If 3G and faster connections are used, the full data is uploaded daily and the site need only be visited if there is a problem with a sensor. If the sensors are deployed long term, they should be visited every year or two even if they appear to be working well to make sure that the antennas, etc. are not damaged/bent. With the newer solar powered sensors, the most common issue is power failure from snow or foliage covering the solar panels for an extended period. The older Rev3 LMA boards would sometimes fail due to intermittent or interrupted pin contact on the socketed chips caused by oxidation and/or thermal expansion/contraction. This especially occurs if the power systems are intermittent and the sensor is allowed to go unpowered for some time. Another common failure occurs with units utilizing IDE to SATA adapters on SSDs, in which the SSD has errors causing the unit to remount the drive as read only. This failure can sometimes be solved with a hard reboot. When possible, he recommends using a CF card or microSD card instead of the SSDs, which can be mounted directly into the pc104 computer. If the sensors are using fast enough internet connections, these need not be too large, as the full data is uploaded daily. If the network is working well, you have sufficient redundancy by using more than 10 sensors, and connections allowing real-time data and the ability to upload the full data are used, local support may not be required. With proper redundancy built into the network, one can lose one or even more sensors without causing a large issue. This will allow time to schedule repairs during the time of your choosing. If all of the sensors are functional before shipment, you can simply ship a few extra parts along with them to allow for damages during shipment. Hopefully, if packed well, damage will not occur. Plan to power up each sensor after shipment to verify they are functional. This being done, deployment should not be a problem. If one has spare sensors and it is possible to deploy them, he would do so. "Hot spares", or using extra sensors in the network, are better than leaving one on the shelf. When they are in the network, and all sensors are functional, they add to the quality of the network, and they still keep the network up, as intended, in the event that one loses a sensor. One also has the added benefit that if the spare is already operational, one doesn't have to send someone out to the area right away just to swap out a sensor. However, if one can't afford an extra site, equipment costs, or communication expenses at the extra site, keeping a spare sensor close to the network is advisable when using a small network of less than 10 sensors. The extra sensor can easily be stored at the most secure of the operational sensors.
	R4: no information provided.
	R5: The 12 stations are monitored through i) the hourly reporting of each station delivering

	information on the station status, and ii) the use of real time lightning display based on decimated data. Three inspection campaigns per year: i) at the end of each year for wintering the altitude stations; ii) resuming at the end of winter for the resumption of activity of the wintered stations, and iii) in September after the active season of the storms. For each operation, maintenance is performed and raw data collected. As part of the EXAEDRE campaign, real-time decision support tools for the SAETTA network and MF meteorological radars have been developed. Likewise, tools based on the real time of the SAETTA network were designed for the support to the Cal / Val activities of LIS and the late TARANIS. No specific requirement to deliver the SAETTA data in real time (Best effort). The SAETTA network is operated with a 40 ns time base, 80 µs raw data windowing and 400 µs decimated data. Real-time update at 1 min, with a delay 3 min before display. To date, no improvement on cooling systems or additional fans have been done. For temperature, the problem is mainly in summer, internal temperatures reached 63°C during the summer of 2020 (outdoor temp ~ 39°C). Normally all the components have an upper limit in temperature of 75°C but there is an accelerating risk of component aging. For strong winds, breakage is inevitable on the VHF antenna, there are no solutions to withstand winds greater than 200 km/h (Cap Corse in North of Corsica), it was chosen the VHF antenna of SIRIO brand offering a good compromise between wind resistance and cost. Although the stations do not suffer from rain or humidity, the structures, on the other hand, undergo very strong corrosion in a marine environment, leading to their replacement more frequently than expected (~4/5 years). The objective is to keep the 12 stations of the SAETTA network in operation. As long as there are no problems the stations will work. The main causes of malfunction are due to meteorological problems: gusts of wind, long cloud coverage. During the EXAEDRE campaign, a person was on site in case of the need for a maintenance intervention. For any maintenance operation on a station, it takes more time to get to the station than to intervene. Any visit to a SAETTA station lasts on the average half a day. Note that no nighttime intervention is conducted. Each visit of the network is prepared at least two weeks ahead to identify in which order the stations will be visited. Note that the visit order can change according to the weather situations, meaning that the visit should be as flexible as possible. During the 7 years of SAETTA activities we experienced two lightning strikes (one burnt the VHF antenna; the second impacted the PC104 and some components through the in-box network cable), a destroyed GPS antenna (its internal preamp caught water, fault assembly), a PC104 power supply out of order, many VHF antennas with the central strand broken by a gust of wind, a GSM antenna torn off by a gust of wind, a solar panel broken by an animal, some batteries destroyed (deep discharge due to lack of sunshine), a CF card and two SSD disks (untimely restart). We have a set of spare parts covering all the functional elements of the stations except for the FPGA board. Another functional aspect that sometimes poses a problem is the loss of mobile communication, which happens frequently in Corsica in each situation of a meteorological event. On the other hand, it is impossible to achieve faultless performance on all 12 stations with a mobile communication network in a mountainous region like Corsica.
	R6: the LMA stations were monitored connectivity establishing reverse SSH tunneling over 3G networks. Scripts were built to then create network status reports. The stations were visited once every few weeks. No real time requirement: only occasionally download “real-time” data to monitor station performance. Damage to PVC frames from strong winds necessitated significant additional glue, duct tape, and wire. Data from LMA sensors were collected once every few weeks. About 9 LMA stations functioned on average at any one time. Main causes of failure were solar power issues (vegetation, season) and LMA board malfunctions. Average time was 1-2 hours per visit. No site visits were done at night during RELAMPAGO.

	The maintenance plan consisted in a mix of regularly scheduled site visits and unscheduled visits to fix emergent issues. Minor problems faced during the LMA operation: rev 3 LMA board malfunctions. had enough spares, but were limited on site visits. Wind damage, insect infestations, vegetation growth.
	R7: real time NALMA imagery available via http://lma-tech.com/nalma. Roughly 10-minute latency. 10 minutes for real-time imagery.
	R8: All stations have 3G communications to check operation. We collect the hard disks manually (we swap disks) visiting the stations. This is done, at least, after each season. This is done either by a member of our group that travels to Colombia or by a local collaborator that has been trained. In that case we are online communicating (Whatsapp) during this operation. To transfer data we supplied hard disk readers to a local collaborator that plugs the disks and then we copy. To communicate stations, we use a tunnel to either a local server in Colombia or to a server at the UPC. In the case of an interesting events we download the data directly from the stations.
	R9: We used MSFC/NASA resources; same as they do DCLMA and NALMA. In a few, the stations were visited twice during the 4 months operation for data collection, or if a problem was detected. We had a few communication failures. One time we replaced cables and probably two GPSs. Real time data was for monitoring the stations themselves and for helping decisions on strategy for a few scans of the XPOL radar. No timeliness requirements to deliver the LMA data in real time On average all 12 sensors were operating. The malfunctions were basically communication problems, either internet (router failures), cable damaged and GPS failure. LMA and LINET stations were maintained by two technicians and one PhD student (with technical skills) from USP for half a day or a day. Local support was only to reboot the sensor, routers or check the internet. Initially we planned to have 10 stations deployed and keep 2 as spares. During the deployment, we decided to install the spares and move them if we had had failure of the 10 main ones (but no LMA station failure happened). We had all spares parts.
8. Data processing	R1: NMT takes care of the data processing.
	R2: no information provided.
	R3: About the deployment of specific computing resources locally or a basic transfer of the LMA data to the Consortium premises, it is completely dependent on the local internet. In some cases, the internet inside the country is not easily accessible from any home country. If that is the case, either a local server, or a virtual server rented from a local provider will be necessary.
	R4: no information provided.
	R5: The decimated data of each station is sent via mobile communication (3G or 4G) to a server connected by Gb network to the INTERNET through RENATER. This server, located in Toulouse at the Laboratoire d'Aérologie, stores the data and calculates VHF events upon reception. This server is sized for the tasks to be performed. Data collected after each network visit is processed to produce 80-µs VHF source locations through the cluster of the laboratory. L0 (raw data), L1 (source data) and L2 (flash data) are stored on two different space disks and on external backup disks
	R6: No requirements in terms of data delivery. NASA processed the data after the fact. Data quality control is performed by NASA.
	R7: NALMA provides near-real time imagery within 10 minutes of collection. New Mexico Tech performs processing, but this is in the process of being switched to the NASA Global Hydrology Resource Center.
	R8: Data is processed by one person of our team. Data is processed locally from a server in Colombia or is transferred to our data server and processed at the UPC. No real time data is used.
	R9: The requirement was to decimate real time data and to reprocess full data within 6 months. The real time data processing was conducted at a server installed at USP.

	Decimated data from all stations were sent to a server at USP and processed there in real time. During the night, full data was transferred to this same server and then to MSFC for reprocessing and quality control. QC and reprocessed data was to be delivered in 6 months.
9. Personnel	R1: did the work with existing staff.
	R2: no information provided.
	R3: no information provided.
	R4: no information provided.
	R5: No personnel specifically hired for the SAETTA operation. Some help from the Air Force (Solenzara Base) for ad hoc helicopter operations. Loan of a room for a base (QUALITAIR Corse for SAETTA, INRA for EXAEDRE).
	R6: Three students were hired to help assemble the RELAMPAGO stations and process the data afterward. They also did rely on a couple individuals from the National University of Cordoba in Argentina to help with emergency visits to the RELAMPAGO LMA. These people had other sources of RELAMPAGO-related funding, so the work was done in-kind.
	R7: no information provided.
	R8: The responsible of the Colombia LMA was hired at the beginning as a PhD student and he is now as a postdoc. The Colombia LMA was necessary for his PhD. We hire local technical support for specific months.
	R9: no personnel contracted.
10. Costs	R1: NOAA funded the data analysis. \$15k per year (communication, maintenance, spare parts)
	R2: no information provided.
	R3: Based on the survey questions, he provided : - Buying new sensors or necessary hardware: new sensors with structures ~39,000 USD each. - Shipping of the sensors (in and out, including customs......): international shipping to location for new sensors and structures are ~950 USD each. (Customs fees are not included as they vary by country and circumstance.) - Installation: The participation of LMA Technologies in the installation of a new network is included in the sales cost shown above (This would include up to two people from LMA Tech). - Operation (hosts, communications, spares, data collection...): Two years of maintenance is included by LMA Tech in the price listed above. This includes all parts and labor necessary, plus the cost of up to two international maintenance trips. - Removal of the sensors: Given the maintenance trips were not all required, a removal trip by LMA Tech would be included in the above pricing.
	R4: no information provided.
	R5: SAETTA is operated with the financial support from CNRS, CNES, Université de Toulouse 3, Collectivité de Corse. The cost to run 12 stations is 25 k€ / year (maintenance, operation). The man efforts are on the average of 20 man.month per year.
	R6: Activities supported by NOAA GOES-R Cal/Val. ~\$200k total. RELAMPAGO Shipping \$13k.
	R7: Activities supported by NOAA GOES-R Cal/Val. ~\$50k/yr.
	R8: Besides the sensors. Contracts with local support after the installation are about 3.5 kEUR per year. Travels twice per year 6 kEUR. Contracts (postdoc) 28 kEUR per year. Repairs: 600 EUR/average per year.
	R9: MSFC/NASA team funding from NOAA GLM Cal/Val activities. Part of the CHUVA Project (Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP). The CHUVA Project provided around 2k USD to support the deployment.
11. Auxiliary data	R1: no reply.
	R2: no information provided.
	R3: no information provided.
	R4: no information provided.
	R5: during EXAEDRE, field mills were installed on the Falcon by ONERA, and an interferometer deployed at the INRA site on the island. No auxiliary measures otherwise

	in addition to the SAETTA network. Meteorological band-X and band-W radars, lidars and disdrometers were also operated to characterize the cloud environment. Outputs from two French cloud models Meso-NH and AROME outputs were also used for forecasting and case analysis.
	R6: other atmospheric electricity measurements performed with CAMMA (Marx Meter network), field mill network, LF network. Significant multiple radar coverage. Soundings, Department of Energy long-term mobile facility deployment, mobile radars, etc.
	R7: other atmospheric electricity measurements performed with HAMMA (Marx Meter network). Significant multiple radar coverage.
	R8: National lightning location system (LINET). National radar network. We have also installed cameras for TLE, and electric field antennas. Also a broadband VHF interferometer.
	R9: 10 different lightning networks operating at the same time, sending data in real time and reprocessed after 6 months: LMA, LINET (6 sensors), Vaisala TLS200 (5 sensors), Brasildat (ENTLN/EarthNetworks, with 6 additional sensors), RINDAT, STARNET, WWLLN, GLD360, ATDNET, TRMM LIS. Upward Lightning Project (Marcelo Saba – INPE; Tom Warner) with high speed video cameras was also connected to that campaign. Auxiliary atmospheric measurements : • based on CHUVA Project instrumentation: XPOL radar, 2 Micro Rain Radars, 10 disdrometers (Joss-Waldvogel, Thies, Parsival), 15 rain gauges, 1 lidar, 2 MP300, 3 radiosonde sites, weather station tower; • 2 S-band operational radars. Cloud Resolving Models BRAMS and WRF were run. All data was sent in real time to a web-based platform, with free access. We also developed a special web-site for the local Civil Defense to monitor rainfall accumulation, 1-3 day forecast, and nowcasting products (including all the lightning data).
12. Lessons learned	R1: the data analysis reveals a poor detection efficiency of “inverted” storms (10-20%); No failure of the instrument; need supporting radar data for analyzing storm structure, preferably polarimetric radar.
	R2: no information provided.
	R3: no information provided.
	R4: no information provided.
	R5: Key points: • Make sure that if the LMA stations are run on standalone mode that the solar panels and the batteries are well dimensioned to offer enough energy especially during long periods of cloud overcast; • Make sure that if a LMA station is plugged on the power grid that i) this power grid is stable to avoid power outage when storms occurred nearby, and ii) to add a UPS to support few hours the station; • Make sure that the communication network exhibits a high quality coverage especially if real time data are required; • Conduct site surveys to assess the electromagnetic noise level and the performances of the communication networks; • Explore the possible use of communications through satellites to limit the intervention on site, especially if local support can be used; • Assess the need to have locally specific computing resources to process the data in real time because of limited transfer capacities to the main SAETTA server in Toulouse; • Study the relief of the region where the LMA network will be deployed to limit its effects on the network performances; • Find sites that are easily accessible and safe.
	R6: Successful 6 months of data as planned. During RELAMPAGO, the Rev 3 LMA boards required a lot of chip replacements and/or reseating. Newer boards don’t have PLCC sockets and thus mitigate these issues. The assistance of an enthusiastic local partner was absolutely crucial to RELAMPAGO. The National University of Cordoba assisted with all aspects of the Argentina deployment,

	from initial site selection & survey thru site disassembly. We could *not* have done it without them. Need capable local partner, especially if deployment is foreign. Lightweight PVC station frames are workable for temporary deployments if lots of duct tape, glue, and wire are used. Winds will demonstrate where your assembly fell short! Unsealed plastic bins worked OK for holding RF/electronics/batteries under the solar panels, but were subject to insect infestations. Buy the batteries in the country should save on shipping costs. Do not use older Rev 3 LMA boards for lightly supervised temporary deployments.
	R7: ongoing successful operations since mid-2019 after ~1-yr interruption related to RELAMPAGO deployment. But RELAMPAGO deployment interrupted NALMA operations more than expected, due to delay in arrival of upgraded NALMA stations. We had intended for NALMA to give up some stations to RELAMPAGO as it was receiving new stations from LMA Technologies, but the latter's schedule was delayed so NALMA went dormant for several months as RELAMPAGO occurred.
	R8: Key points: Local support is necessary and needs to be trained and committed with the campaign.
	R9: Unprecedented data on the 3D structure of cloud electrification in the tropics. Unprecedented number (10) of Lightning Location Systems agreed to participate and be intercompared. Not a failure, but a limitation. The only lightning sensor in space was LIS and the short time of the campaign (4 months) limited the optical data into 8 overpasses with lightning (776 seconds total). Advice: Meet with the potential local hosts in person (assuming the pandemic will be over…). People are really kind and receptive when talking face-to-face. They also really like to help with science, especially if well-known and recognized research institutes are involved, in our case INPE, USP and NASA. Their enthusiasm in helping was very transparent, and I could literally see some sparkles in their eyes when those names were mentioned. Lessons learned: It is hard to put 10 different LLS managers on the table to talk, but not impossible. They were reticent about the inter-comparisons, but saw a great science opportunity.
13. Missing items	R1: no information provided.
	R2: no information provided.
	R3: no information provided.
	R4: no information provided.
	R5: no information provided.
	R6: no information provided.
	R7: no information provided.
	R8: no information provided.
	R9: no information provided.

3.2.3 Synthesis

The following section aims at providing a preliminary summary of the main information gathered from the literature review and based on the survey answers.

The deployment of a LMA network starts with a series of site surveys to identify potential sites. This survey should also include some electromagnetic noise recording and a study of the quality of the communication possibilities to get the LMA stations online. The operation of a LMA network will require enough human resources to support the different stages of the LMA deployment. Support from local personnel is required not only to identify the sites but also to install, maintain and operate the stations. The shipping of the instrumentation and tools should be done through specific companies/services that will deal with customs declaration and fees on both ways. Local storage and operation infrastructures and pick-up like vehicles are required to store, to deploy, to operate and dismantle the LMA network. One day should be enough to deploy and test one station in the field, adding an additional week before having the LMA network operational if two teams of two/three persons are on the field simultaneously. It is suggested to buy the batteries locally to avoid shipping issues. The structure of the LMA stations should be able to handle strong wind and heavy precipitation. According to the internet capacities available, data needs to be processed locally to avoid uploading heavy L0 LMA data files either within the country or to Europe.

None of the campaigns described in Table 3.2.2.2 was conducted in Africa except one in Benin during the AMMA project (Höller *et al*., 2009; Huntrieser *et al*., 2011) but no detailed feedback from DLR was received. Of course, one should be very careful in drawing conclusions from field campaigns in American countries for a validation campaign in sub-Saharan Africa as local reality is very much different. Interaction with local hosts should help set up plans and mitigation for not only the site survey, but also the deployment, the operation, the security of the equipment and the team, and the dismantlement. One should also consider buying some part of the equipment locally instead of shipping but it needs to be carefully studied in advance by the team and the local host in terms of local availability, quality/compatibility and purchasing delay/tracking.

Table 3.2.3.1 summarizes the previous paragraph according to the different items of Table 3.2.2.2.

Table 3.2.3.1. Preliminary conclusions for each item of Table 3.2.2.2.

Item	***Conclusions***
1. Team	Teams of from about 6 up to 15 persons with different roles. Installation and maintenance teams of minimum 2 persons. Two teams are recommended.
2. Sensors	Minimum 8 stations, recommended 10 and ideally 12.
3. Before shipping and installation	Check the general use of the LMA frequencies. Sensor sites shall be arranged and visited before. Site survey is highly recommended. Definition of the resources at each site is necessary (accessibility, electric power, 2G/3G/4G coverage, safety, etc).
4. Shipping	LMA can be shipped as part of baggage in flights to some countries with soft customs restrictions. It is recommended to hire a freight company with experience in customs (customs brokers). It is absolutely mandatory to have a local contact for custom clearance. Consider buying some material locally (e.g. batteries, solar panels, etc). Overall shipping related activities can take one month or more. So it needs to be included in the schedule of a campaign.
5. LMA sites	For better performance isolated locations powered by solar and with 3G communications are recommended. Such requirements will have to be investigated with the help of the local host. Security of the equipment is critical in many places in Africa, as electronic equipment, solar panel, cables, are quite precious equipment. LMA stations have to be deployed in fenced areas; otherwise guards will have to be hired. Careful selection of the sites is important for network performance. Some stations are in public areas, private properties, airports and institutions. Commonly sensor hosts are not paid.
6. Installation	Planning is very important to not increase costs. The shortest time to set a single station is about 3 hours for a ground level solar

	powered station. But half a day and one entire day per station are also common. In some locations accessing the roof is necessary and prevents thefts. So, it is necessary to have the hardware and personnel to access the roofs. Some places require fences etc. The minimum installation team is two persons. A local person from the main host institution and a driver are also advisable in foreign countries. It is important that someone (preferably local) manages the sensor host contacts and keeps the host contacts alive. The first two weeks are critical for the sensor performance (stability, noise, etc...).
7. Operation	Some communications (e.g. 2G/3G) are highly recommended to check the status of the sensors. Stability of power is important. If there is no good 3G/4G coverage, data shall be collected periodically. Station failures shall be expected. This ranges from the electronics itself to the mechanics including supports and antennas. LMA has demonstrated to be a robust system. The LMA is stable in different types of weather (e.g. affected by low winter temperatures and highly humid tropical weather). In operation LMA stations are typically visited from every few weeks in campaigns to months in the case of permanent setup. For Africa, one might need to visit all stations more often, the revisiting time will have to be discussed with the local host according to the local environment and traveling possibilities/restrictions.
8. Data processing	If there is fast and stable internet in the region processing can be done remotely. If the internet is not so good, some facility (server) is needed to process the data locally (i.e. at the location where the team will be based).
9. Personnel	In some cases additional personnel to assist are hired.
10. Costs	Typical annual support for stable networks is between 15 k€/year to 40 k€/year. As reference, activities supported by NOAA GOES-R Cal/Val. The RELAMPAGO campaign was ~$200k total. RELAMPAGO shipping about $13k.
11. Auxiliary data	Lightning detection and radar are common. Based on the survey replies, it depends on the purpose of the field campaign. The LMA campaigns discussed so far were conducted in areas covered either by national or global operational lightning locating systems. Additional local lightning locating systems, operating at other frequency bands than the LMA one, were deployed. One should consider at least three different lightning detection systems using different principles to provide a reliable unambiguous ground truth as suggested in Defer et al. (2010, EUMETSAT study). Any flash detected simultaneously by a LMA and any operational lightning locating system, or several, should also be depicted by other lightning sensors such as slow antennas (detection of ground connection at close range), electric field mills or/and video cameras (with proper frame rate).
12. Lessons learned	To checklist all possible sources of station failures. To take care about communications with the station. To have efficient and committed local support. Meet with the potential local hosts in person. In some cases unexpected failures of electronics.
13. Missing items	Void

3.3 WP2 – European LMA networks for dedicated campaigns.

An assessment on the potential of the Consortium LMA networks in their current configuration has been conducted based on the information found in the literature and the answers to the Consortium survey. The following sections address the 4 main objectives of WP2.

3.3.1 Potential of the Consortium LMA networks

UT3 and UPC LMAs have successively demonstrated their capability to measure lightning activity on the stand alone from their bases (Corsica – Coquillat et al., 2019 - and Ebro Delta – van der Velde et al., 2013, Pineda et al., 2019 - respectively) and remotely (e.g. ASIM Colombia for UPC LMA; López et al., 2019). The observations of the two LMA networks have contributed to ISS-LIS (Erdmann et al., 2020; Montanyà et al:, 2019, EUMETSAT study), ISS-ASIM and GLM (van der Velde et al 2020; Montanyà et al., 2021) cal/val activities.

As a reminder each LMA station detects the VHF radiation per 80-µs time window. It then stores the L0 data locally and can send the data to a main computer to reconstruct in real time the lightning activity. The real time dataset is degraded (400-µs time window; threshold on the VHF amplitude) to deliver the data rapidly and avoid any saturation of the communications. This degraded real time capability should be kept during the deployment in Africa even if the no real time requirement is asked by EUMETSAT. The L0 data, either stored locally but recovered later during a visit to the stations or sent in real time, is then used to build the LMA data which consists of the locations of the VHF sources. According to the strength of the lightning activity and environmental noise level, the data processing to reconstruct L1 data can take many hours, but at the end, a 10-min L1 data file is much smaller in size than the 10-min L0 files of each LMA station, which suggests that computing resources will be needed in the field if EUMETSAT requires L1 data within few days.

The two groups have currently a total of 27 LMA stations (12 in France, 7 in Spain and 8 in Colombia). The version of the LMA sensors is Rev. 3. The UT3 sensors are 7 years old whereas the UPC sensors are already 10 years old. Finally, the personnel involved currently with the LMA are 8 for UT3 and 5 for the UPC.

EUMETSAT indicated during the study that the deployment of the LMA should be similar to the one of a scientific project, meaning that with no real time requirements with delivery to EUMETSAT headquarters. This decision will ease the actual operations of the LMA taking into account the possible communication limits that might be faced during the campaign. Indeed, based on the daily operations of UT3/UPC LMAs, delivering data from Africa would be highly dependent on the quality of the cell phone networks and/or satellite communication services in terms of bandwidth (mainly outgoing flow) and on the need to deploy and operate locally some dedicated computing resources. Note that if possible, degraded real time capability will be deployed on the best effort basis for a better monitoring of the network in terms of behavior monitoring and storm tracking. All LMA stations will be visited as often as possible especially if L1 data are required within a few days after each storm for comparison with MTG-LI records.

3.3.2 Relevance to complement the LMA deployment with other instruments

One should already suggest the need to bring other lightning sensitive instruments to consolidate the description of the lightning activity. As an example Fig-3.3.1 shows the case of a negative cloud to ground flash detected by a LMA, several European operational lightning locating systems, a slow antenna, a fast antenna and a camera (Defer *et al*., 2015). While the LMA maps well the in-cloud pulsed processes but cannot locate the last kilometer of the downward stepped leaders, the VLF/LF systems detect ground connections and intra-cloud components, the slow antenna confirms the connections to the ground and documents the transfer of electrical charges within a range of 10-20 km, the fast antenna reveals the occurrence of fast flash components, and the camera provides the ground truth of optical radiation.

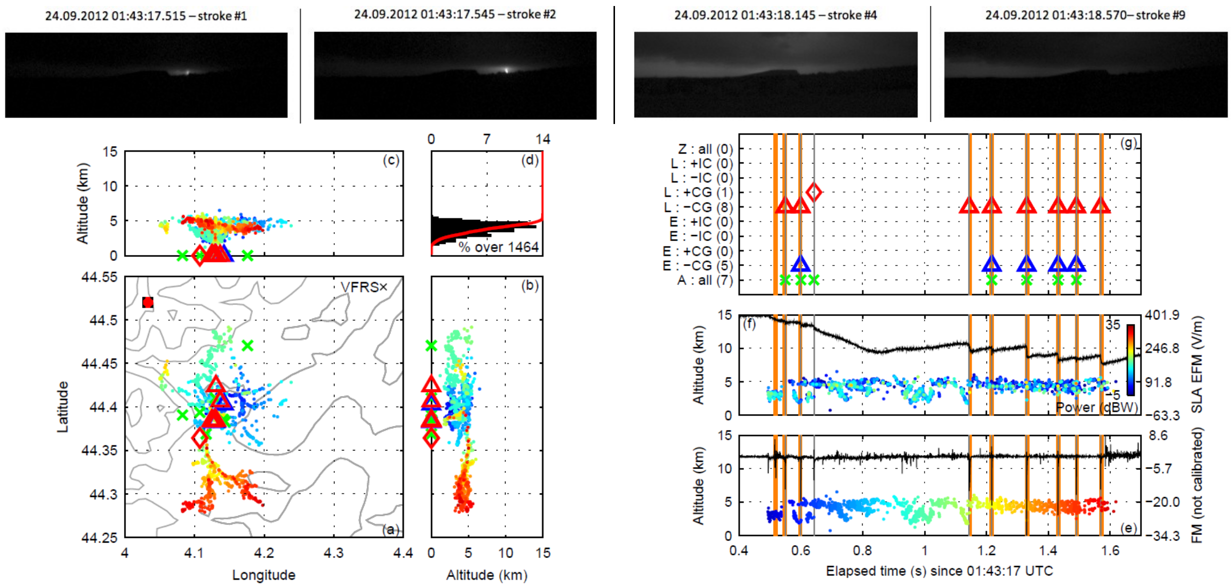

Fig-3.3.1. Records during a -CG flash with multiple ground connections (24 September 2012, 01:43:17 UTC) with (a) ground projection of the lightning records; (b) latitude–altitude projection of the lightning records; (c) longitude–altitude projection of the lightning records; (d) histogram (bars) and cumulative distribution (red cure) of the VHF source altitude; (e) time–height series of VHF sources and record of the Uzès Slow Antenna; (f) amplitude–height series of VHF sources and record of the electric field observations; and (g) records of operational LLSs per instrument and type of detected events available only for EUCLID and LINET. The orange bars correspond to ground strokes as identified from the electric field records. The location of the electric field and video measurements (VFRS) is also indicated in (a). Gray lines indicate times of all operational LLS reports. Records from ATDnet, EUCLID, LINET and ZEUS are plotted with green crosses, blue symbols, red symbols and black stars, respectively. Top: enhanced video 5 ms frames recorded during the nine ground strokes of the -CG flash. From Defer et al. 2015.

A local Low Frequency (LF) network should be deployed at the same sites as the LMA stations, especially in African areas poorly covered by national LF or long range Very Low Frequency (VLF) networks. Adding such sensors at each LMA station, when run in a standalone mode, will require assessing the energy budget required if the same power supply is shared. It will also require some modifications in the data transmission protocol if the LF lightning data are needed in real time. Another way would be to operate the two networks independently. Note that the second network would have to be deployed and operated by another team. In addition, as stated in Defer (2010, EUMETSAT study), at least three different lightning detection techniques should be used to help alleviate uncertainties in some flash component detection. Additional instruments like slow and fast antennas, electrostatic field mills and fast video cameras should definitely be considered. One of the instruments providing coverage in Africa is the UPC Extremely low frequency (ELF) magnetometer receiver for Schumann resonance. This sensor is located in Cape Verde (Sal Island) and provides magnetic waveforms related to highly energetic lightning such as positive cloud-to-ground flashes that contain significant continuing current. This station is the second one available in Africa together with South Africa.

Cloud sensitive observations should also be considered to document the cloud context through which the optical light radiated by the lightning flashes has propagated. Scanning research cloud radars operating at the proper band should be deployed a bit away from the LMA network to provide <5-min volume scans of the thunderclouds. One should also consider operational weather radars in the identification of the LMA site, if any weather radar is operated in the vicinity. In both cases (scientific scanning radar and operational radar), the coverage area of the LMA network should be compared with the radar coverage area to maximize their common coverage area but without positioning too far the LMA network relative to the area where to expect thunderstorms. As an example Fig.-3.3.2 shows the GLM detection efficiency as a function of the flash size and the Above Flash precipitation Ice Water Path (AF-IWP). AF-IWP calculated from radar data represents the ice water associated with precipitation-sized particles. The precipitation Ice Water Content (IWC) is integrated vertically upward from the mean LMA flash height to a maximum height of 12 km and 14 km for Colorado and Alabama, respectively (Rutledge *et al*., 2020). Fig.-3.3.2 definitively shows lower GLM detection efficiency in Colorado, but Rutledge *et al*. (2020) report that "GLM DE is found to vary with the geometric size of the flash and with cloud water path, the latter depending on flash height and cloud water content." Cloud radar profilers should also be deployed mainly within the LMA networks. Ground-based passive microwave sensors will not provide a detailed vertical description of the cloud content while ground-based lidar signal will be rapidly attenuated in deep convective clouds.

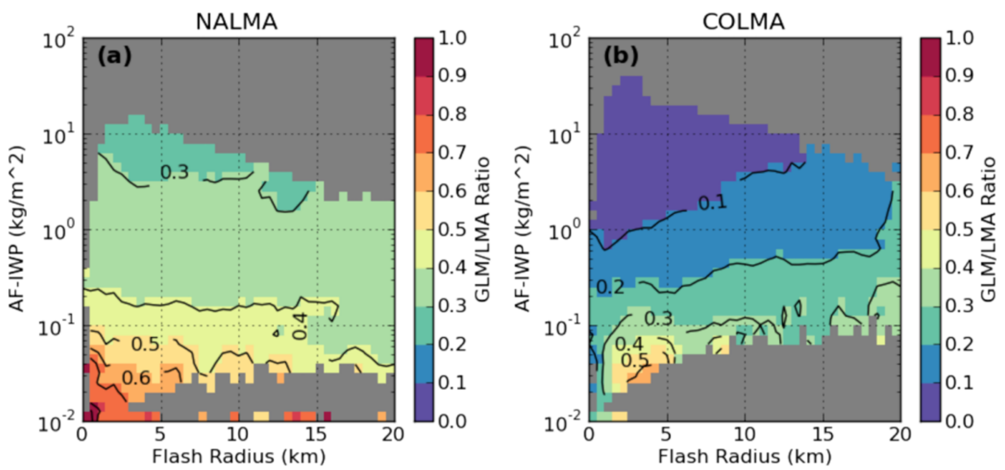

Fig-3.3.2. Detection efficiency (GLM/LMA flash rate ratio) versus AF-IWP and flash radius for (a) North Alabama NALMA and (b) Colorado COLMA networks. From Rutledge et al., 2020.

3.3.3 Required and available human resources and facilities during the MTG-LI campaign

In this section, we discuss what a LMA-based MTG-LI campaign would require in terms of facility and human resources for a deployment of a single LMA network in Africa, LMA network being either UT3 LMA or UPC LMA or a combination of compatible UT3 and UPC LMA stations.

Table 3.3.3.1. Preliminary analysis of the required and available resources during the MTG-LI campaign.

<table>
<tr><th>Item</th><th>Answers</th></tr>
<tr><td>1. Team</td><td>• The team should be enough in terms of personnel and efforts to handle the different stages of a deployment in Africa, including :
- Looking for hosts/sites of the sensors;
- Site survey in Africa (1 year ahead; VHF spectrum analysis and communications);
- Recovery of the LMA stations that are operated in Europe;
- Verification and preparation of the LMA stations to be deployed in Africa;
- Preparation of the shipping (LMA stations, equipment, paper works);
- Installation of the LMA stations and in-field resources (e.g. computing resources);
- Field operation (maintenance and monitoring);
- Remote support in Europe;
- Data processing and quality controls;
- First “live” analysis of L0 and L1 data;
- Dismantlement of the LMA stations;
- Preparation of the shipping (LMA stations, equipment, paper works);
- Verification and preparation of the LMA stations to be redeployed in Europe;
- Redeployment of the LMA stations in Europe.
• Make sure that there are overlaps between team shifts both on the field and at European laboratories.
• Local personnel from the main host institution shall be incorporated in advance. The personnel shall be involved in almost all the activities of the campaign.</td></tr>
<tr><td>2. Sensors</td><td>• Between 9 and 12 sensors should be deployed for redundancy.
• Equipment spares (electronics, cards, cables, antennas, GPS, modems, telecoms) to be included in the shipping → local storage/laboratory capacity required for maintenance, replacement and tests before redeployment in the field.
• Critical elements to be shipped are batteries due to the safety restrictions and solar panels due to their size.
• The European LMA networks are run in Europe without a cooling system. In Corsica, temperatures up to 60°C have been recorded in the electronic boxes. In Colombia, UPC/LPG has reported no temperature issue.</td></tr>
<tr><td>3. Before shipping and installation (two ways)</td><td>• Inbound:
• List of the available LMA stations in Europe to be moved;
• Definition of a clear data/architecture/telecom plan before shipping that will be designed after the first survey
• Definition of network geometry and possible locations;
• Contact possible sensor hosts by local partners;
• Site survey in Africa including power availability, consolidation (for mobile phone communication) or redesign of the communication block (for satellite communication for example);
• Recovery of the LMA stations in Europe;
• Verification and preparation of the LMA stations (communications, power, electronics,…) and computing resources to be deployed in Africa;
• Preparation of the shipping (boxes and paper works);
• Preparation of the personnel that will travel (visas, consulates, vaccines, lodgment, etc.).
• Outbound:
• Recovery of the LMA stations in Africa;
• Preparation of the shipping (boxes and paper works);
• Verification and preparation of the LMA stations (communications, power, electronics,…) to be redeployed in Europe;</td></tr>
</table>

	• Redeployment of the LMA stations in Europe.
4. Shipping (two ways)	• ***Inbound:*** • Use adequate services including customs brokers; • Have a local recipient of the items (e.g. main host institution) able to deal with customs requirements; • Take into account the time it will take to get the material in the field → local storage building required! • ***Outbound:*** • Use adequate services including customs brokers; • Local storage building required while waiting for the material to be taken away.
5. LMA sites	• Site survey (VHF spectrum, telecom; typical weather conditions – wind, flooding – that any site can experience) to be conducted; • Identify at least 6 more sites than the number of LMA stations to deploy; • Avoid populated areas and sites with electric transformers and power suppliers; • Sites accessible by pick-up trucks, hire drivers; • Fences to secure the stations, hire guards; • Investigate the possibility of a site to be flooded during a major storm, strong winds…
6. Installation & dismantlement	• Build partially or totally the station before its deployment in the field; • Use a pick-up to move/remove the LMA station to/from the field; • Check local safety and labor rules and recommendations; • Hire local support; • Set up at least the electronic boxes at certain height from the ground to avoid floods; • Secure as much as possible the stations against animals (cattle; snakes; insects), vegetation and flash floods; • Establish a commissioning period to validate the station (stability, noise level, etc).
7. Operation	• Set up status web page to monitor remotely the LMA stations; • Design a maintenance plan/protocol to follow in the field; • Conduct any field activity during daytime; • Dedicated weather forecasting in support to any field trip; • Train local support to maintain the instruments operational; • Collect the data as often as possible according to EUMETSAT requirements; • Deploy locally computing resources according to EUMETSAT requirements; • Specific room for the monitoring of the LMA network, for guidance and decision when a team is in the field.
8. Data processing	• Identification of the needs according to EUMETSAT requirements; • Specific room with internet access and all computing resources to back up the data (hard disks) and to process the data.

3.3.4 Requirements to maintain the Consortium LMA networks until the MTG-LI campaign

On that specific question on the maintenance of the Consortium LMA networks while waiting for the MTG-LI campaign, UT3 and UPC are running their networks through national and European projects of more or less short duration.

UT3 is running its LMA on secured funding provided by CNES, CNRS and OMP (Observatoire Midi Pyrénées) until the end of 2021 thanks to the label of National Instrument of Excellence (NIE) earned for the years 2020 and 2021. The proposal to maintain that NIE label have been submitted in July 2021. If the NIE label is maintained, the operation costs of the SAETTA network will then be covered for the years 2022 and 2023. A letter of support has been provided by EUMETSAT to strengthen UT3 proposal. In addition, SAETTA human resources (permanent staff) will diminish in 2023 and a strategy to recruit new permanent staff (through that NIE label) is currently designed internally.

UPC will operate its LMA with secured funding (MICINN Ministry of Science and Innovation) until the end of 2022 as an instrument for ASIM ground support. In July 2021, UPC submitted a proposal to the Spanish MICINN/AEI call for infrastructures. The proposal focuses on renewal of the Ebro-LMA network with 15 new stations and updating the old sensors. If this proposal succeeds, there will be 10 sensors available for dedicated campaigns. In addition, the UPC will apply for funding to the regular MICINN/AEI research call to continue operating the LMA networks as UPC has been doing for the last 10 years. UPC has used these projects to support personnel contracts involved in the operation of the LMA. The chances of success will be reduced if ASIM definitively ends its operation at the end of 2021.

Even if UT3 and UPC have access to a pool of Master and PhD students and possibility to host EUMETSAT post-docs, there will be a need to define a HR strategy for the years to come to keep current personal working on soft money, to get recruitment of new permanent staff, and to define as well a more general UT3-UPC strategy at national, European and international levels to keep the LMA networks in operation as the UPC and UT3 LMA stations are 10 years and 7 years old, respectively, and an upgrade will have to be investigated in support to long term operations, including MTG-LI validation in Africa and in Europe.

3.4 WP3 – Best sites in Africa and their observational properties.

WP3 aims at building and analyzing the storm climatology in terms of location and severity over the African continent to identify relevant sites for the deployment of LMA stations in support of MTG-LI cal/val activities. Seasonal and diurnal cycles of the convection need to be investigated to derive several field campaign properties (e.g. best locations, campaign duration, period during the year).

Two approaches are followed: one uses the cloud information as available with Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI) to derive the convection properties while the second one exploits lightning observations measured separately by the space borne TRMM-LIS and the ground-based operational lightning locating system Global Lightning Dataset 360 (GLD360). Whatever the data used, the methodology applied here aims at providing monthly, weekly, daily, hourly when relevant, storm climatology of a series of macroscopic storm characteristics, such as hour of the convection peak of the storm activity, at relevant spatial resolution relative to the typical coverage area of a LMA network, to identify potential campaign locations.

The following sections first provide climatology of the convection, then discuss on the definition of sites of interest, and then detail more the convection properties for identified regions of interest and associated sub-regions.

3.4.1 Storm activity at the scale of Africa

The following sections describe the climatology of the convective clouds and lightning activity at the scale of Africa.

3.4.1.1 SEVIRI-based assessment

Storm climatology at the scale of the African continent, mainly between 40S and 40N and 30W and 60E, has been built based on SEVIRI 10.8 µm brightness temperatures (BTs). Ten years of SEVIRI data stored at the French Data Center AERIS/ICARE (https://www.icare.univ-lille.fr/) have been processed to generate a rather comprehensive description of the atmosphere over the geographical domain of interest at relatively high temporal resolution, i.e. SEVIRI 15-min time resolution.

Fig.-3.4.1a and Fig.-3.4.1b show maps of SEVIRI 10.8 µm IR brightness temperatures measured on 01 July 2020 at 04:00 UTC and 16:00 UTC, respectively. Several storms are easily identified mainly over the African continent. Fig.-3.4.1c shows the geographical 1°-latitude x 1°-longitude distribution of 10.8 µm IR brightness temperatures below 200 K cumulated over the 24 hours of the studied day. This distribution computes the percentage of brightness temperatures below 200 K found within a given grid box and cumulated over a 24-h period. For that day, the daily storm activity mainly occurred between 6S and 18N and 30W and 40E (Fig.-3.4.1c). A maximum of 19% was recorded on that day, but it does mean that one of the grid boxes exhibited 10.8 µm IR brightness temperatures below 200 K for about one fifth of day as this distribution simultaneously depends on time and on the actual 2D distribution of the brightness temperatures, and consequently the 2D cloud extension and cloud properties, within each grid box.

Note that the typical nominal range of a LMA array with satisfying 3D flash reconstructions is about 150 km range, so the 1°X1° resolution of the SEVIRI climatology should provide enough details compared to the LMA nominal coverage area.

Other products derived from SEVIRI records are explored, including the characterization of the diurnal cycle of the 10.8 µm IR brightness temperatures as shown in Fig.-3.4.1d. In that figure, for each SEVIRI image, the distribution of the 10.8 µm IR brightness temperatures, expressed in % relatively to the number of brightness temperatures measured in that grid box for each given 15-min period, is computed every 15 minutes by considering a 10° latitude x 10° longitude domain – smaller domains will be investigated for the sites that will be discussed in Sections 3.4.3, 3.4.4 and 3.4.5 – and plotted as function of time during the 24-h period. Different features can be seen in that figure: i) convective clouds starting their development during the beginning of the afternoon (for example for the grid box 0E-10E and 10N-20N) with more cold IR brightness temperatures recorded while the day goes on, ii) the sun heating of the surface that leads to an increase of the IR brightness temperatures up to 330 K at mid-day (for example within the band 10N-40N over the entire African continent).

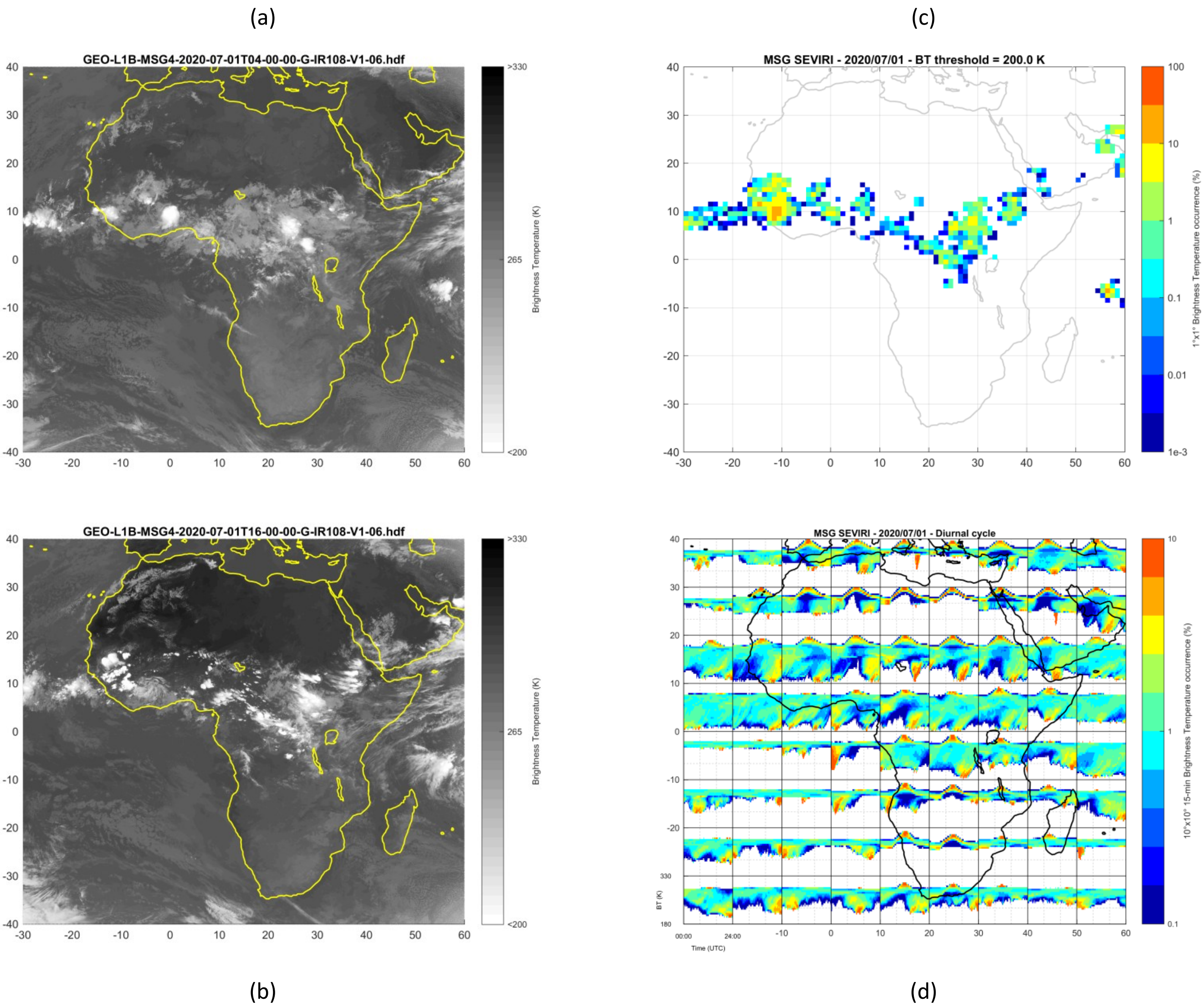

Fig.-3.4.1. (a) map of SEVIRI 10.8 µm IR brightness temperatures measured on 01 July 2020 at 04:00 UTC; (b) map of SEVIRI 10.8 µm IR brightness temperatures measured at 16:00 UTC; (c) daily 1°-latitude x 1°-longitude distribution of SEVIRI 10.8 µm IR brightness temperatures below 200 K measured during the entire day of 01 July 2020; (d) 24-hour diurnal cycle of SEVIRI 10.8 µm IR brightness temperatures per 10°-latitude x 10°-longitude geographical domain measured on the same day

The SEVIRI-based climatology built for the present study then consists of products similar to the ones shown in Fig.-3.4.1c and Fig.-3.4.1d based on 10 years of MSG records for the period 2011-2020. Those products are produced for each day and are summed up on the daily, weekly, monthly and yearly basis. A basic visual inspection has been conducted to identify issues with SEVIRI observations and 29 days with such issues were removed from the 10-year SEVIRI climatology.

Fig.-3.4.2 to Fig.-3.4.13 show the monthly distribution of the convection as derived from the 10-year SEVIRI dataset (from 2011 to 2020). The geographical distribution of the convection is plotted in linear and log10 scale for each month. From month to month one can see, as expected, the latitudinal motion of the storm activity according to the season. One can also see the predominant occurrence of the convection over land. One can also identify some regions with higher occurrence of the convection like the Mozambique Channel in January-February, Central Africa from February to

May with a peak in April and later in October-November, Nigeria in April-May, and along the Sub-Sahel region in July to September.

As expected, and considering 10° latitude x 10° longitude grid, the convective systems start developing at mid-day and reach their maximum vertical development in the middle of the afternoon in local time (see diurnal cycle plots in Fig.-3.4.2 to Fig.-3.4.13), but local features as shown later in the report can exist like over the Lake Victoria (see Section 3.4.3). According to the season, the convective clouds have the tendency to reach higher altitude and potentially to exhibit higher lightning activity due to deeper convection. The diurnal cycle plots shown in Fig.-3.4.2 to Fig.-3.4.13 also suggest the possibility of cloud overcast all day long, suggesting the need to double the solar panels and batteries of the LMA stations for enough power all day long to mitigate cloud overcast during several successive days.

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January

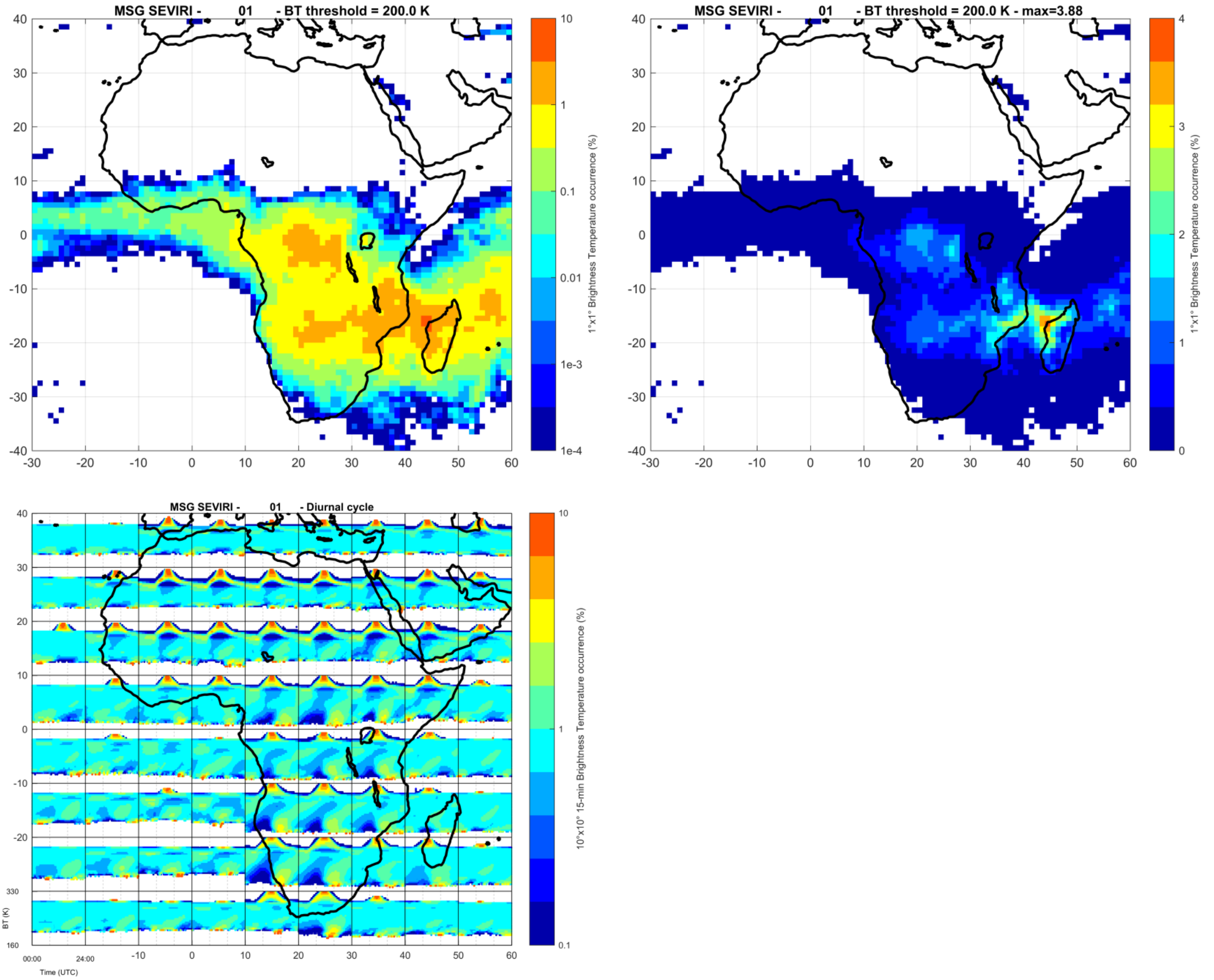

Fig.-3.4.2. Monthly distribution of the IR 10.8 µm brightness temperatures (BTs) based on 10 years of SEVIRI records (from 2011 to 2020) for January with from left to right and from top to bottom geographical distribution of IR 10.8 µm BTs below 200 K in log10 scale, geographical distribution of IR 10.8 µm BTs below 200 K in linear scale, and diurnal cycle of IR 10.8 µm BTs per 15-min period cumulated over all days of January 2011 to January 2020.

February

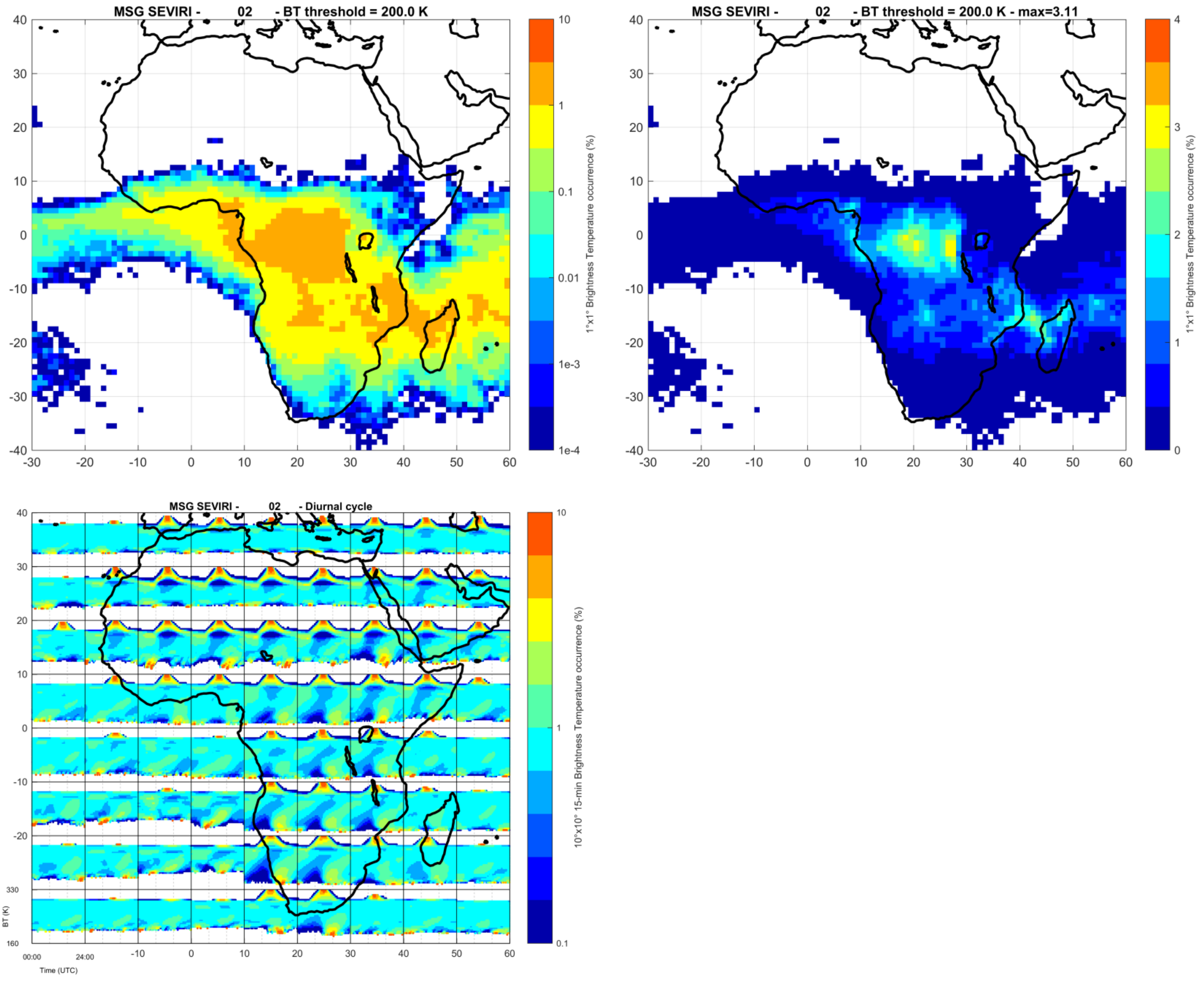

Fig.-3.4.3. Same as Fig.-3.4.2 but for February.

March

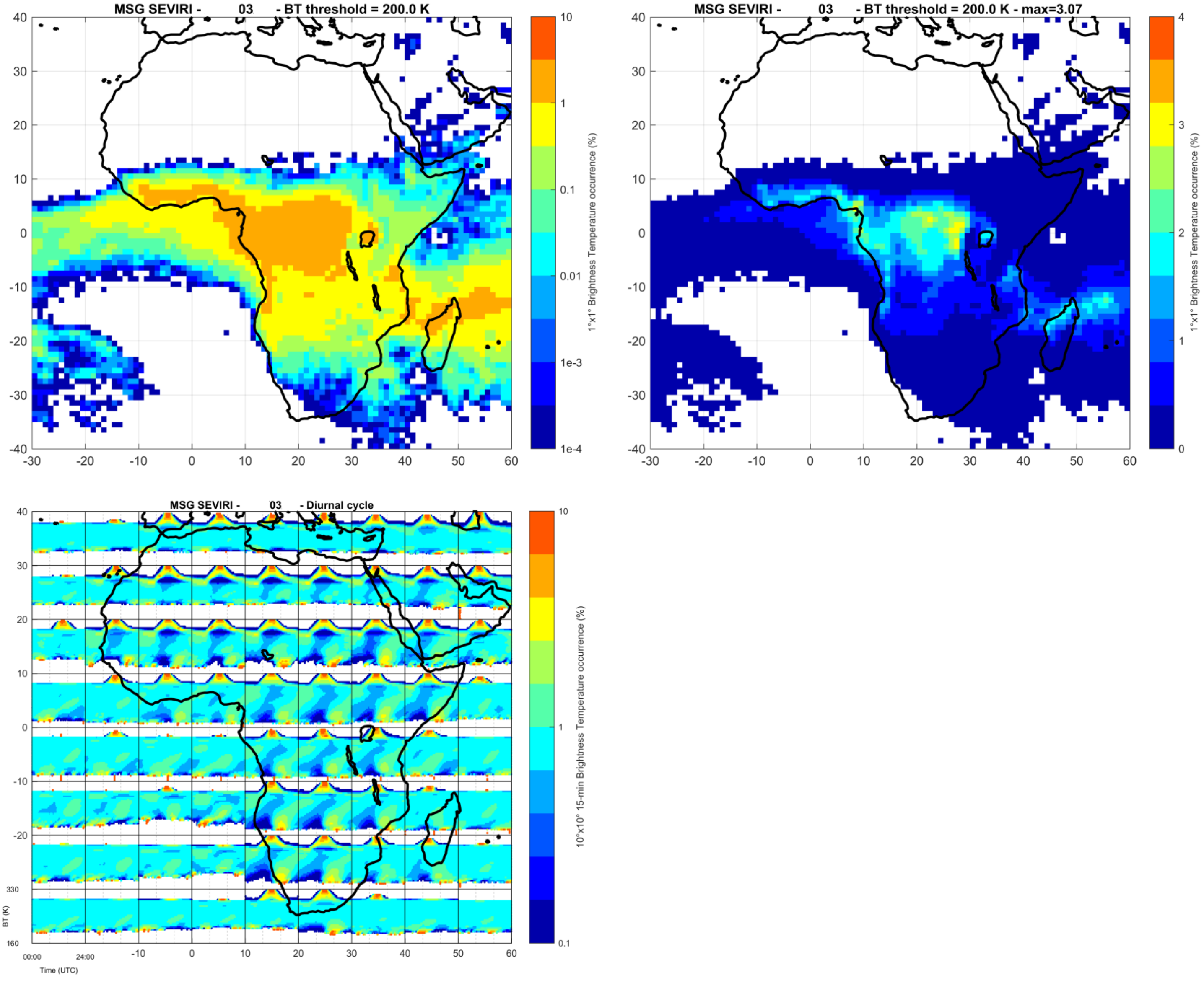

Fig.-3.4.4. Same as Fig.-3.4.2 but for March.

April

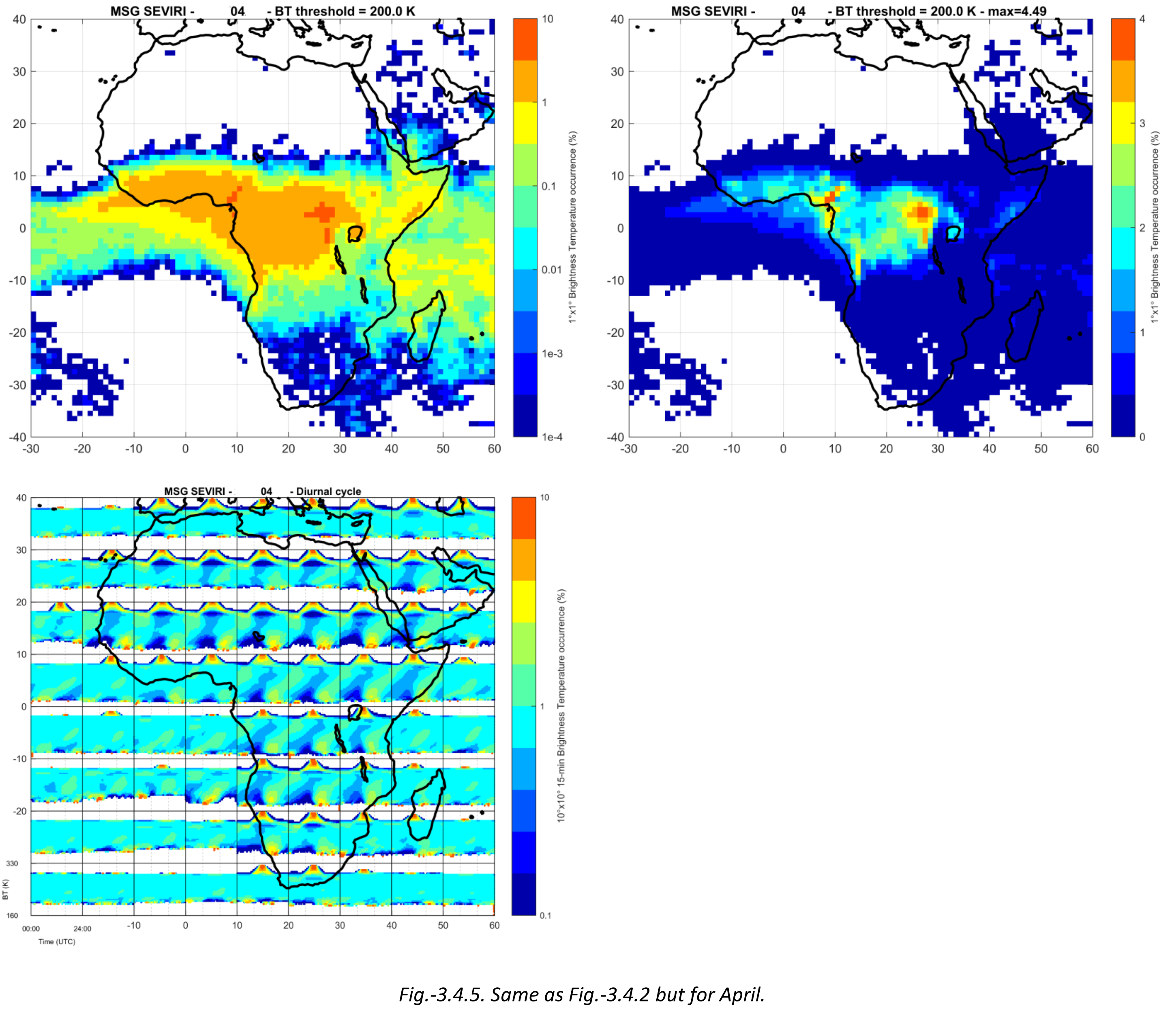

Fig.-3.4.5. Same as Fig.-3.4.2 but for April.

May

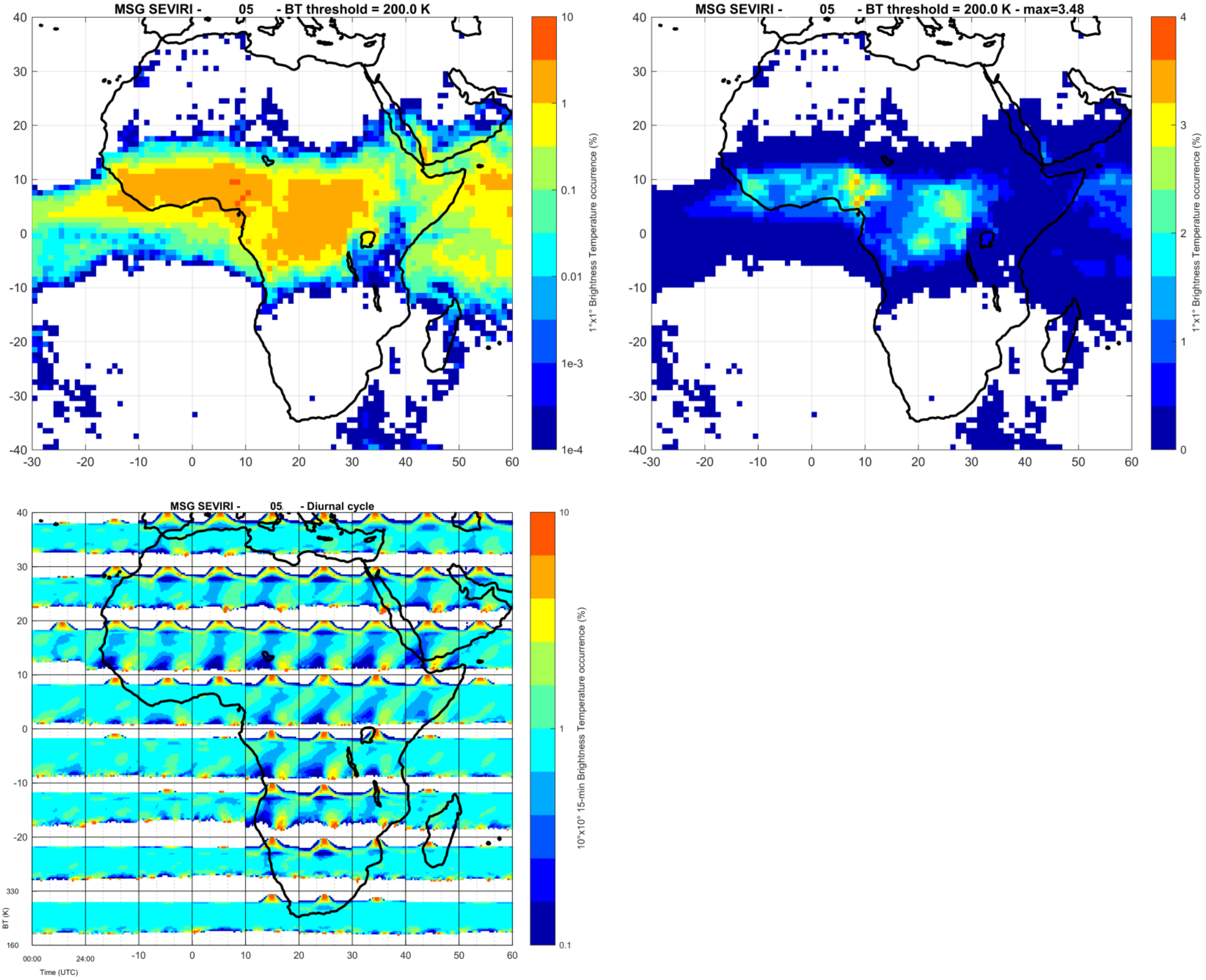

Fig.-3.4.6. Same as Fig.-3.4.2 but for May.

June

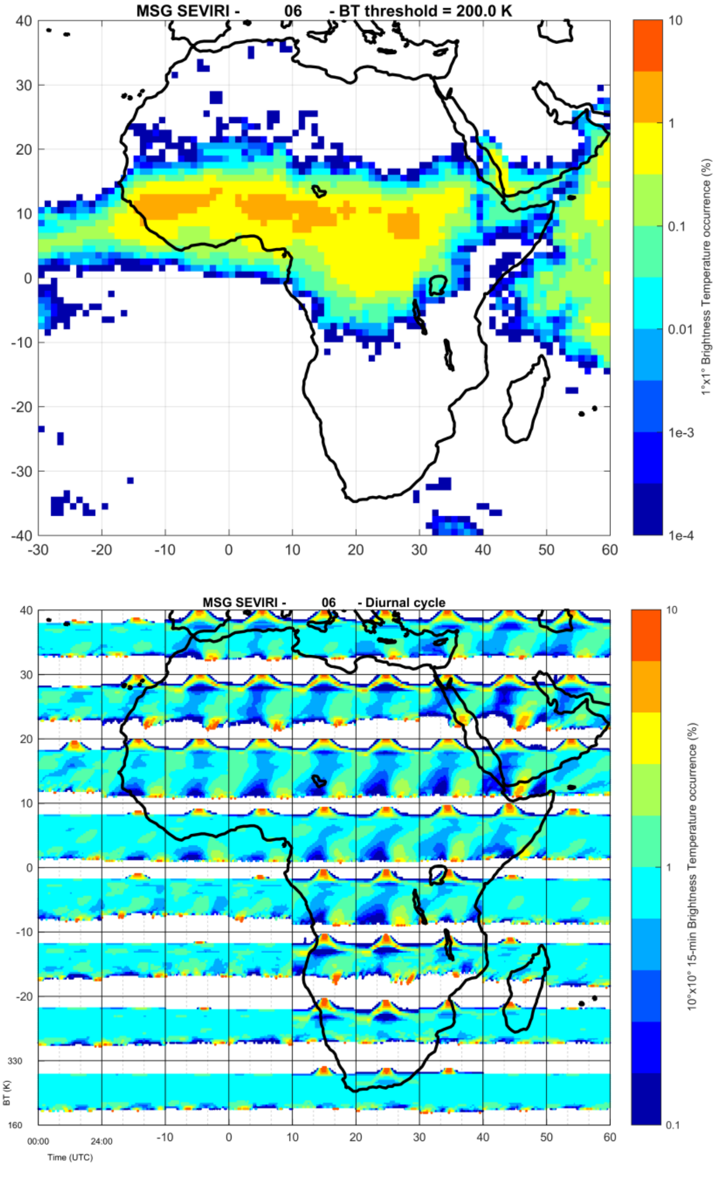

Fig.-3.4.7. Same as Fig.-3.4.2 but for June.

July

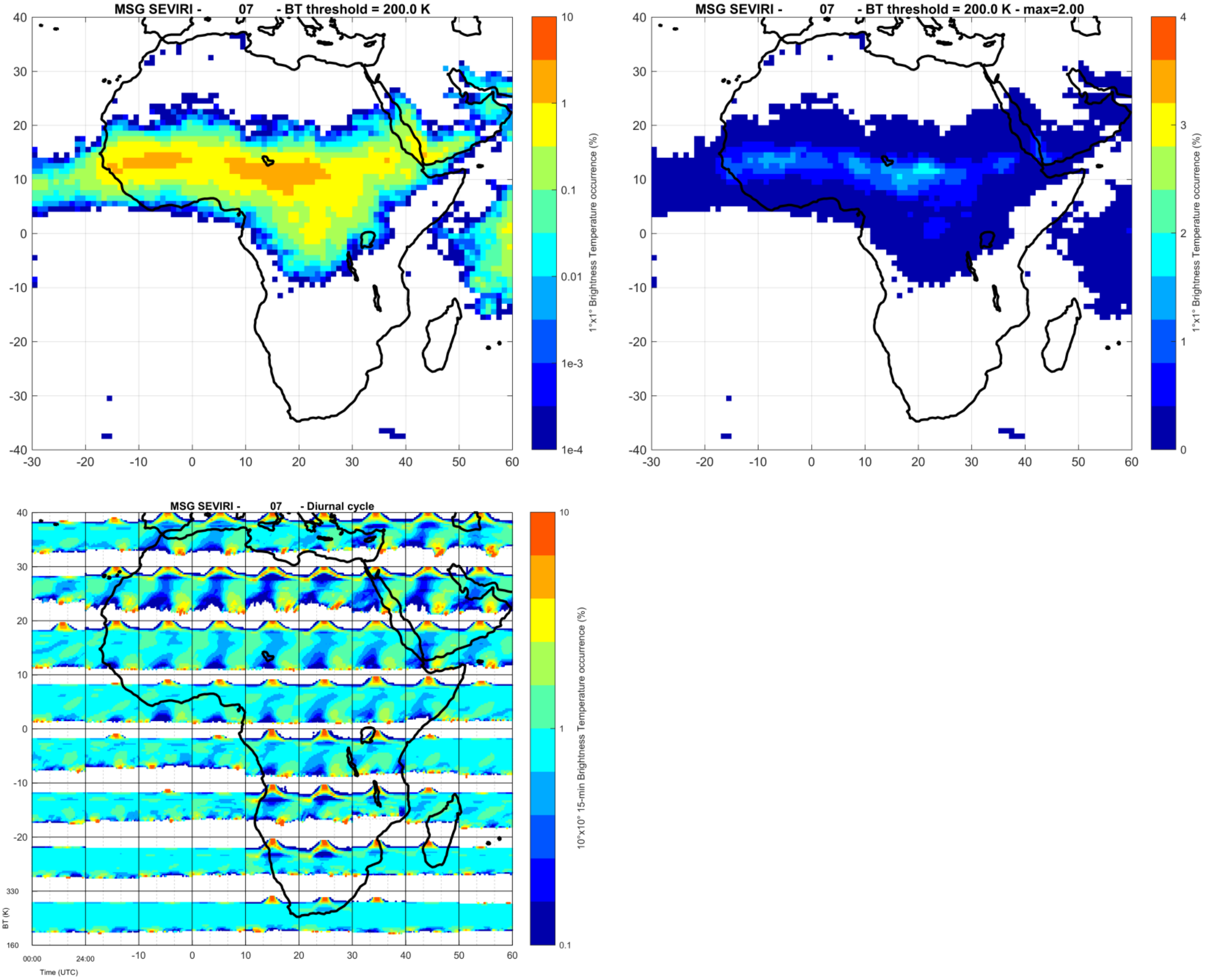

Fig.-3.4.8. Same as Fig.-3.4.2 but for July.

August

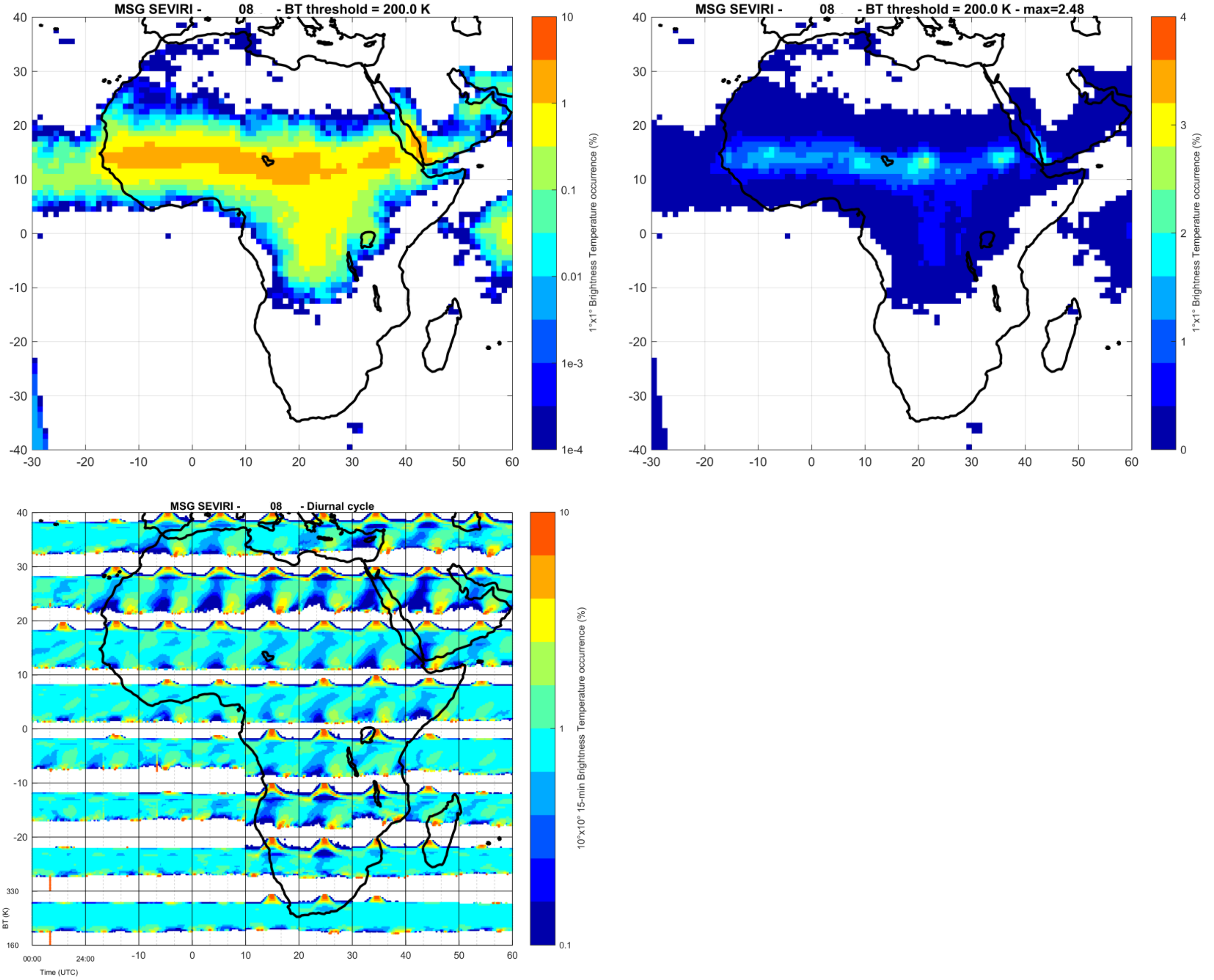

Fig.-3.4.9. Same as Fig.-3.4.2 but for August.

September

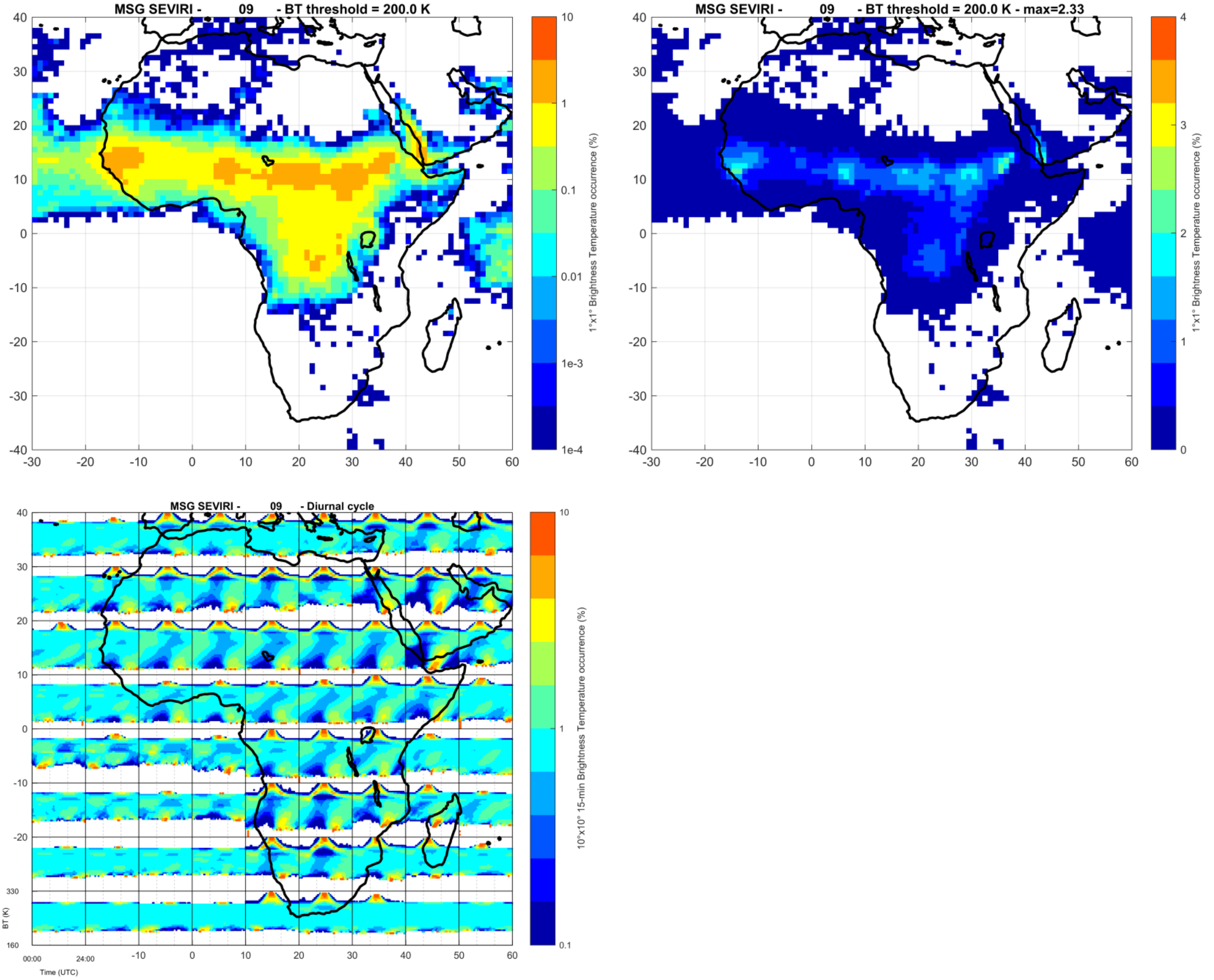

Fig.-3.4.10. Same as Fig.-3.4.2 but for September.

October

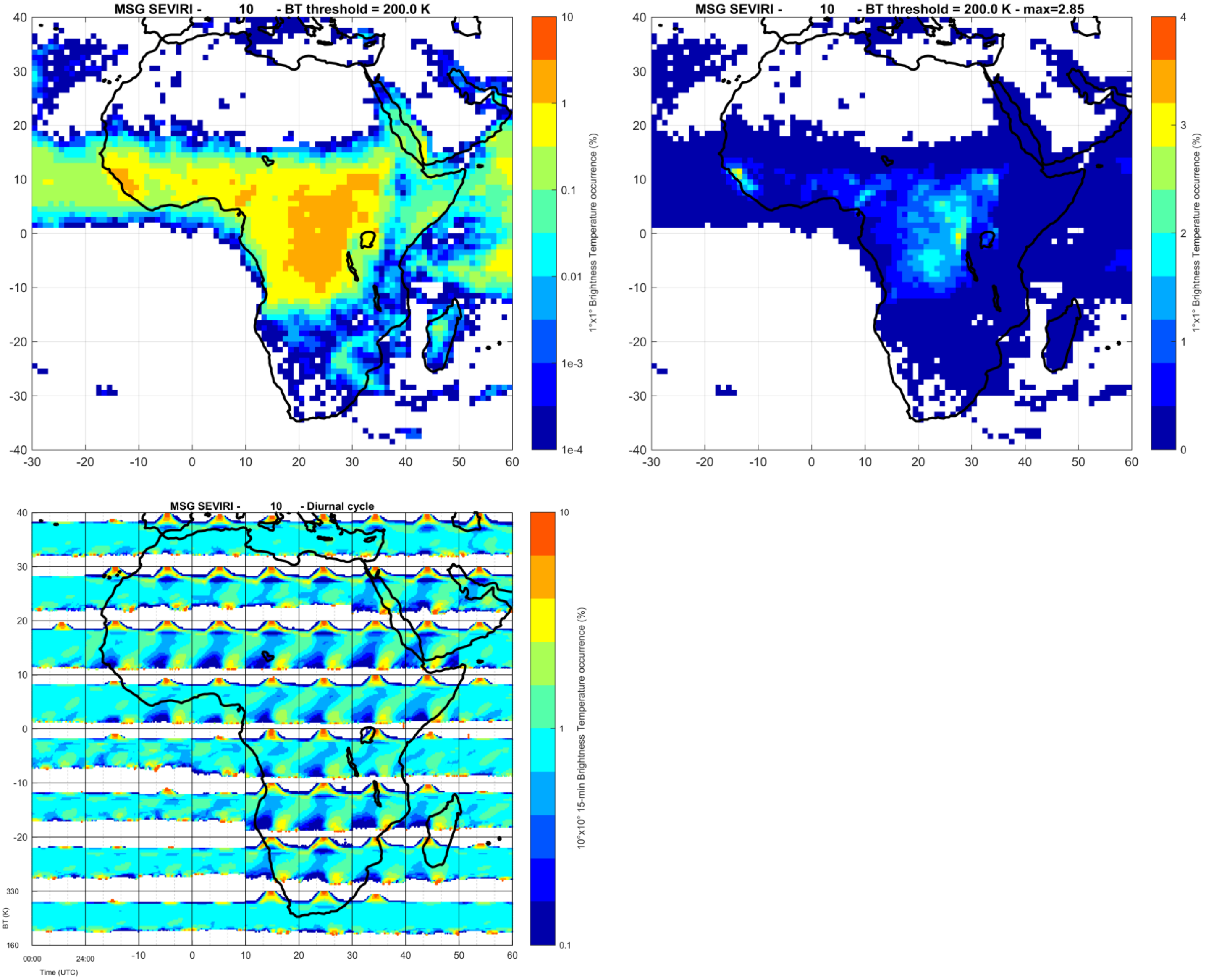

Fig.-3.4.11. Same as Fig.-3.4.2 but for October.

November

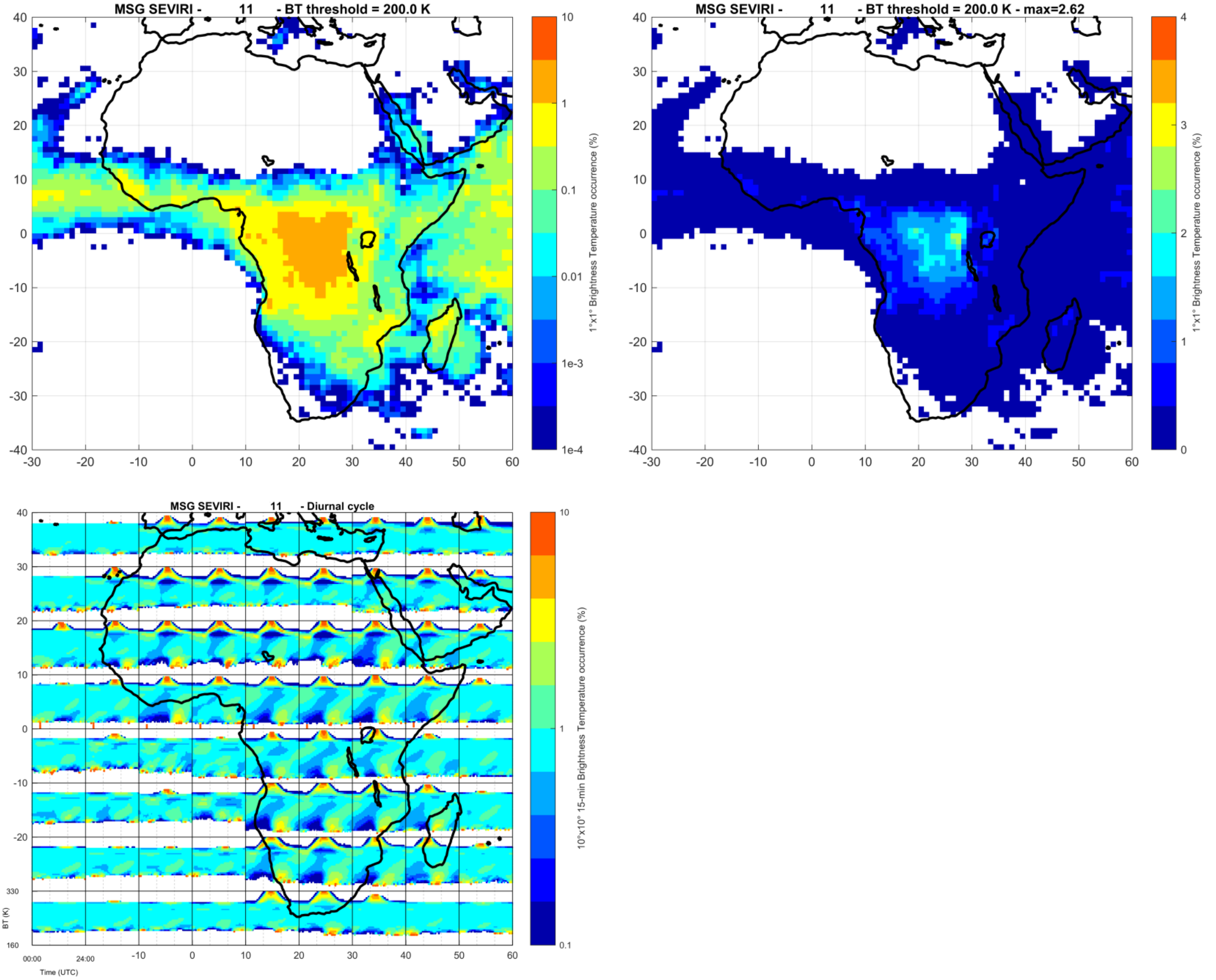

Fig.-3.4.12. Same as Fig.-3.4.2 but for November.

December

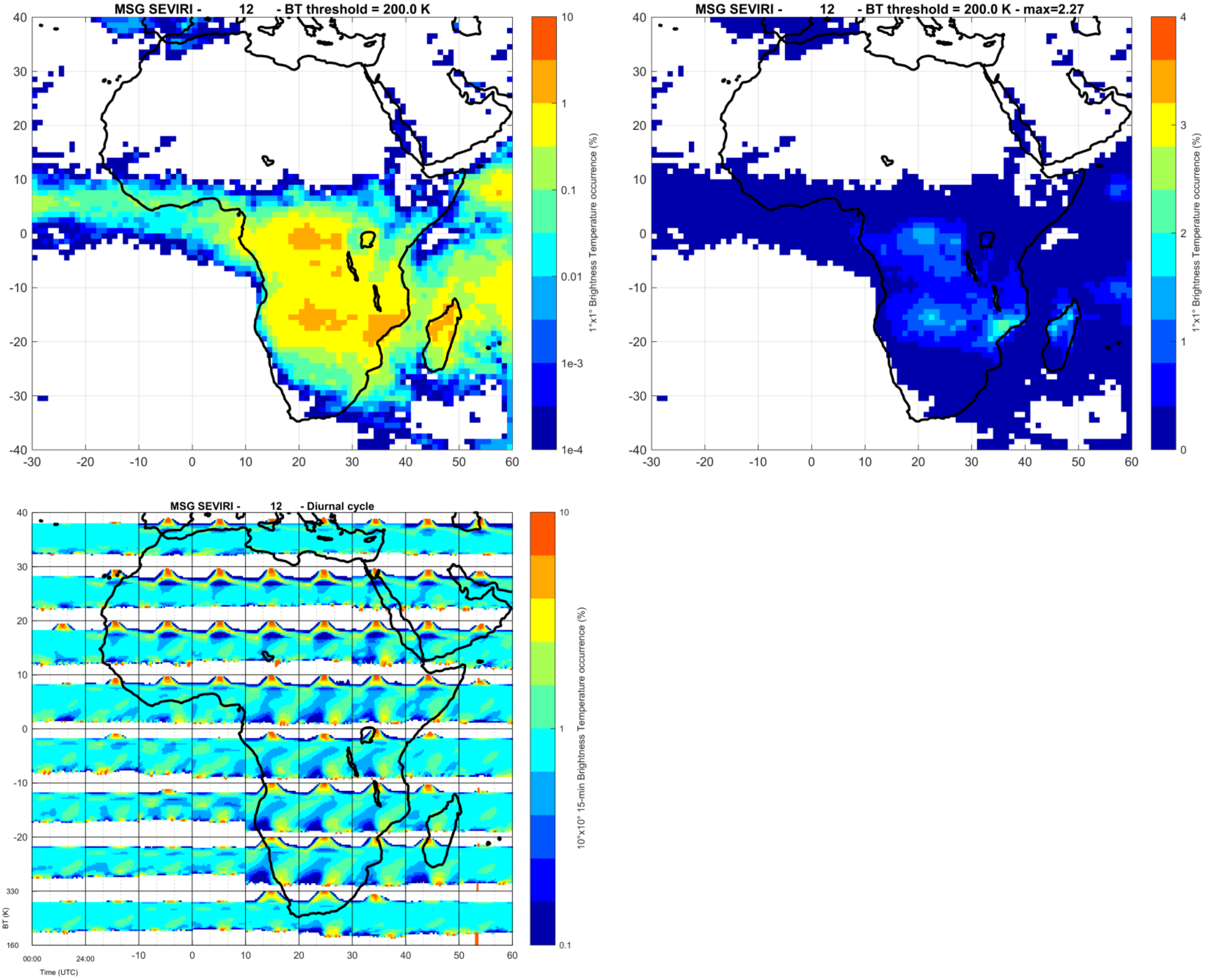

Fig.-3.4.13. Same as Fig.-3.4.2 but for December.

3.4.1.2 TRMM-LIS-based assessment

TRMM-LIS 0.1 Degree Very High Resolution Gridded Climatology data collection has been used to compute monthly and diurnal cycles for the period from 1998 to 2013 (16 years). This dataset is constructed from individual observations made by TRMM-LIS based on the observed flashes and the amount of view time for every 0.1°-latitude x°0.1-longitude grid box. Monthly (Fig. 3.4.14) and diurnal cycles (Fig. 3.4.15) are computed for the same 10°-latitude x 10°-longitude geographical domain used in the SEVERI assessment presented in the previous section. Average monthly and diurnal flash rates of 100 x 100 0.1°-side grid boxes have been computed to calculate the corresponding flash rates of a 10°x10° grid box.

Fig. 3.4.14 depicts the monthly cycle with 10°x10° resolution for the selected geographical domain. It shows how close to the equator, thunderstorm activity is evenly distributed over the year, with levels of 5e-2 to 1e-1 flashes/km^2/day. The northern Sahel sees activity from May through September, with deep minima (1e-4 flashes/km^2/day) in other months. In central southern Africa the trend is the opposite, with similar peak from November through February. Eastern South Africa and southern Madagascar also keep quite strong minimal activity (just below 1e-2 flashes/km^2/day) during May-September, which is a similar level as the summer maximum in areas like Morocco, Algeria and Tunisia. As a reminder, if the LMA covers a region of 100x100 km, 1e-1 flashes per km^2 per day means 1000 flashes a day.

The distribution of lightning activity, as derived from the TRMM-LIS climatology built for the present study, during the day is presented in Fig. 3.4.15. Overall, the typical diurnal cycle with a peak in the afternoon and a minimum in the early morning is present in the entire continent. The differences are found in their minima and maxima: equatorial Africa reaches a mean 1e-2 flashes/km^2/hour during the afternoon, followed by central southern Africa and Sahel regions (>1e-3 flashes/km^2/hour). In most places, the minimum is around 1e-4 flashes/km^2/hour, except in Central Africa (1e-3 flashes/km^2/hour). In fact, around the equator the levels stay at 1e-3 flashes/km^2/hour a significant part of the night, except regions close to the east coast. Again, it must be noted that if the LMA covers a region of 100x100 km, 1e-2 flashes per km^2 per hour means 100 flashes per hour.

In order to gauge more the strength of the lightning activity, Fig.-3.4.16 shows the actual value of the flash rate that corresponds to the 99% of the flash rate distribution. Again, the flash rate is computed per 0.1°x0.1° then aggregates per 1°x1° sub-regions. Then for each sub-region, the cumulative distribution function of the flash rate is computed for grid point boxes with more than 100 TRMM-LIS orbits with lightning observations. Different percentages of the cumulative distribution function of the flash rate have been considered (50, 90, 95 and 99%). The region of the Red Sea presents some high values as shown during the SON period (see the ellipse in Fig.-3.4.16d) as well as the Mozambique Channel (see the ellipse in Fig.-3.4.16a,b), both regions are on the edge of LI field-of-view. The regions of Democratic Republic of Congo and Central African Republic are the locations where one should expect the highest chance to have a flash rate statistically exceeding 15 flashes per min. Fig.-3.4.16 also shows the locations of the regions of interest (yellow boxes) that were initially identified in the early phase of the analysis as potentially interesting for the present study.

Fig.-3.4.17 provides additional properties of the lightning activity as sensed by TRMM-LIS and over the 16 years of records, and more specifically the mean flash rate at daytime (Fig.-3.4.17a) and at nighttimes (Fig.-3.4.17b). Fig.-3.4.17c presents the difference between daytime and nighttime mean flash rate divided by the daily mean flash rate. Fig.-3.4.17d finally provides local time of the flash rate maximum as derived from the 16 years of TRMM-LIS data. South of the African continent mainly exhibits a maximum of the flash rate at around 16:00 LT (Fig.-3.4.17d), while along west Africa, the TRMM-LIS climatology shows a maximum of the flash rate at the end of the day (Fig.-3.4.17d) with a more pronounced activity during daytime (Fig.-3.4.17c).

Fig.-3.4.14. 10°-latitude x 10°-longitude monthly cycle from 16 years of TRMM-LIS data

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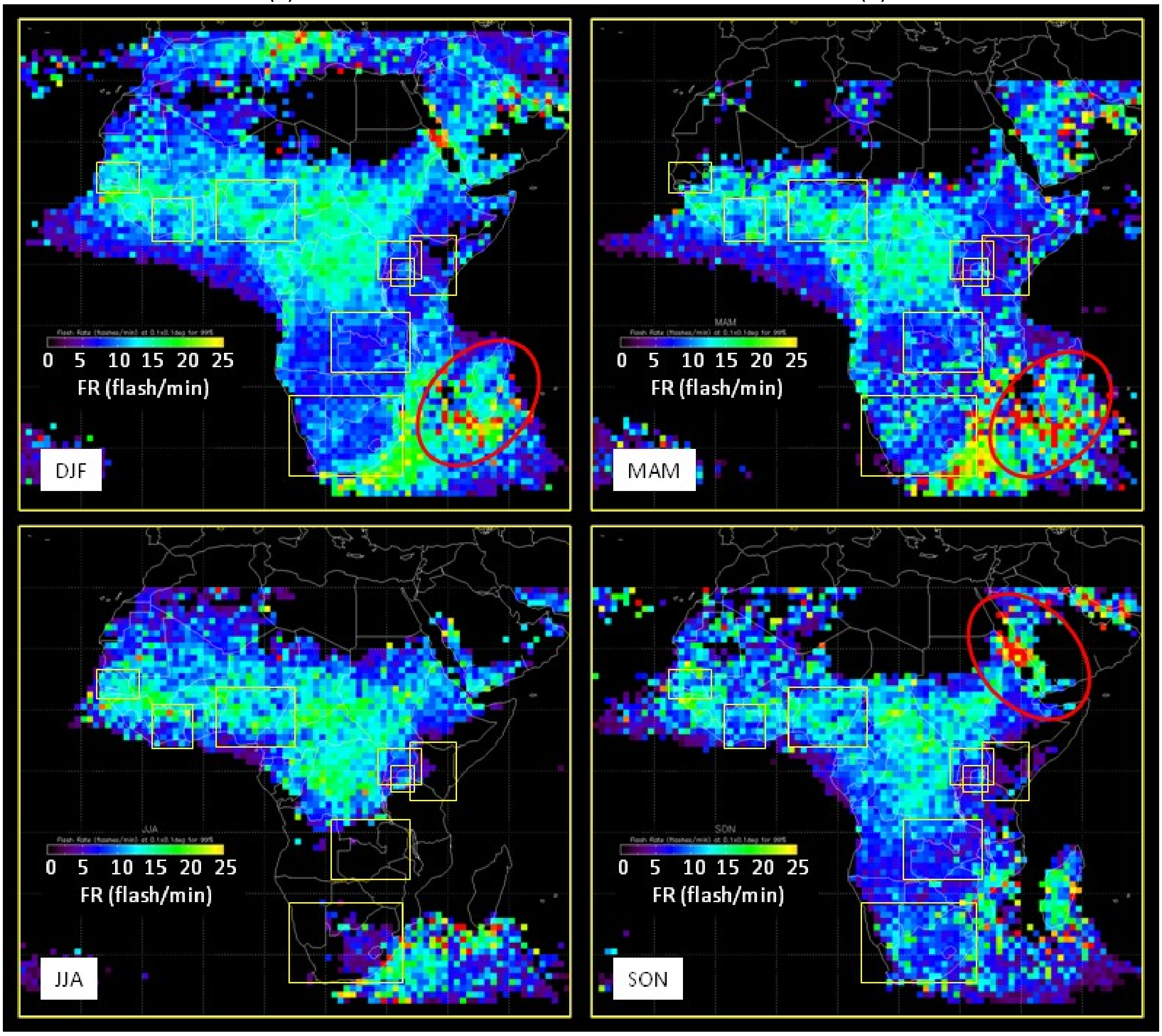
Fig.-3.4.15. 10°-latitude x 10°-longitude diurnal cycle from 16 years of TRMM-LIS data.

(a) (b)



(c) (d)

Fig.-3.4.16. 1°-latitude x 1°-longitude TRMM-LIS flash rate at 99% of the flash rate distribution according to the seasons. The ellipses show the location of the Red Sea and the Mozambique Channel (see text). The yellow boxes show the locations of the regions of interest that were initially identified as potentially interesting for the present study.

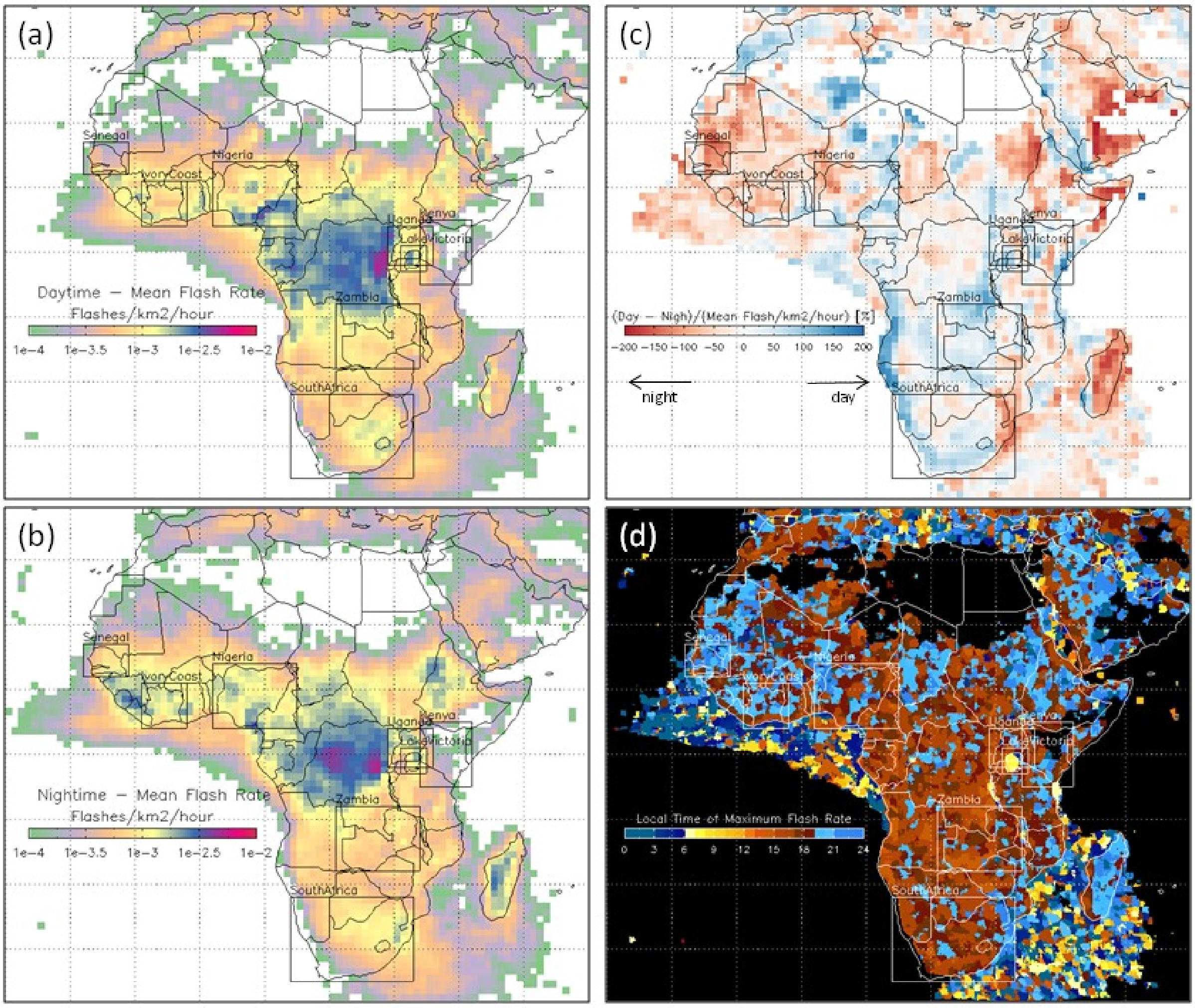


Fig.-3.4.17. 1°-latitude x 1°-longitude TRMM-LIS mean flash rate during day (a) and night (b), mean flash rate difference between day and night relative to mean flash rate (c), and local time of the maximum flash rate (d) as derived from TRMM-LIS records. The black (in a, b, c) and yellow (in d) boxes show the locations of the regions of interest that were initially identified as potentially interesting for the present study.

In order to be more confident with the flash rate distribution retrieved in Africa with TRMM-LIS records, TRMM-LIS flash rate distribution was computed in South America and compared with the corresponding 0.1°x0.1° grid boxes GLM flash rate distribution computed for the year of 2020. Fig.-3.4.18 shows the flash rate distribution retrieved for areas of 10°x10°, similarly to what has been done for Africa, but for both GLM and TRMM-LIS sensors. The flash rate distribution obtained by GLM distribution (continuous line, Fig.-3.4.18) is quite similar to LIS distribution (dashed), except for flash rates below 3-5 flashes/minute. To highlight the difference between the two flash rate distributions within a given 10°x10 region, Fig.-3.4.19 shows the difference between the cumulative frequency of occurrence of flash rate detected by TRMM-LIS and by GLM. The positive values mean that TRMM-LIS detected more flashes in that category. From these panels, we can see that TRMM-LIS is more sensitive to low flash rates than GLM and the probable cause could be due to the altitude and the footprint pixel size differences. Despite the detection differences, both sensors show similar distribution for flash rates above 5 flashes/min, suggesting that using TRMM-LIS to compute the expected flash rate distribution in Africa is correct to identify the best locations for validation.

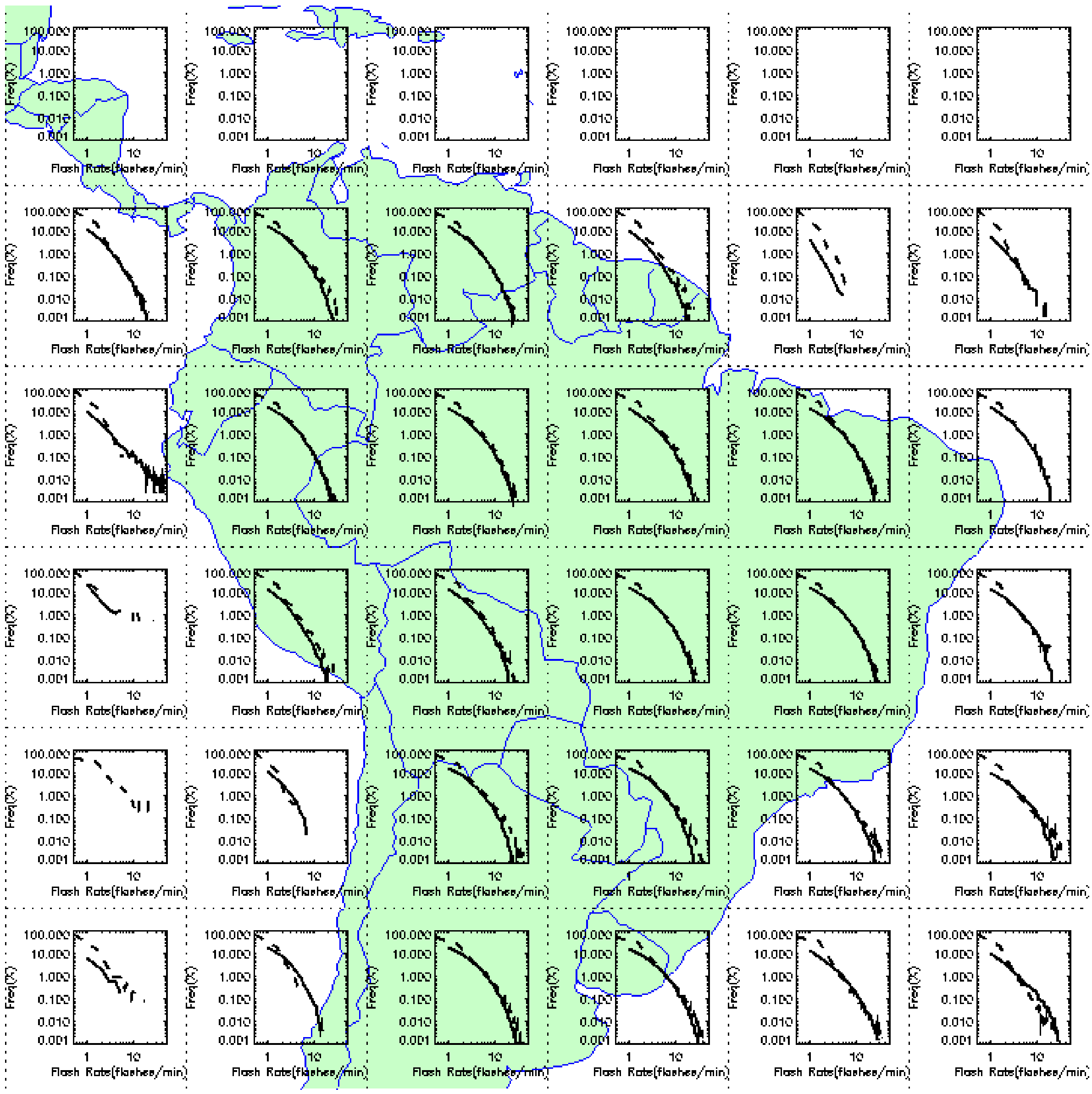


Fig.-3.4.18. 0.1°x0.1° flash rate distribution (computed per minute) computed on GLM records (solid lines) and LIS observations (dashes lines) over South America gathered in 10°x10° regions.

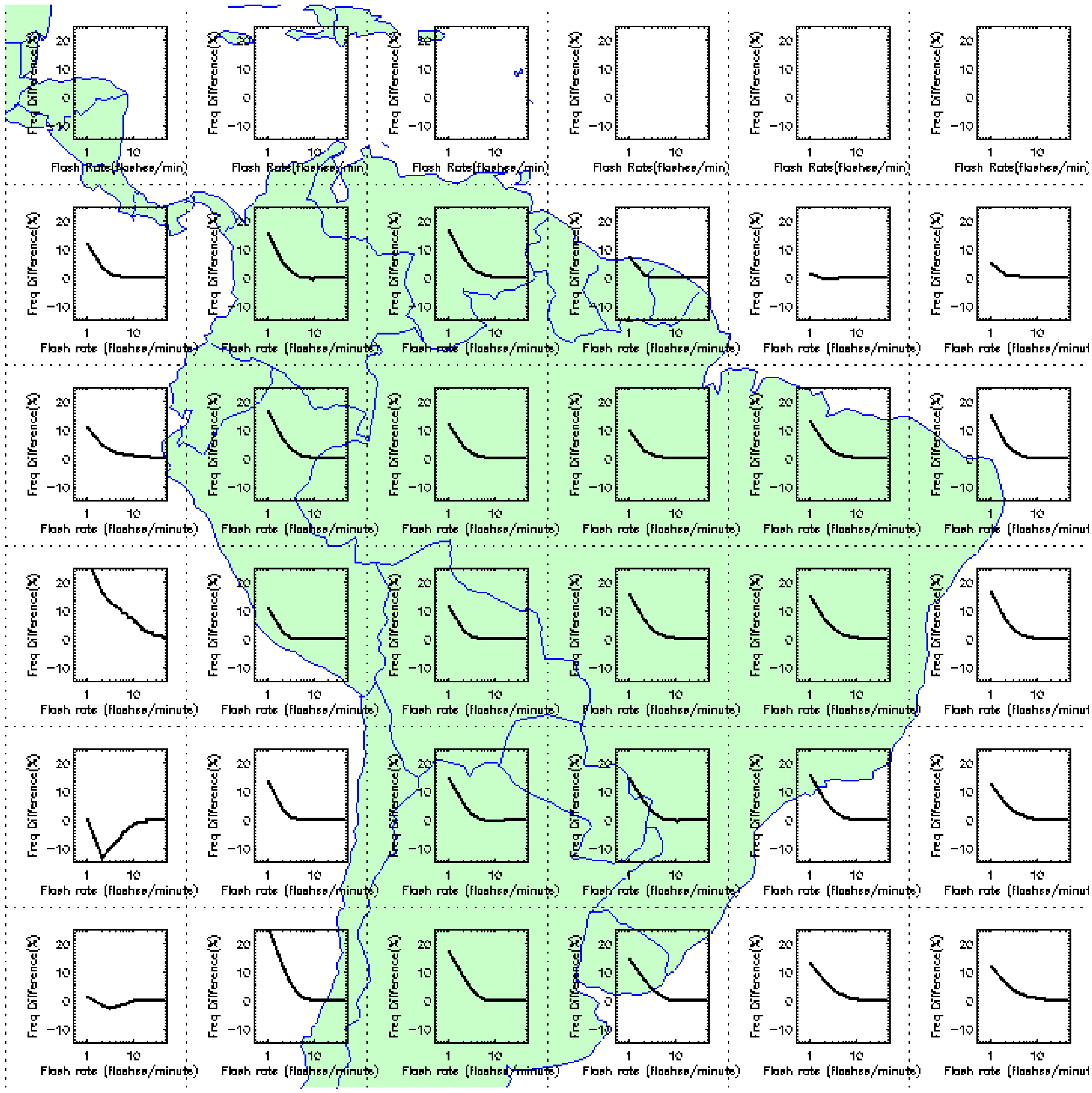


Fig.-3.4.19. Difference between the cumulative frequencies of occurrence of flash rate detected by LIS and GLM over South America, computed per 0.1°x0.1° grids and gathered in 10°x10° regions.

3.4.1.3 GLD360-based assessment

EUMETSAT provided 6 months of GLD360 data to explore the lightning properties over Africa for the period July to December 2020. This 6-month dataset, even if it is not statistically representative, has still been analyzed to document even over a short period of time the lightning activity over Africa and the regions of interest.

Fig.-3.4.20 presents the monthly distribution of the flash density (expressed in flash/km^2/month) for each of the 6 months of the GLD360 dataset. The maximum of the flash density is mainly located over Democratic Republic of Congo, where lightning activity has been recorded in the north part of the country during the entire period. The GLD360 dataset is further discussed for the three regions of interest (see Sections 3.4.3 to 3.4.5).

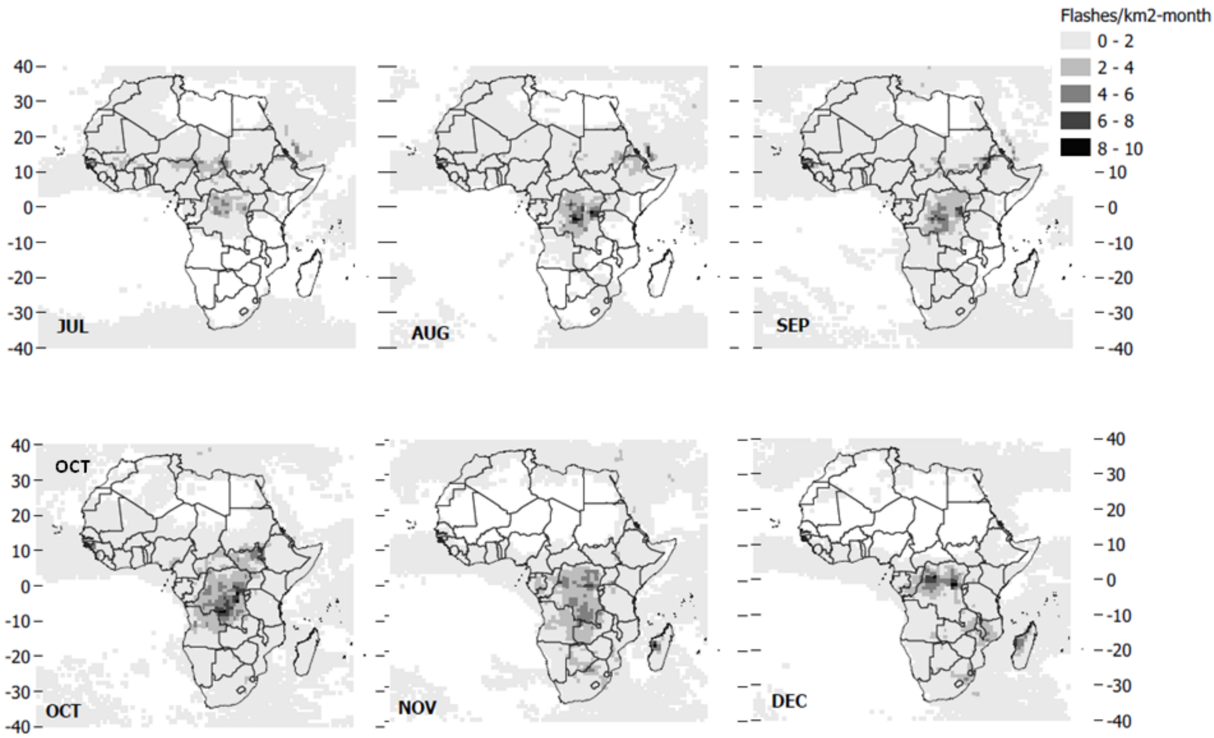


Fig.-3.4.20. Flash distribution expressed in Flash/km^2/month per month as derived from 6-month GLD360 dataset (July to December 2020).

3.4.2 Criteria to define a "relevant site" to support to MTG-LI cal/val activity

The different figures of Section 3.4.1 reveal that numerous regions in Africa exhibit interesting lightning and convection features with different amplitudes, all year long in some places, and during specific periods of the year at other places. In order to reduce the number of regions to analyze in details, EUMETSAT asked to specifically explore three regions: Kenya/Uganda/Lake Victoria, Côte d'Ivoire, and South Africa, as for the three regions EUMETSAT is in contact with the National Weather Services (NWSs), and because of the existence of a ground-based VLF lightning location network (SALDN) operated by the South Africa NWS.

Table 3.4.2.1 summarizes the different criteria that can define a relevant site from the perspective of the thunderstorm/lightning occurrence, the LI evaluation needs, and the characteristics of the site.

Table 3.4.2.1. Criteria that define a relevant site in terms of occurrence of lightning activity, LI evaluation needs and site characteristics.

	Criteria	Description
LIGHTNING	Lightning activity	The covered area must be active in terms of storms and lightning. A convenient site would have a wide spectrum of flash rates. LMA network can be installed in the site with potential coverage over land and water.
	Monthly activity	Lightning activity can be occurring in some periods of the year.
	Hourly distribution	Sites with lightning activity during daytime and nighttimes allow investigating the performances of the LI in both day and night. This is affected by the type of convection and local conditions that trigger the convection. To have a broad spectrum of flash size, duration and rate during the day.
	Effects on the society	Relevance in terms of the effects of lightning in the region of interest (e.g. damages, injures, fatalities).
LI	LI FOV	Location of the site versus the LI field of view and pixel size. Center and edges of the field of view, distance to the satellite sub-point (parallax).
	Day/Night	Interest in day performance, night performance or both.
	Flashes, groups, pulses	To have a broad spectrum of flash size, duration and rate for the quantification of LI detection efficiency, false alarm rate, location accuracy, time accuracy, and for the validation of the event-to-group and group-to-flash merging algorithms.
LMA sites	Local support	Hosting during the campaign and support the installation, the operation and the dismantlement. Former collaborations.
	Accessibility	Travel to the country, transportation to the sites, safety.
	Equipment availability	Capacity to purchase locally hardware (batteries, cables, masts...).
	Power	The site shall provide the conditions to power the LMA stations (from the grid or from solar panels).
	Effects of thunderstorms to the sites	The site might suffer the effects of thunderstorms (e.g. flooding, string winds) or other phenomena (e.g. power outages).
	Environmental electromagnetic noise	The regular LMA operation frequency is tuned to frequencies of analog TV channels (typically CH3: 60-66 MHz).
	LLS and radar	Coverage of concurrent lightning location systems (LLS) and/or weather radar.

The minimum requirement for the operation of an LMA station is the availability of a power source. Commonly, sites with low electromagnetic noise are isolated from buildings and power lines, and required to be solar powered. Fig.-3.4.21 shows pictures of a standalone LMA station operated in Corsica, powered by a solar panel and two batteries.

Fig.-3.4.22 shows the monthly variation of the photovoltaic (PV) power potential. This refers to how much energy (kWh) is produced for every KWp (power peak) of solar module capacity. Those numbers come from global solar data (e.g. from Global Solar Atlas). The period of data comprises, approximately, from 1994 to 2018. The three Africa countries (Kenya, Côte d'Ivoire, South Africa) are considered and one site in Europe (Corsica) as the LMA sensors operated in Corsica are all solar powered. While PV power potential shows a single mode centered in summer in Corsica, the more or less uniform PV variation for three African regions of interest suggests the need to double the solar panel surface to avoid power outage after several cloudy days. The power consumption of a Rev. 3

LMA station (including modems) is about 24 W, so each month it will require 17.8 kWh. From the analysis, if we assume a conservative yield of 100 kWh/kWp for the three African regions, the solar capacity shall be 178 W. So, a solar panel of 180 W would be enough. The experience in Corsica has shown that with the current solar power system with a panel of **175 W,** the system does not guarantee the power supply during the winter months where the yield is below 100 kWh/kWp. In conclusion, it is recommended to install at least 400 W of power in order to avoid power outages after several cloudy days. This will also depend on the version of the LMA stations (e.g. Rev. 5 LMA electronics consume about 6 W compared to 12 W for Rev. 3) and the type of communications (mobile phones versus satellite links) that will be used during the campaign.

Fig.-3.4.21. One of the 12 LMA stations operated in Corsica (France).

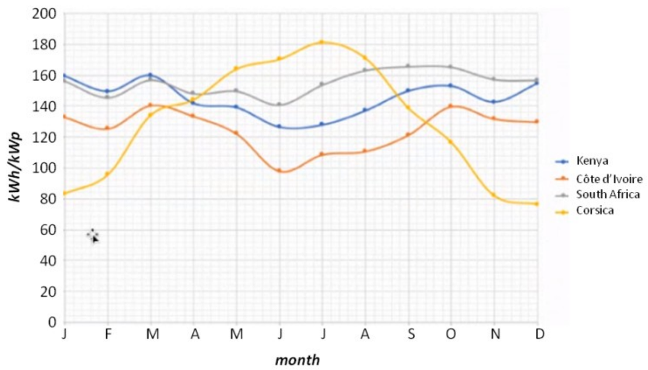


Fig.-3.4.22. Photovoltaic power potential for Kenya, Côte d'Ivoire, South Africa, and Corsica (data source: Global Solar Atlas).

3.4.3 Analysis for the Lake Victoria region (Kenya/Uganda/Lake Victoria)

The following section synthesizes the numerous graphs and results that have been gathered to characterize the electrical activity in the Lake Victoria Region.

Fig.-3.4.23 shows the monthly distribution of the convective clouds as derived from SEVIRI observations for the domain of interest, and more specifically two periods during the year when convection occur over Lake Victoria: the first one ranges from February to April, the second one with less amplitude between October and November. Fig.-3.4.24 focuses on April and November and shows that during those two months the whole lake as well as the northern and the eastern shores experience convection (Fig.-3.4.24a,b). Fig.-3.4.24c,d show the diurnal cycle of the convection and reveals a specific signature: convection occurs meanly over land during the afternoon but during the second part of the night to the early morning over the lake itself.

Fig.-3.4.25b shows the lightning distribution computed from the 6 months of GLD360 records, while Fig.-3.4.25a shows the convection distribution as derived from SEVIRI observations for the same period. During July-December 2020, the lightning activity was mainly located over the lake, the eastern shore and the northeastern shore (Fig.-3.4.25b). Similar locations of the convection can be observed from SEVIRI records (Fig.-3.4.25a).

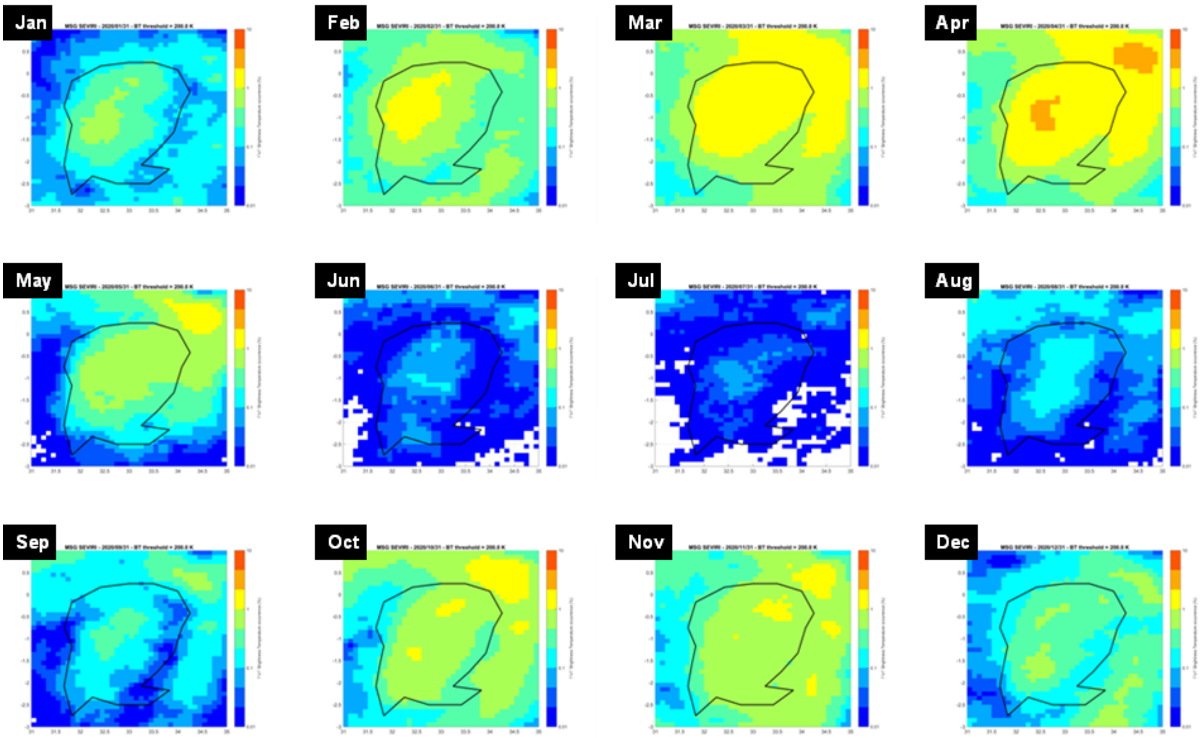


Fig.-3.4.23. Same as Fig.-3.4.2-13a but zoomed on Lake Victoria region and for each month of the year.

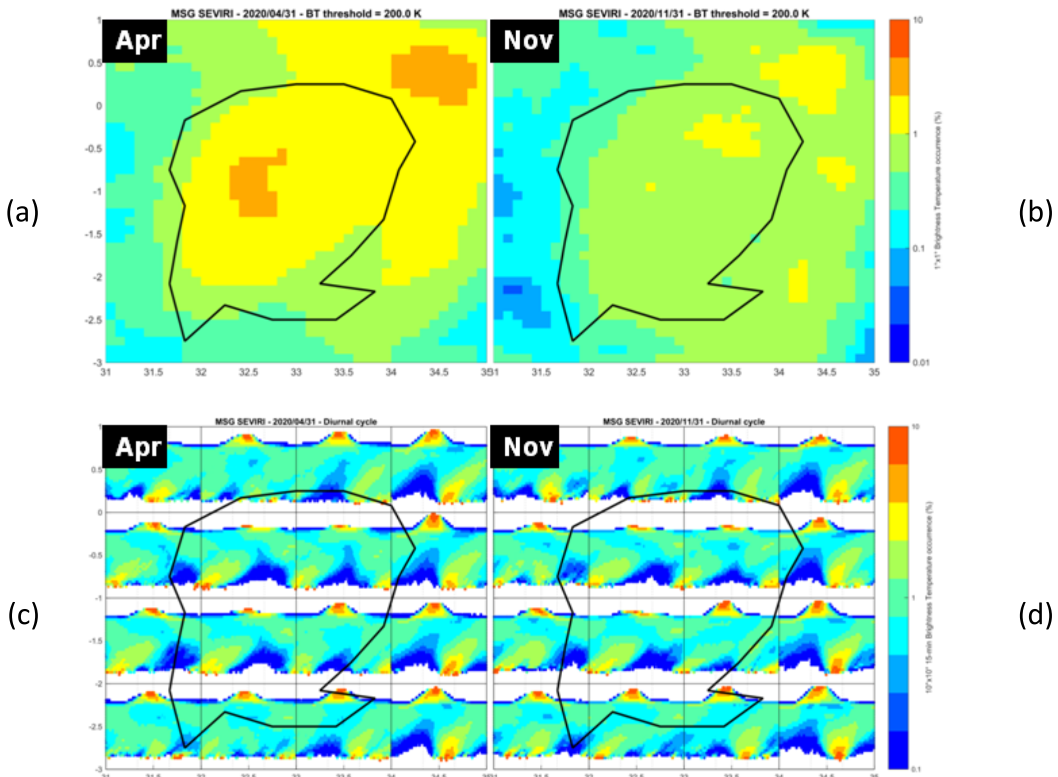


Fig.-3.4.24. Same as Fig.-3.4.2-13a but zoomed on Lake Victoria region but for April (a) and November (b), and diurnal cycle as derived from the brightness temperatures for April (c) and November (d).

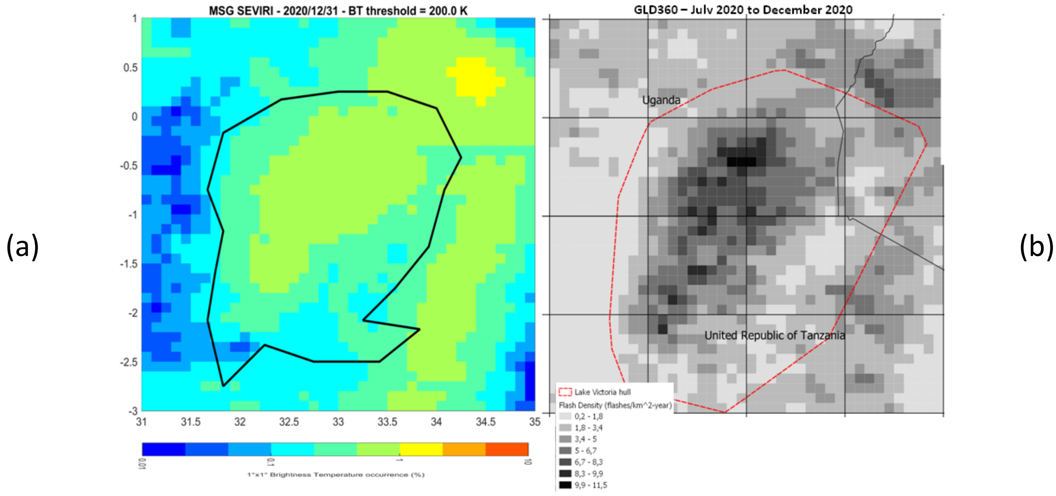


Fig.-3.4.25. SEVIRI based convection distribution (a) and GLD360 flash density (b) measured during the period July-December 2020.

Fig.-3.4.26b presents the geographical distribution of the number of storm days as derived from the 6-month GLD360 data. To compute that distribution, any 0.1°x0.1° box counting at least one GLD360 record per day is incremented. As expected the same regions are found: the lake itself, the eastern shore, and more generally the northern shore. Fig.-3.4.26c confirms that the convection and the lightning activity are dominant during the afternoon over land and during the night over the lake. Fig.-3.4.26d shows that in most 1°x1° sub-regions, it is in October and in November that high flash rates are measured, based again on the 6-month GLD360 dataset.

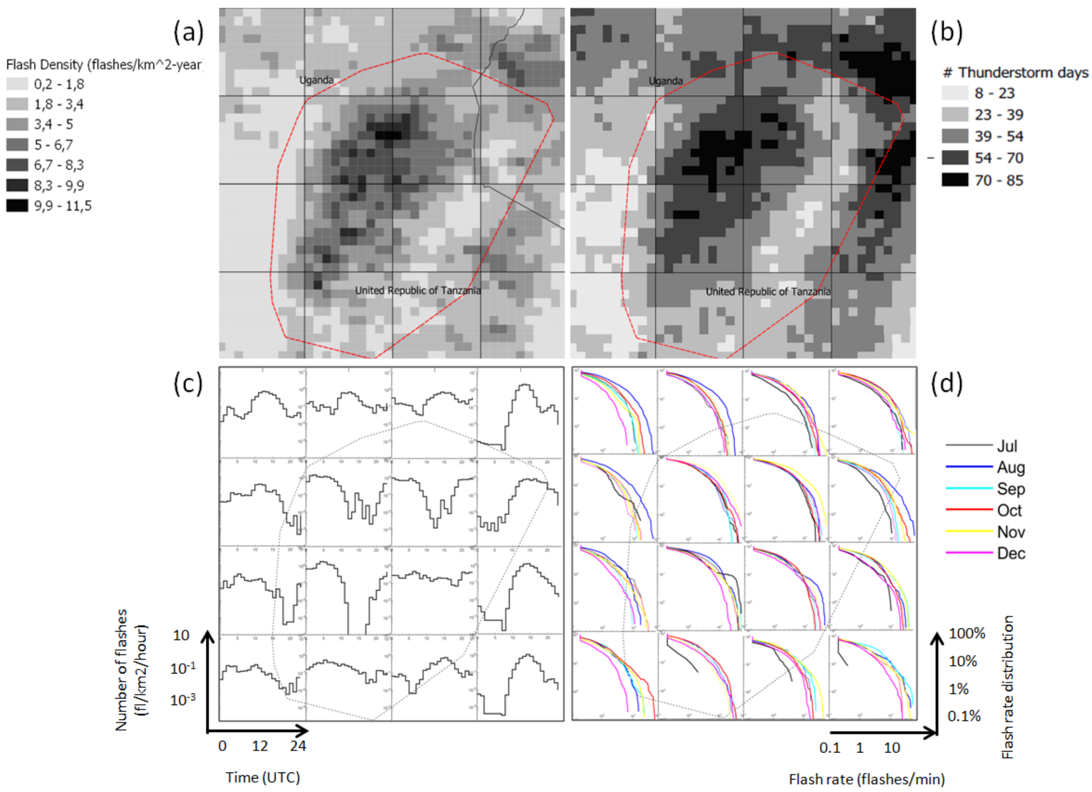


Fig.-3.4.26. GLD360 flash density (a), number of thunderstorm days (b), diurnal evolution of the number of flashes (c), and distribution of the flash rate per month (d), for the period July-December 2020.

Based on the 16 years of TRMM-LIS, Fig.-3.4.28a shows interestingly a rather similar lightning distribution to the one built from the 6-month GLD dataset (Fig.-3.4.26a), with hotspots located over the lake, the eastern shore and the northeastern shore. For comparison, Fig.-3.4.28b shows a rather consistent geographical distribution of the cloud climatology based on all observations summed up for the 10 years of SEVIRI data used in the present study. Fig.-3.4.28c confirms the two periods of convection in the region of interest, February-April and September-November. Finally Fig.-3.4.28d shows different patterns of the diurnal cycle at daytime and at night with the lightning activity being predominant in the afternoon over the land and during the night over the lake. This difference in diurnal cycle was also pointed out through the SEVIRI-based climatology (Fig.-3.4.24c and Fig.-3.4.24d for April and November respectively).

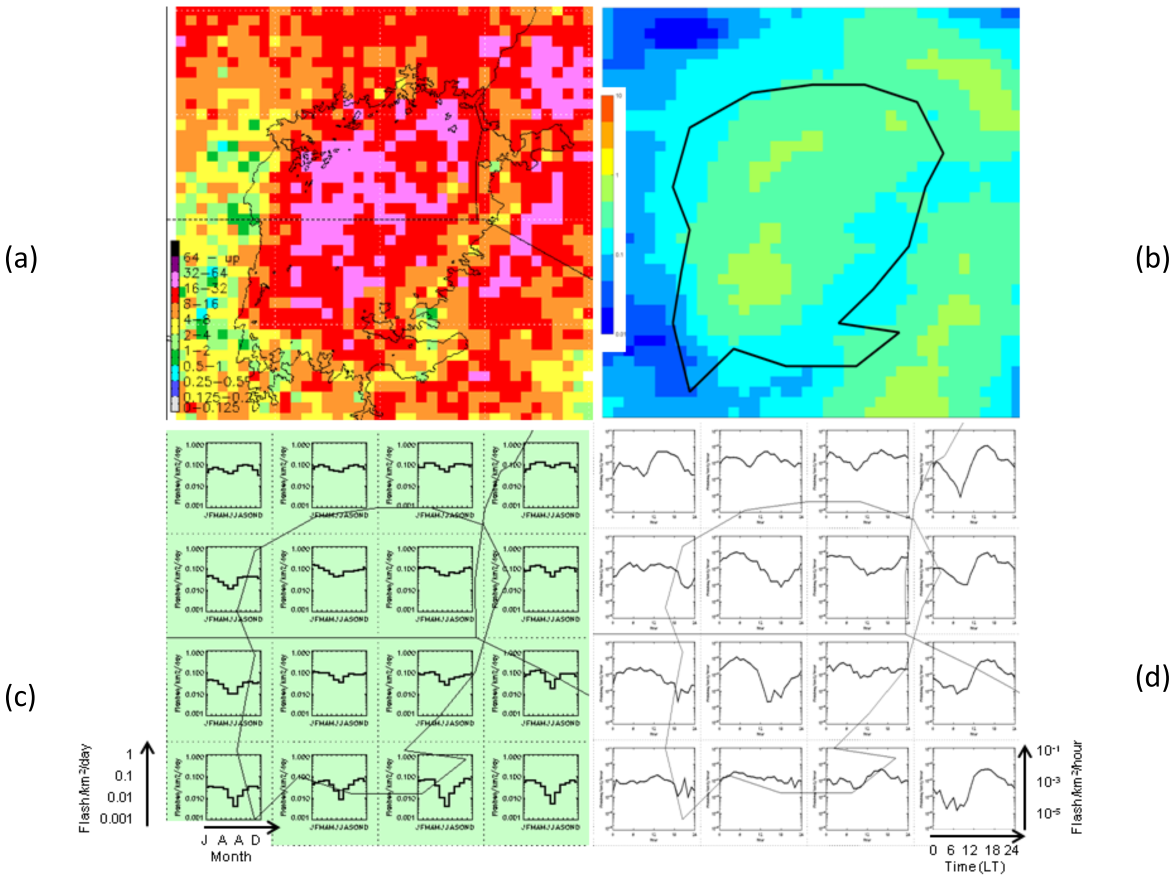


Fig.-3.4.28. TRMM-LIS flash density (a) for 16 years of data, SEVIRI convection distribution (b) for 10 years of data, (c) monthly flash rate as a function of the months, and (d) diurnal cycle of hourly flash rate.

The results found here are consistent with the ones given in Virts and Goodman (2020), where, based on 4 years of Earth Networks Global Lightning Network (ENGLN) records (September 2014–August 2018), "*diurnally, solar heating and lake and valley breezes produce daytime lightning maxima north and east of the lake, while at night the peak lightning density propagates southwestward across the lake.*" Storm initiation occurs northeast of the lake, over the lake and northern lowlands. They also report that "*daytime thunderstorms dissipate without reaching Lake Victoria, and annually 85% of* [lightning] *clusters producing over 1000 flashes over Lake Victoria initiate in situ.*" They also report that the larger electrical storms (Fig.-3.4.29) are most common during February–April and October–November, which is also what is found in the present study. Fig.-3.4.30, still from Virts and Goodman (2020), confirms the diurnal cycle feature with more flashes over the lake (land) during night (day).

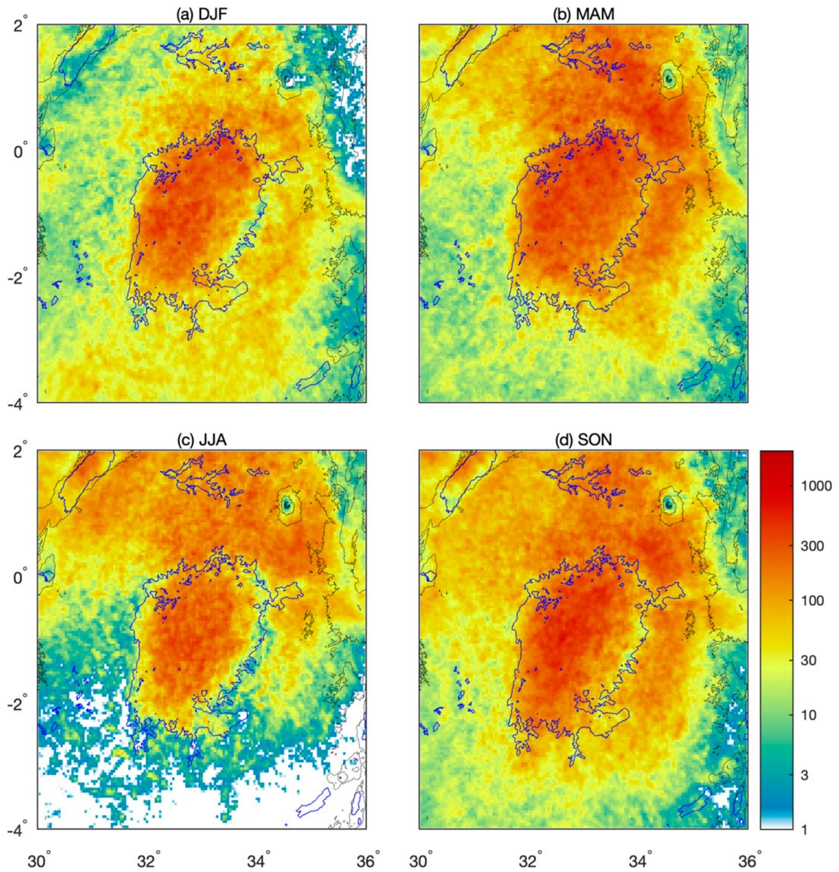


Fig.-3.4.29. (from Virts and Goodman, 2020) ENGLN seasonal-mean lightning density (flashes/km^2/yr) during (a) December–February (DJF), (b) March–May (MAM), (c) June–August (JJA), and (d) September–November (SON). Elevation contours at 1000-m intervals are in black (period September 2014–August 2018).

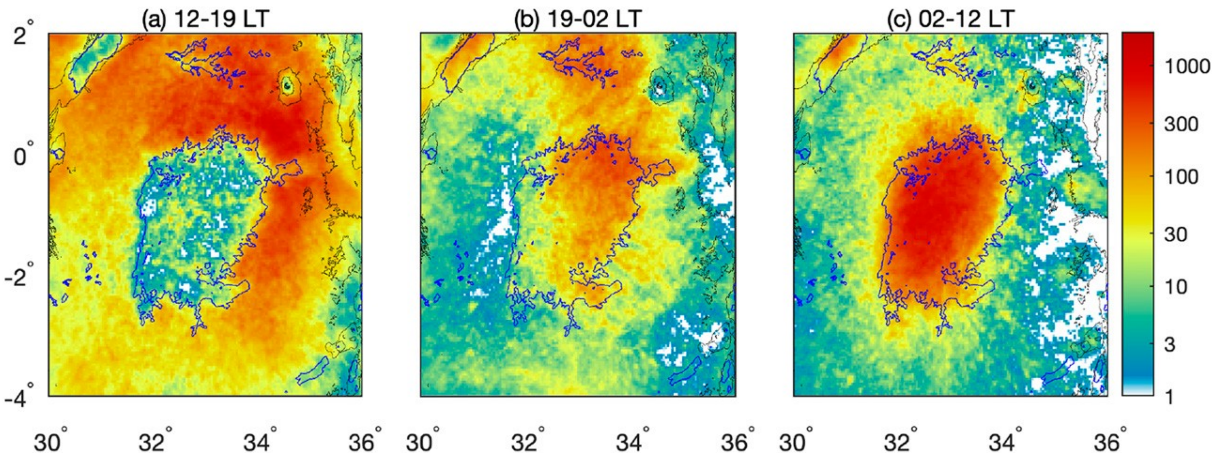


Fig.-3.4.30. (from Virts and Goodman, 2020) Diurnal summary of ENGLN lightning density (flashes/km^2/yr) during (a) daytime (1200–1900 LT), (b) evening and early night (1900–0200 LT), and (c) night and morning (0200–1200 LT). Elevation contours at 1000-m intervals are in black.

Fig.-3.4.31 and Fig.-3.4.32 show the convection distribution over Uganda and Kenya based on SEVIRI observations. The two figures clearly show that a deployment of a LMA from February to April and from October to November, as also reported by Virts and Goodman (2020), at close vicinity of Lake Victoria along the eastern and northern shores should document the lightning activity with a higher chance of success.

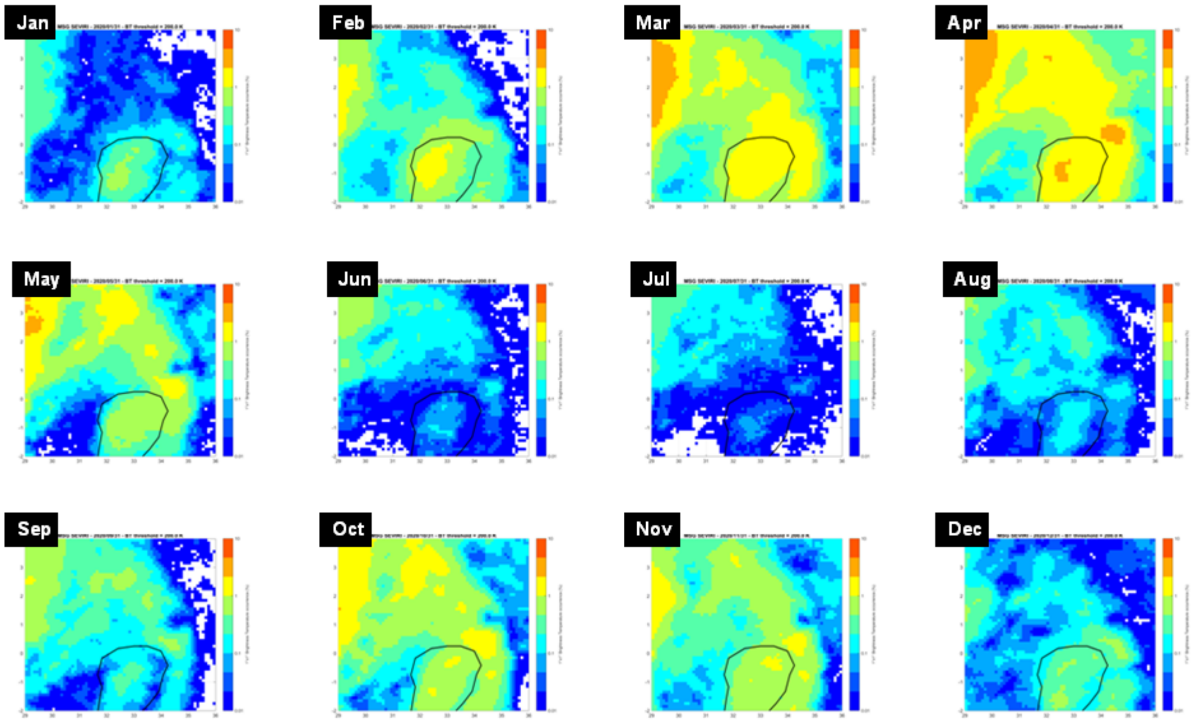


Fig.-3.4.31. Same as Fig.-3.4.2-13a but zoomed on Kenya and for each month of the year.

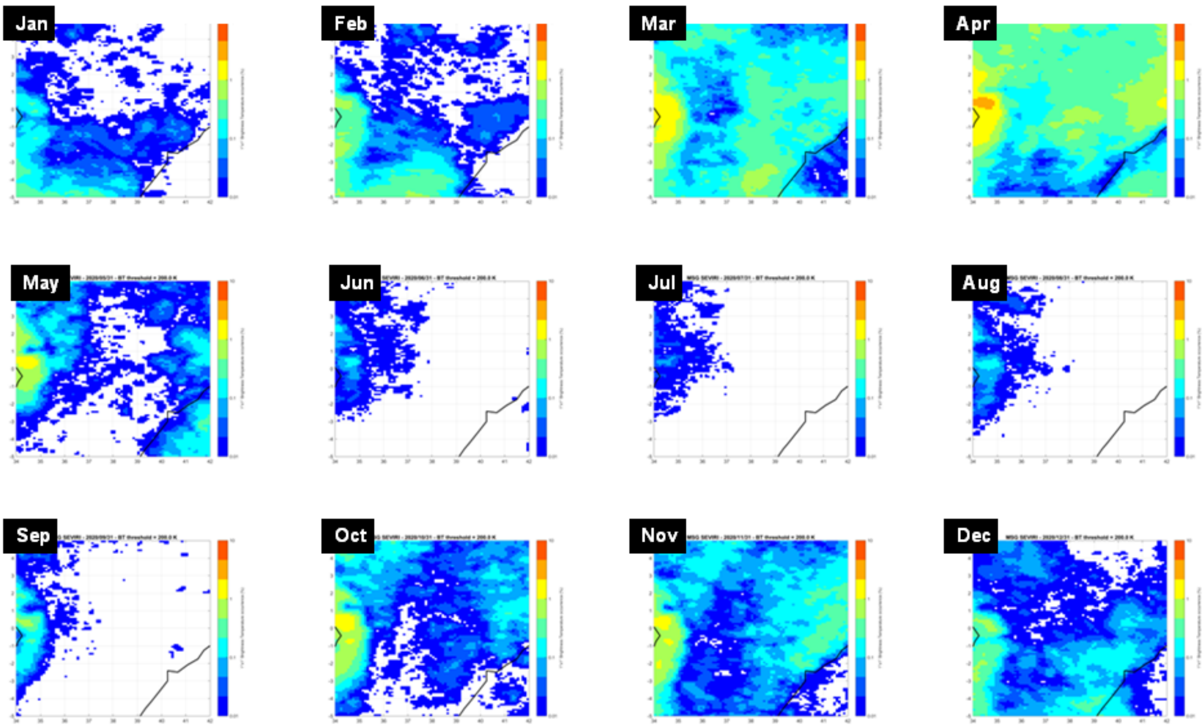


Fig.-3.4.32. Same as Fig.-3.4.2-13a but zoomed on Kenya and for each month of the year.

For comparison, Fig-3.4.33 and Fig-3.4.34 show a 3-year GLD360 lightning climatology as detailed in Holle and Murphy (2016). Holle and Murphy (2016) basically reported that lightning occurs mostly between 0300 LST and noon over the lake, while over the rest of the map area shown in Fig-3.4.33, strokes occur mostly between noon and 20:00 LST. They also report that the two seasonal maxima in lightning counts in the study region, one in March-April and the other in September and adjacent months (Fig.- 3.4.34).

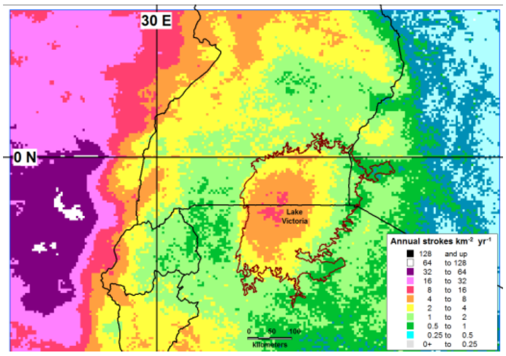


Fig.-3.4.33. Annual stroke density detected by GLD360 over Lake Victoria and surrounding region in a 5 x 5 km grid from 2012 through 2014 (from Holle and Murphy, 2016).

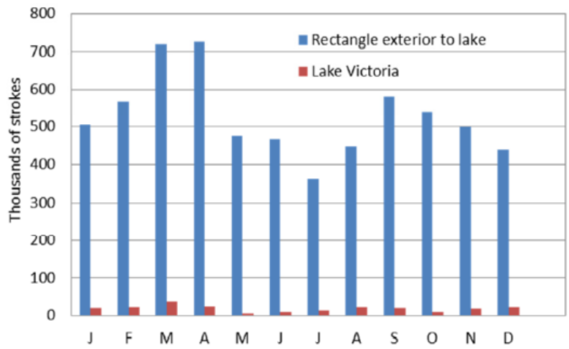


Fig.-3.4.34. Number of strokes by month over Lake Victoria and within the almost entire domain of Fig.-3.4.32 exterior to the lake (from Holle and Murphy, 2016).

EUMETSAT provided GLD360 data for only the period of July-December 2020. Flash density (Fig-3.4.35) shows a local maximum over land northeast of Lake Victoria on the Kenya side of the border of the lake. It appears, according to the 6-month GLD360 dataset used here, that August is the month with the highest flash rates (Fig-3.4.36) and July, the lowest.

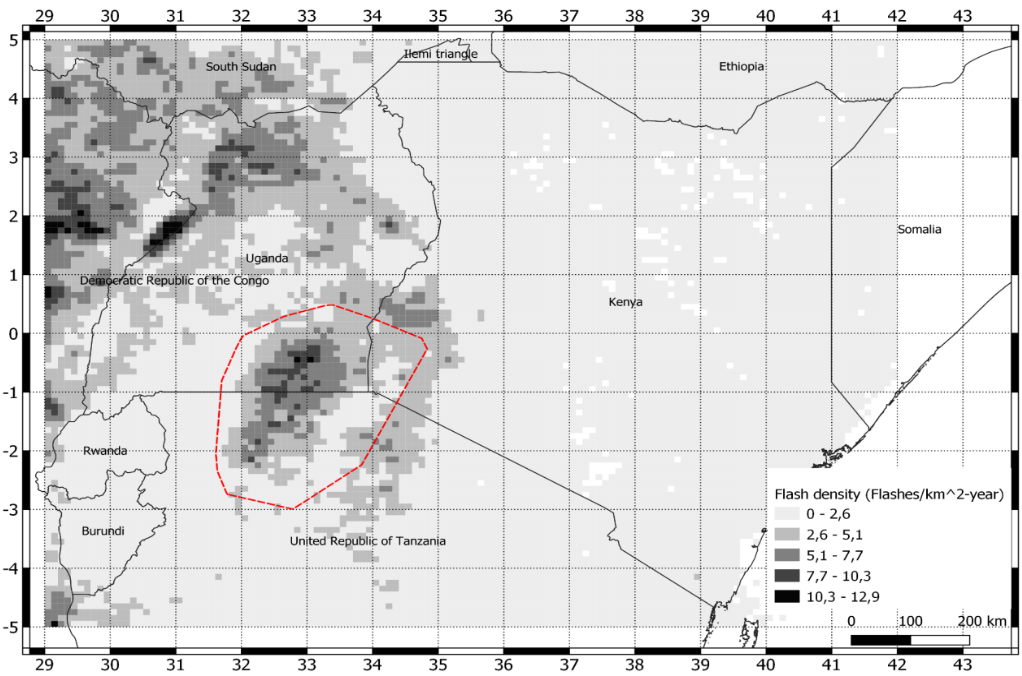


Figure 3.4.35. GLD360 Flash density (Jul-Dec 2020).

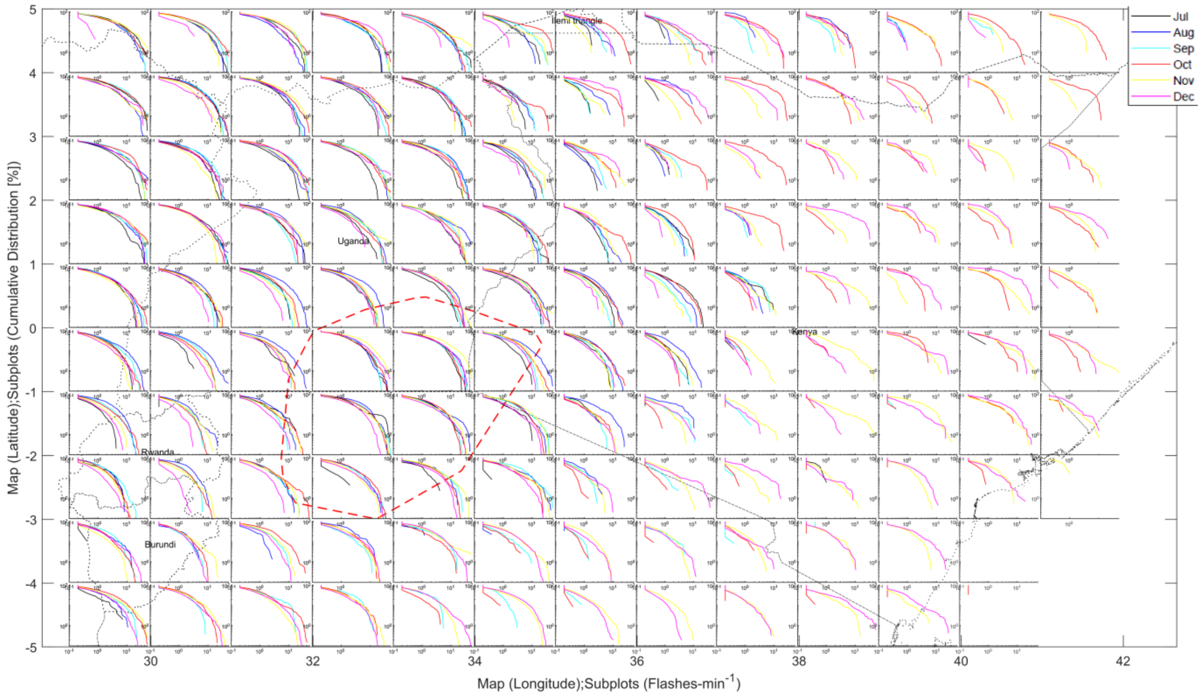
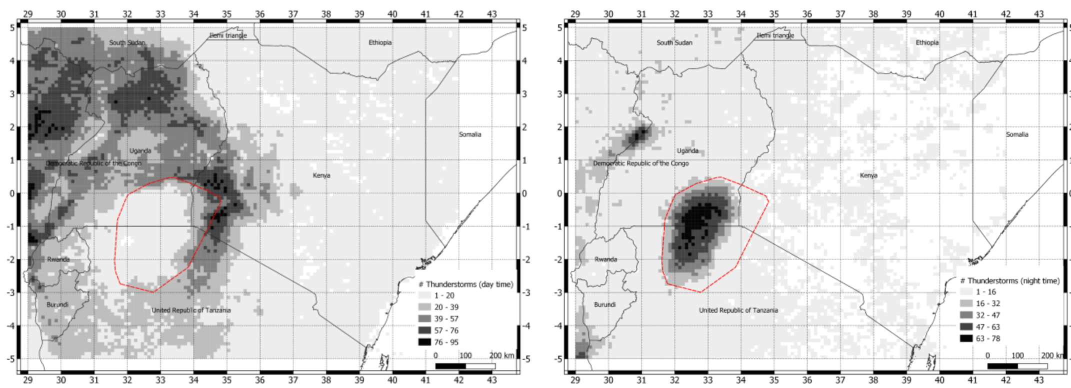


Figure 3.4.36. GLD360 Flash rates (Jul-Dec 2020).

During this half year, a clear maximum is present during daytime along the northeast shore (Fig-3.4.37a). It ranges from 60 to 90 storm days – a day is considered as a storm day if at least one lightning flash has been detected in a given grid box. Much of the east and north shores (e.g. Kampala, Uganda) have >40 storm days. The south and west of the lake experienced only 10-30 storm days during the daytime in this season. Note also that northern Uganda (Gulu) reaches 60-75 storm days. Nighttimes maxima over the lake (Fig-3.4.37b) falls outside of the best range of any LMA installed near the eastern shoreline (>50 km). During the night, only the western 2/3rds of the lake is active in this season and is far away from the eastern shore. A similar daytime maximum in density is found in northern Uganda (Gulu).

Monthly cycle plots (Fig-3.4.38) show generally July the worst, with August-November equally active. Over land south of the lake, the later months are the only ones with somewhat significant lightning activity.

(a)



(b)

Figure 3.4.37. Number of storm days during daytime (a) and nighttime (b) for the Jul-Dec 2020 period.

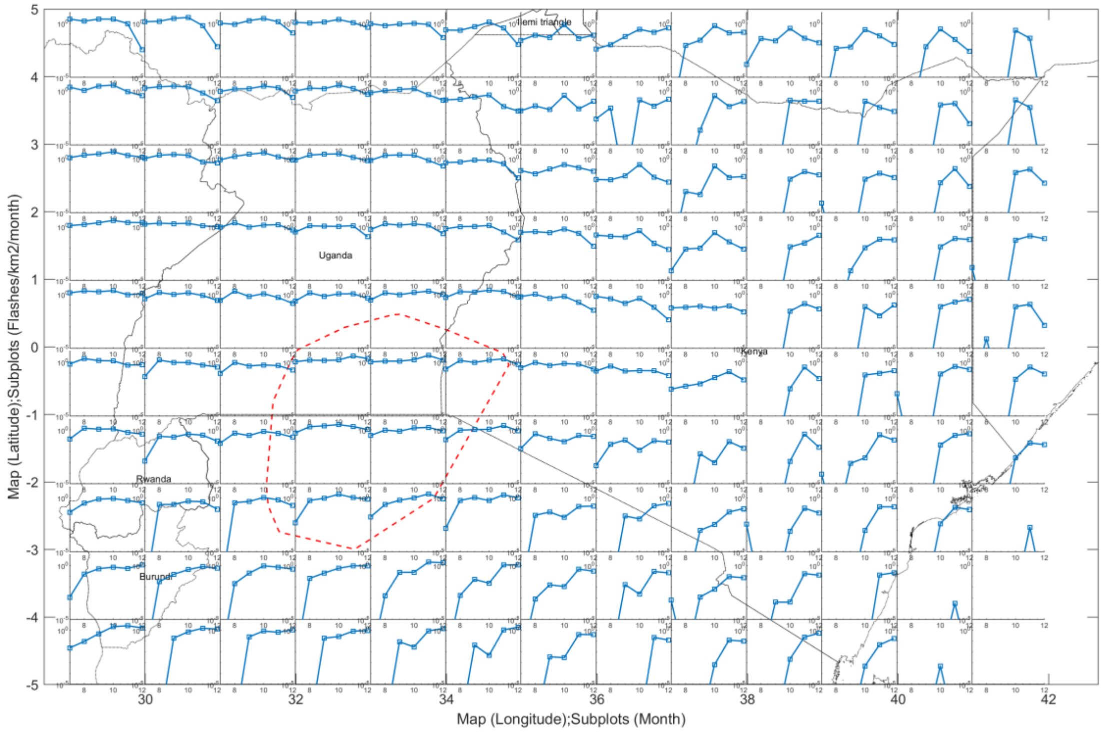


Fig. 3.4.38. Monthly distribution of the flash rate based on GLD360 dataset (Jul-Dec 2020).

Table 3.4.1 synthesizes the main results in terms of period of storm occurrence and diurnal cycle. The period between February and April appears the most interesting in terms of lightning activity over both the lake and the shores. Finally Fig-3.4.39 proposes several geographical sub-regions in the Lake Victoria area (Kenya/Uganda/Lake Victoria) where lightning activity should be documented in support of MTG-LI validation. These sub-regions of interest will then require the deployment of a LMA either on the eastern shore, on the northeastern shore or southern shore of Lake Victoria. Because deploying the LMA network all around the lake will lead to too large distances between the LMA stations, and because the LMA stations have to be operated on land, the LMA will only cover the eastern part, the northeastern part or the northern part of the Victoria Lake.

Table 3.4.1. Summary of the period of convection during the year over Kenya/Uganda/Lake Victoria as derived from SEVIRI, GLD360 (6 months) and TRMM-LIS climatologies. Red and yellow indicate for a given sensor the best period of the year and the second period of interest of the year, respectively. Orange gives the best period of the year identified in the 6 months of GLD360 dataset used in the present study. The other months of the year also analyzed independently from SEVIRI, GLD360 and TRMM-LIS are shown in grey. Occurrence of nighttimes and daytime convection/lightning activity is shown in blue and green, respectively.

SEVIRI based period	J	F	M	A	M	J	J	A	S	O	N	D
SEVIRI diurnal cycle												
6-month GLD360 period	~~J~~	~~F~~	~~M~~	~~A~~	~~M~~	~~J~~	J	A	S	O	N	D
6-month GLD360 period												
TRMM-LIS based period	J	F	M	A	M	J	J	A	S	O	N	D

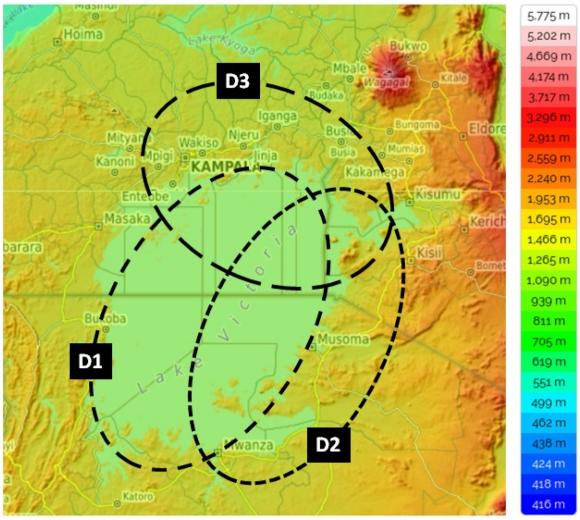


Fig.-3.4.39. Three geographical sub-regions (D1, D2 and D3) in the Lake Victoria area (Kenya/Uganda/Lake Victoria) where lightning activity should be documented in support of MTG-LI validation, as derived from the analysis of the lightning/convection activity, and independently to the ground-based lightning locating system of reference.

3.4.4 Analysis for Côte d'Ivoire

Following a similar methodology, SEVIRI, GLD360 and TRMM-LIs data have been analyzed for Côte d'Ivoire (Ivory Coast). Indeed Fig.-3.4.40 shows that the period April-May exhibits the higher chances for deep convective clouds with a latitudinal variation while the months go on. There are no sub-regions with specific features based on those 10 years of SEVIRI data.

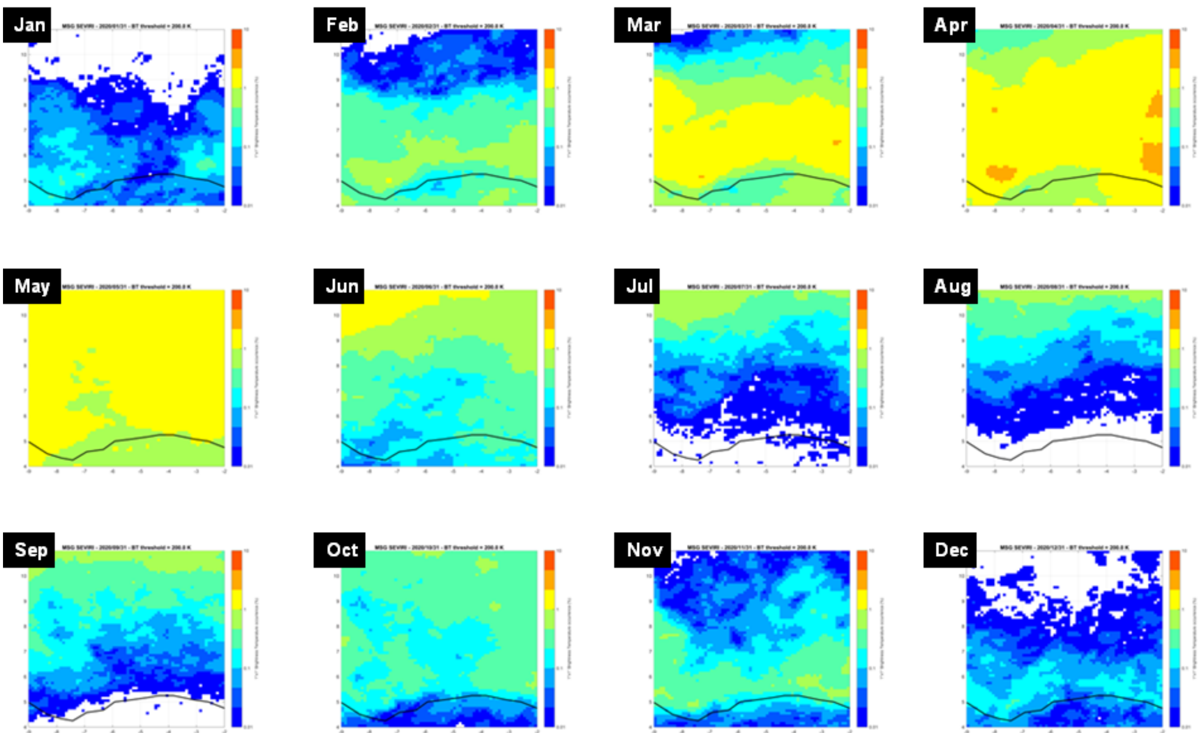
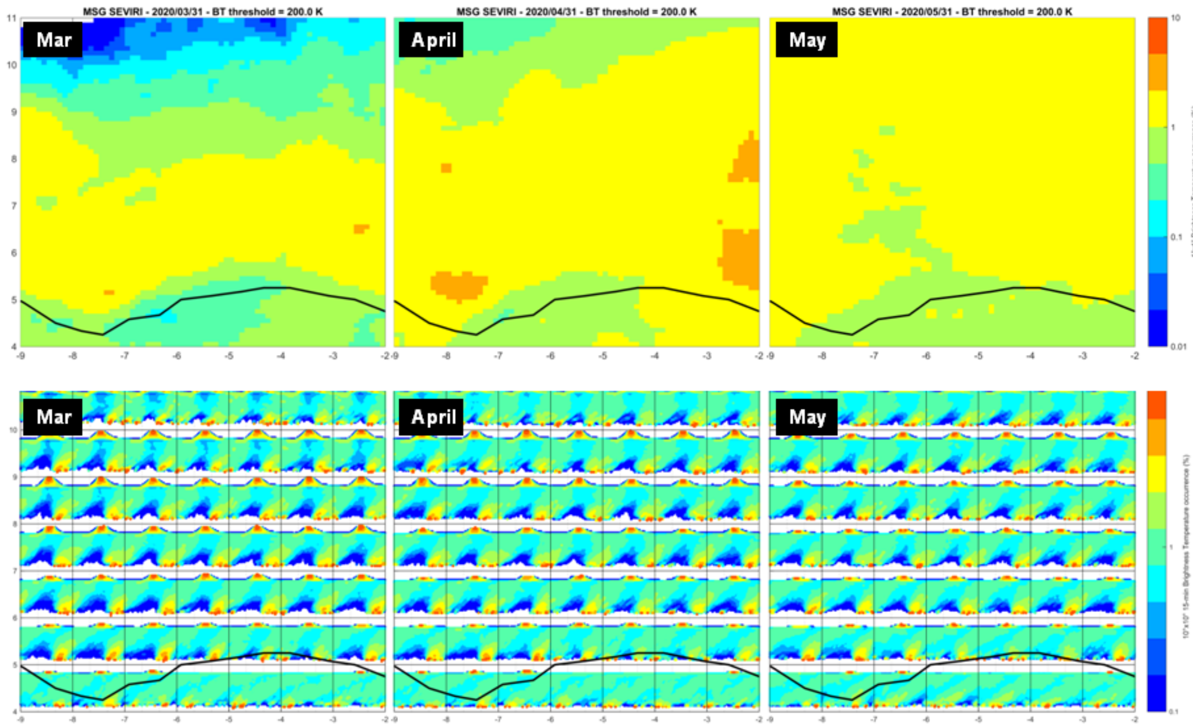


Fig.-3.4.40. Same as Fig.-3.4.2-13a but zoomed in Côte d'Ivoire and for each month of the year.

Fig.-3.4.41 shows that for the period March to May the convection generally starts in the afternoon. Note that the different two-dimensional time-brightness temperature distributions plotted in Fig.-3.4.41 have their time expressed in UT time. It is why the occurrence of convection, detected through cold brightness temperatures, is detected later compared to what is found in Lake Victoria region (Fig.-3.4.24) because of the use of UT time instead of LT time.

(a) (b) (c)

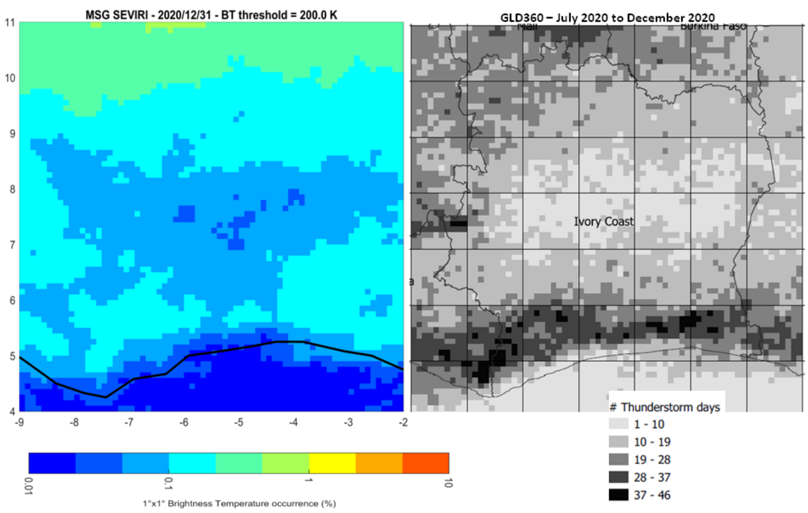


(d) (e) (f)

Fig.-3.4.41. Same as Fig.-3.4.2-13a but zoomed on Côte d'Ivoire but for March (a), April (b) and May (c), and diurnal cycle as derived from the brightness temperatures for March (d), April (e) and May (f).

Fig.-3.4.42 shows the 2D distribution of the thunderstorm days computed from the 6-month GLD360 dataset. The maximum in Côte d'Ivoire is about half of the maximum found in Lake Victoria region as shown in Fig.-3.4.26b.

(a)



(b)

Fig.-3.4.42. SEVIRI based convection distribution (a) and GLD360 storm day density (b) measured during the period July-December 2020.

The 2D distribution of the thunderstorm days exhibits some maxima all along the coast line but on the continent, and other maxima on the western and northwestern borders of the country (Fig.-3.4.43b). Contrarily to the case of Lake Victoria, less than 0.1% of the brightness temperatures were below 200 K, suggesting less deep convection. Indeed Fig.-3.4.43a shows the flash density, and here too, the maximum of the flash density is about three times less than what was recorded in Lake Victoria (Fig.-3.4.26a). The rather weak convection as pointed out in Fig.-3.4.35 (from July to December) makes difficult to extract more information on the diurnal cycle of the lightning activity except that it exhibits a typical afternoon increase, especially in the 5N-7N latitude band (Fig.-3.4.43c). The distribution of the flash rate shown in Fig.-3.4.43d definitively shows lower values of one order of magnitude than for the region of Lake Victoria (Fig.-3.4.26d) for the same period of the year, assuming that GLD360 exhibits the same detection efficiency in both regions.

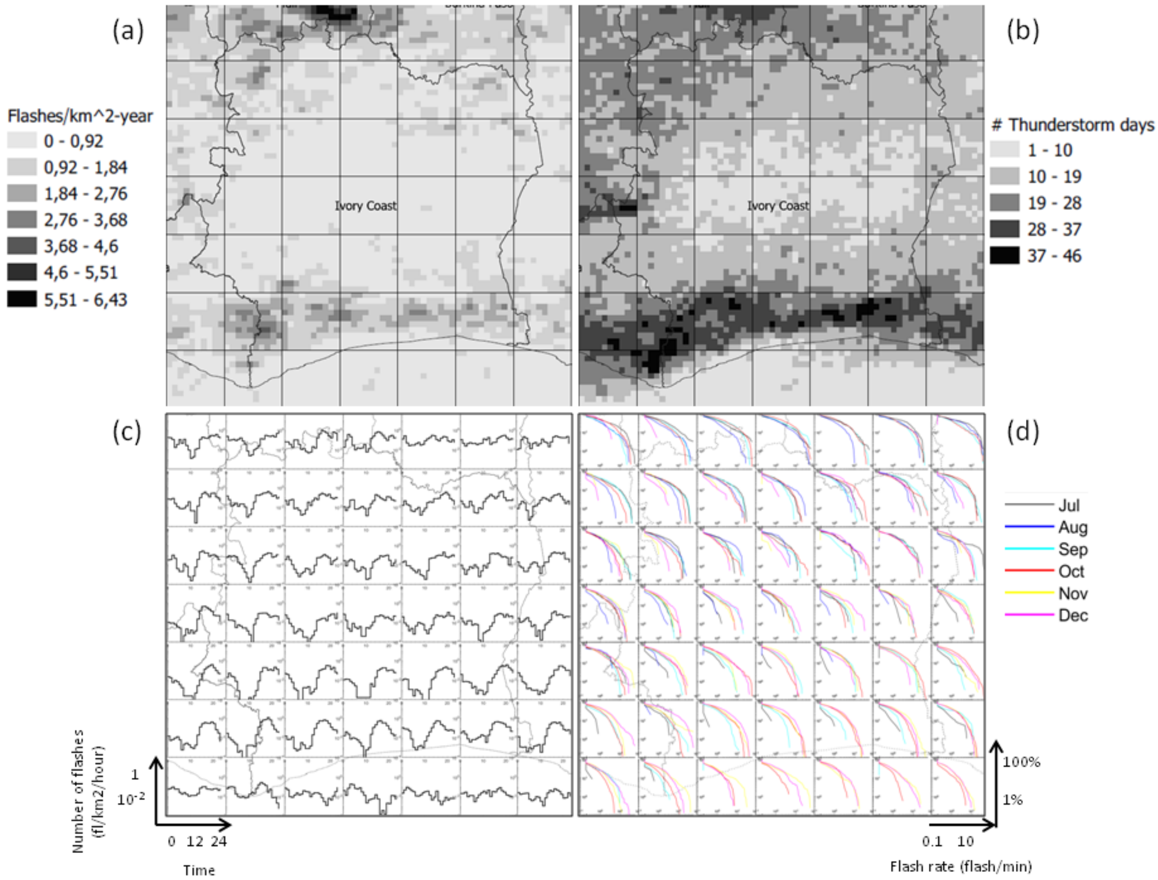


Fig.-3.4.43. GLD360 flash density (a), number of thunderstorm days (b), diurnal evolution of the number of flashes (c), and distribution of the flash rate per month (d), for the period July-December 2020.

Fig.-3.4.44 shows the main results of the analysis of the TRMM-LIS data. As expected, more lightning flashes are recorded over the continent than the ocean (Fig.-3.4.44a). The southern part of the country shows two modes of lightning activity during the year, one mode during the period March-May and the second mode October-November (Fig.-3.4.44c). The northern part of the country shows a less pronounced bi-modal distribution with a peak later during the year between May and July (Fig.-3.4.44c). Finally Fig.-3.4.44d confirms that the lightning activity should peak in terms of activity in the afternoon.

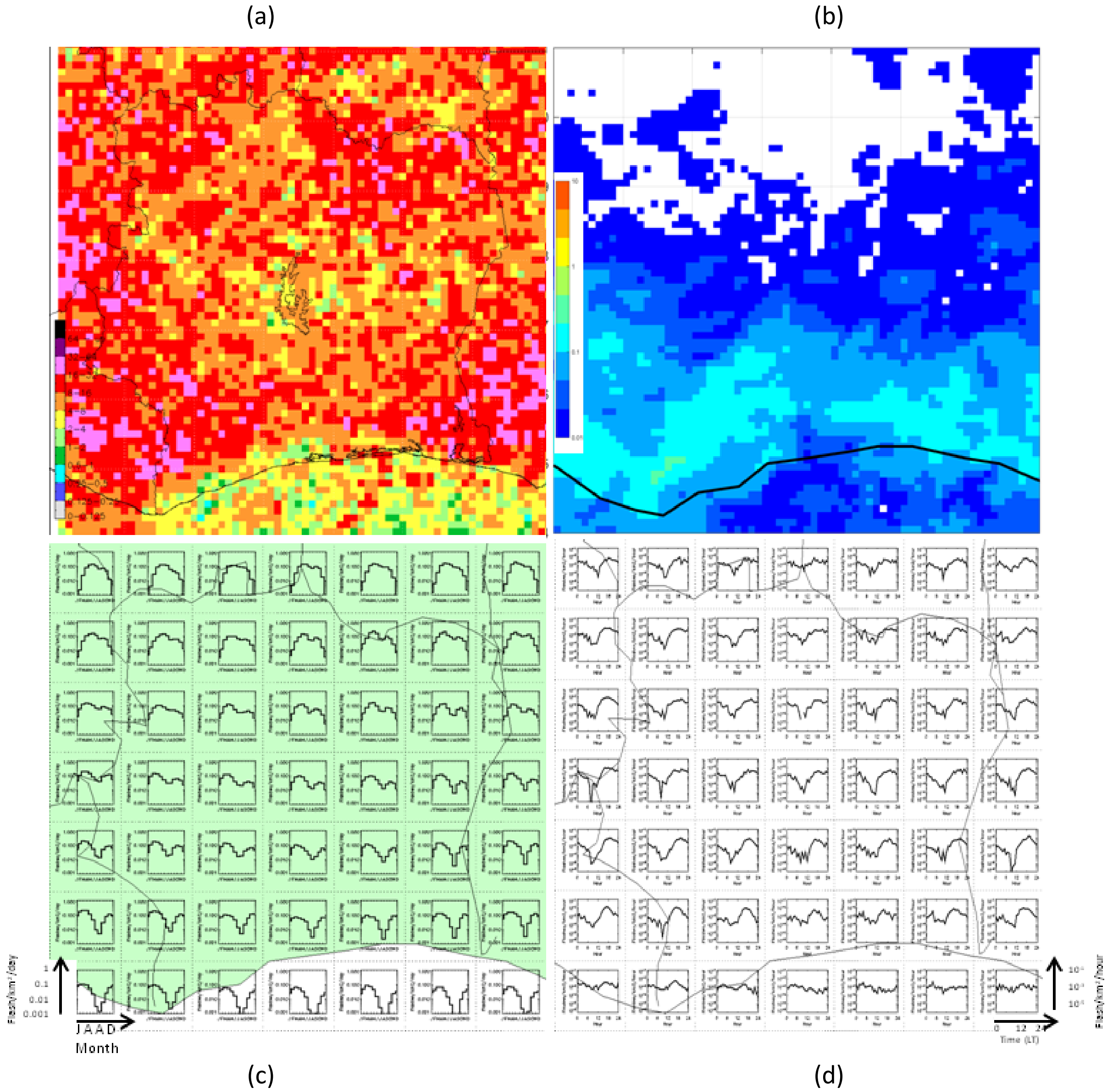


Fig.-3.4.44. TRMM-LIS flash density (a) for 16 years of data, SEVIRI convection distribution (b) for 10 years of data, (c) monthly flash rate as a function of the months, and (d) diurnal cycle of flash rate.

The 6 months (Jul-Dec 2020) of GLD360 data show that daytime lightning activity is maximized along a 25-75 km strip along the coastline, likely caused by the sea breeze convergence (Fig.-3.4.45a). The coast itself is almost free of lightning. The southwest of the country has the maximum, helped by elevated terrain. The rest of the country has less than half the activity, except a mountainous spot north of Danané. At night (Fig.-3.4.45b), activity concentrates along the southeast coast, as well as in a band about 75-150 km parallel to the coastline. The other active region is the northwest, especially within 50 km of the border with Guinea. Flash density (Fig.-3.4.45a) matches with the west-east band of daytime storm activity, best near the Liberia border.

From the monthly data (Fig.-3.4.46) the three months October-December are the active months in the South. The numbers suggest that in the period of July-December there are along the coast east of the capital Abidjan with the maximum of ~35 to the north just at 50 km range and up to 15 at night.

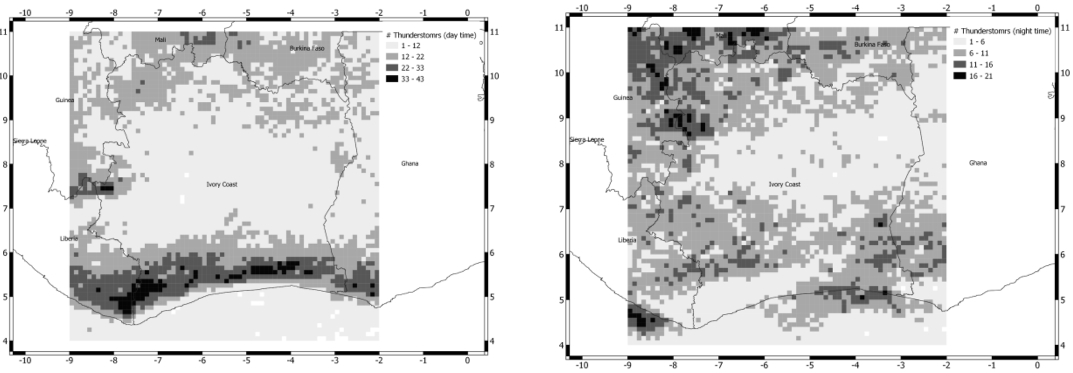
(a)  (b)

Fig.-3.4.45. Number of GLD360 thunderstorm days during daytime (a) and nighttimes (b) (Jul-Dec, 2020).

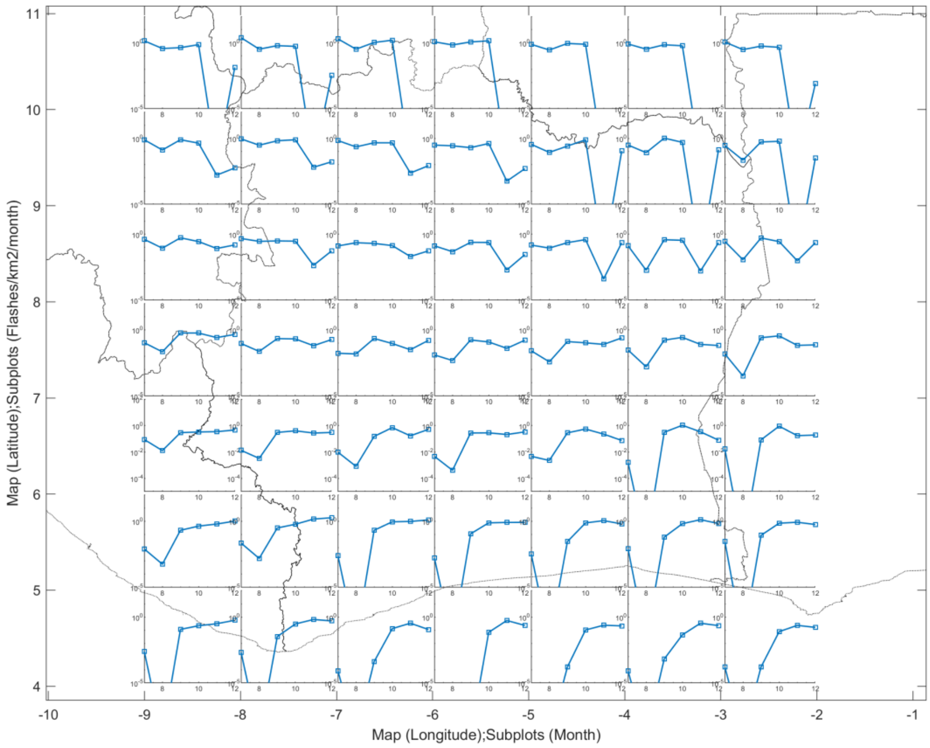


Fig.-3.4.46. GLD360 monthly distribution (flash/km^2/month) for the Jul-Dec 2020 period.

Finally Table 3.4.2 synthesizes the main results in terms of period of storm occurrence and diurnal cycle. The period March-May appears the most interesting in terms of lightning activity over the southern and western part of the country, while the period May-July seems to be more adequate for the northern part of the country. Finally Fig-3.4.47 shows the geographical domain that should be partially or totally covered with mainly a potential deployment on the eastern (D2), northeastern (D3) and southern (D1) borders of Côte d'Ivoire. One additional sub-region (D4 in Fig-3.4.47) centered over Abidjan could also be considered in case of weather radar operation at the time of the LMA-based campaign and to ease the deployment of the LMA if the three other regions are unworkable.

Table 3.4.2. Summary of the period of convection during the year over Côte d'Ivoire as derived from SEVIRI, GLD360 (6 months) and TRMM-LIS climatologies. Red and yellow indicate for a given sensor the best period of the year and the second period of interest of the year, respectively. Orange gives the best period of the year identified in the 6 months of GLD360 dataset used in the present study. The other months of the year also analyzed independently from SEVIRI, GLD360 and TRMM-LIS are shown in grey. Occurrence of daytime convection/lightning activity is shown in green.

SEVIRI based period	J	F	M	A	M	J	J	A	S	O	N	D
SEVIRI diurnal cycle												

6-month GLD360 period	~~J~~	~~F~~	~~M~~	~~A~~	~~M~~	~~J~~	J	A	S	O	N	D
6-month GLD360 period												

TRMM-LIS based period	J	F	M	A	M	J	J	A	S	O	N	D

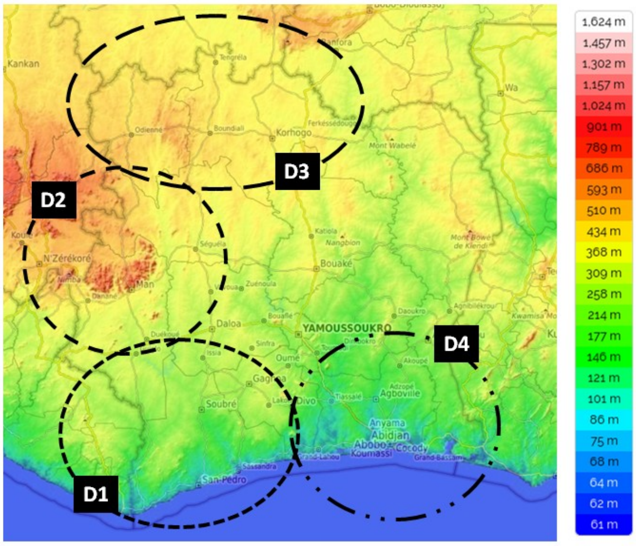


Fig.-3.4.47. Geographical domain that should be partially or totally covered with mainly a potential deployment on the southern (D1), western (D2), northwestern (D3) and southern (D4) borders of Côte d'Ivoire.

3.4.5 Analysis for South Africa

Fig.-3.4.48 shows the lightning distribution as shown by M. Gijben (South African Weather Service) during the EUMETSAT LIMAG meeting hold on Feb 09 2021. The South African Lightning Detection Network (SALDN) consists of 24 LS700n sensors of Vaisala technology. The lightning activity is predominant in the northeastern part of the country (Fig.-3.4.48). A monthly climatology of the lightning activity as sensed by SALDN should validate the main conclusions of the present section and details more specific features if any.

Fig.-3.4.49 shows the distribution of deep convection as detected by SEVIRI. Deep convective systems have more chances to occur in the northern to northeastern part of the country during the period December to February. The analysis of SEVIRI records as a function of time confirms that the convection is characterized by a typical diurnal cycle with an increase of the convection in the afternoon over land (not shown).

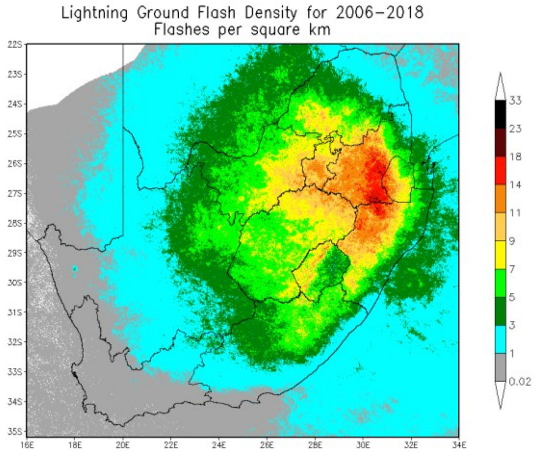


Fig.-3.4.48. Ground flash density for the period 2006-2018 in South Africa as recorded by SALDN.

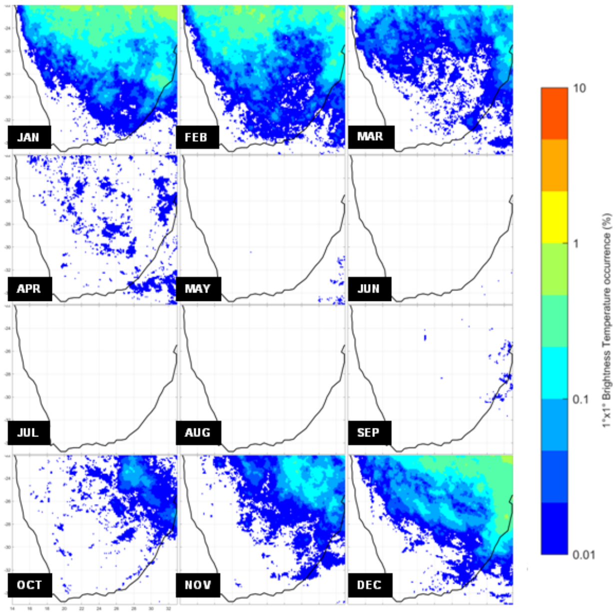
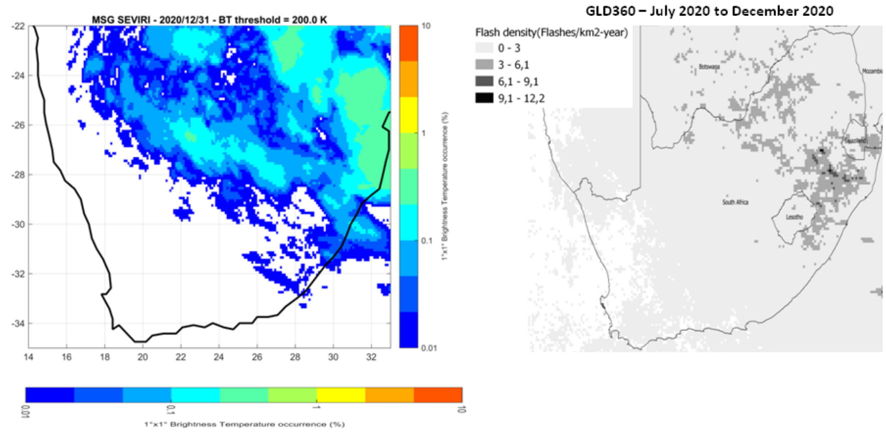


Fig.-3.4.49. Same as Fig.-3.4.2-13a but zoomed over South Africa.

Fig.-3.4.50 shows the distribution of the 6-month GLD360 dataset and concurrent SEVIRI product for the same period. For the studied period, the flash density exhibits similar mean values to the ones recorded in Côte d'Ivoire and some peaks close to what is recorded in Lake Victoria but at a much smaller size.

(a)



(b)

Fig.-3.4.50. SEVIRI based convection distribution (a) and GLD360 flash density (b) measured during the period July-December 2020

Fig.-3.4.51 presents the monthly TRMM-LIS climatology. The geographical distribution of the lightning activity is rather similar to the one computed from SALDN (Fig.-3.4.48). Two main hot spots can be identified: one located at the northeastern side of Lesotho, and a second west of Pretoria. Fig.-3.4.51 also suggests a third hot spot, located west of Swaziland, less obvious in the TRMM-LIS climatology.

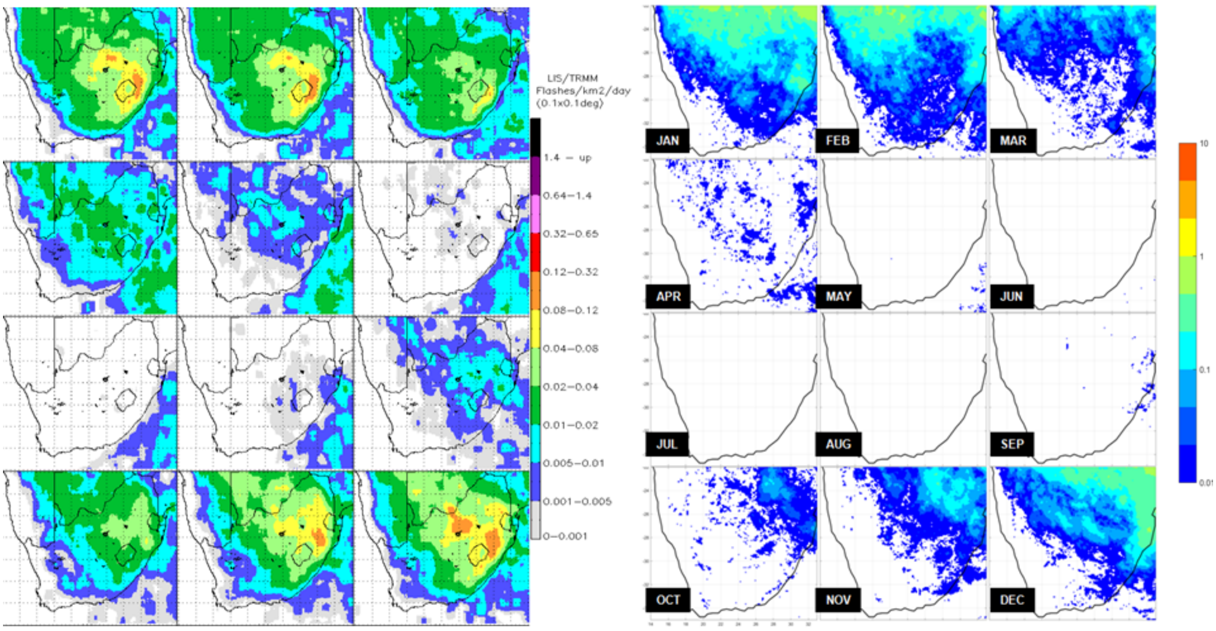


Fig.-3.4.51. TRMM-LIS flash density (left) and SEVIRI based convection distribution (right) for 16 years and 10 years of records, respectively.

Fig.-3.4.52 shows that the lightning activity in the three regions of interest is dominant between November and February, while Fig.-3.4.53 confirms that the lightning activity follows a typical diurnal cycle with a maximum in the afternoon.

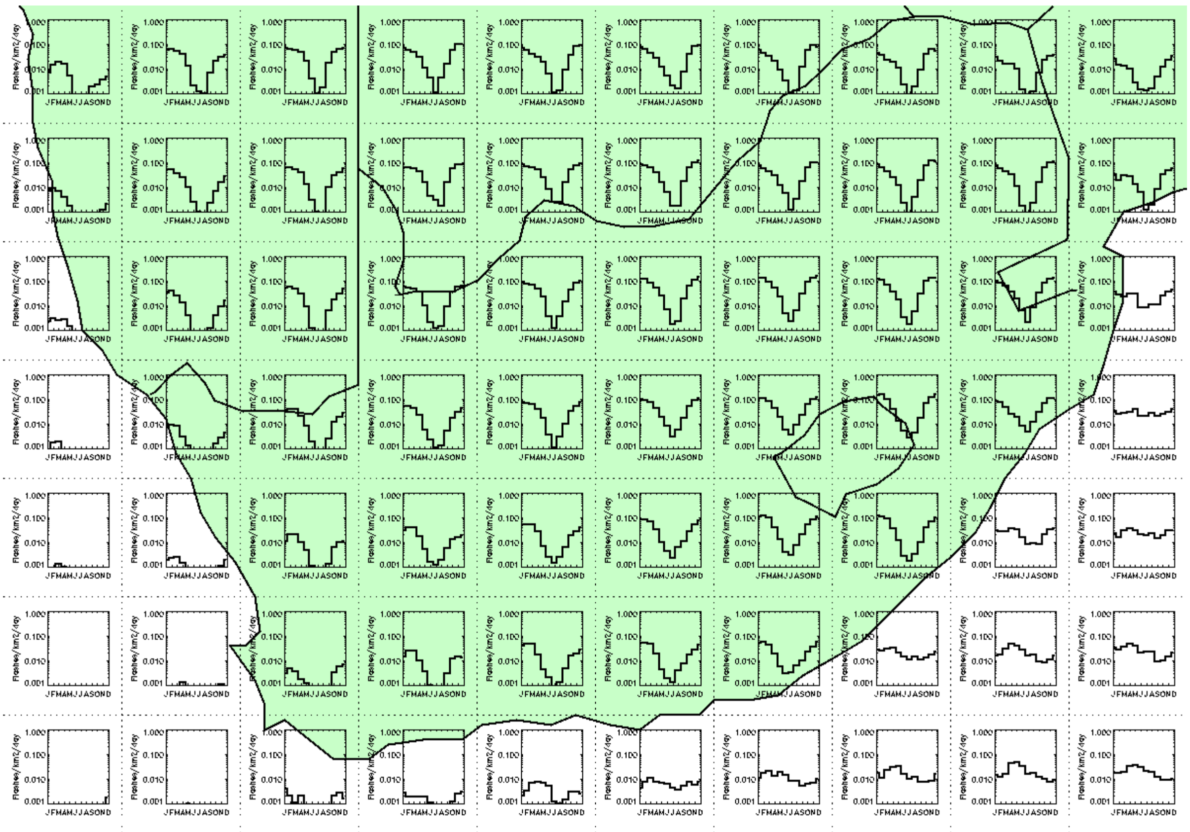


Fig.-3.4.52. TRMM-LIS based monthly distribution per sub-region of 2°x2°.

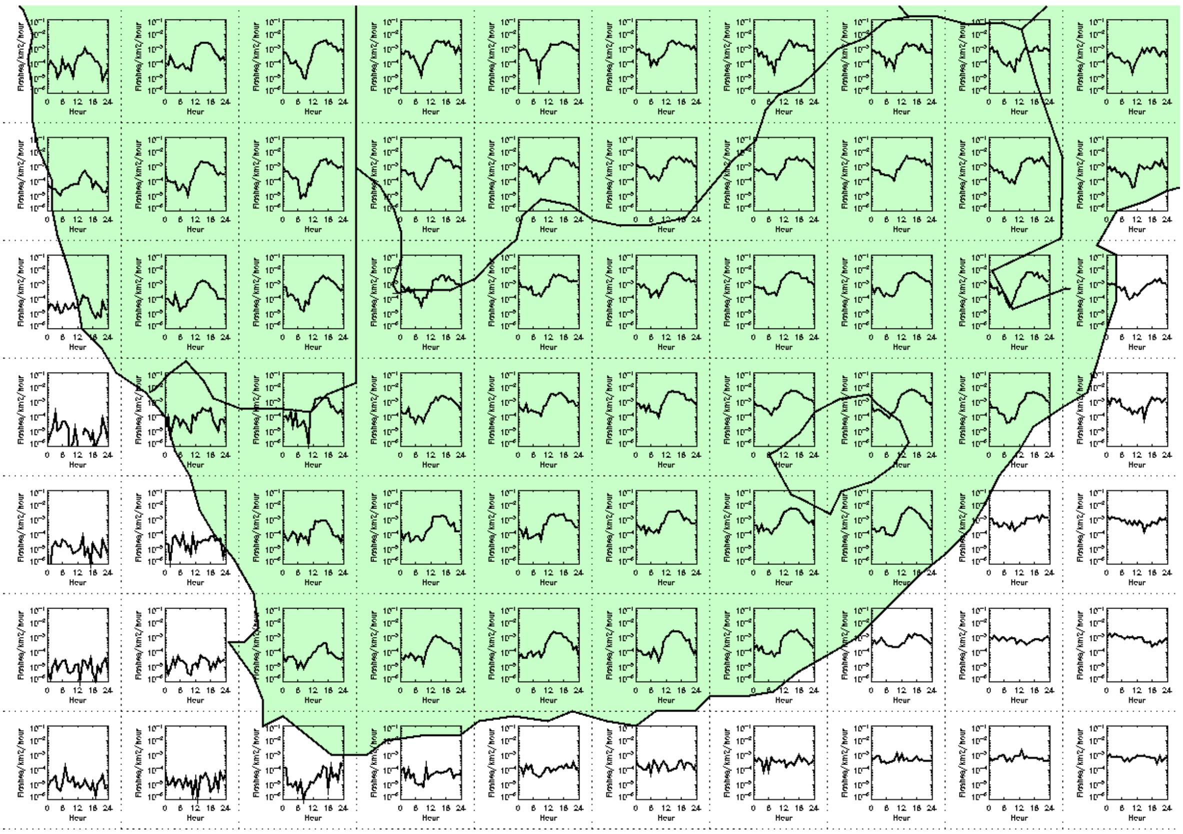
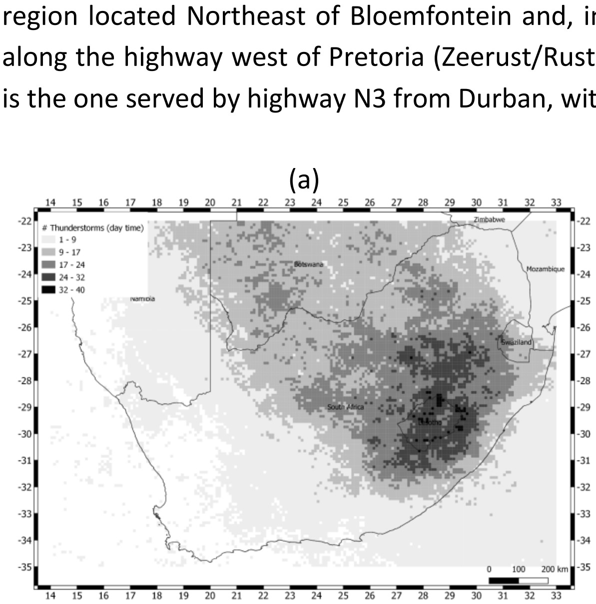


Fig.-3.4.53. TRMM-LIS based diurnal cycle over the year per sub-region of 2°x2°.

The six months (Jul-Dec, 2020) of the GLD360 data (Fig.-3.4.54a) indicates that daytime activity is at a level over 20-40 thunderstorm days over a large area East of Bloemfontein, South of Johannesburg, and about 100 km away from the Southeast coast. The maxima are found around the Lesotho border, in a very mountainous area, but it is not much lower in the flat area between Johannesburg and Lesotho. The Northwestward highway from Durban at the coast is within 50 km range from the maximum. At night (Fig.-3.4.55b), activity is reduced, but still maximized around the northern border of Lesotho (10-20 storm days) and plains northeast of that. Other spots are the region located Northeast of Bloemfontein and, in the North, a solid maximum of >15 storm nights along the highway west of Pretoria (Zeerust/Rustenburg). The most consistent day/night active area is the one served by highway N3 from Durban, with 35 storm days and 15 storm nights.

(a)



(b)

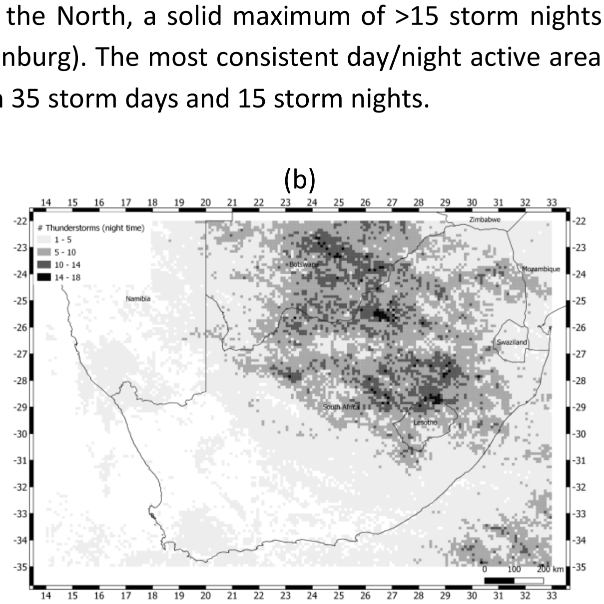


Fig.-3.4.54. Number of GLD360 thunderstorm days during daytime (a) and nighttimes (b) (Jul-Dec 2020 period).

Fig.-3.4.55 depicts that October-December is the most active period for flash rates, of the available data. Flash density maps (Fig.3.4.50b) show local maxima just east of Lesotho, and between Standerton and Vrijheid.

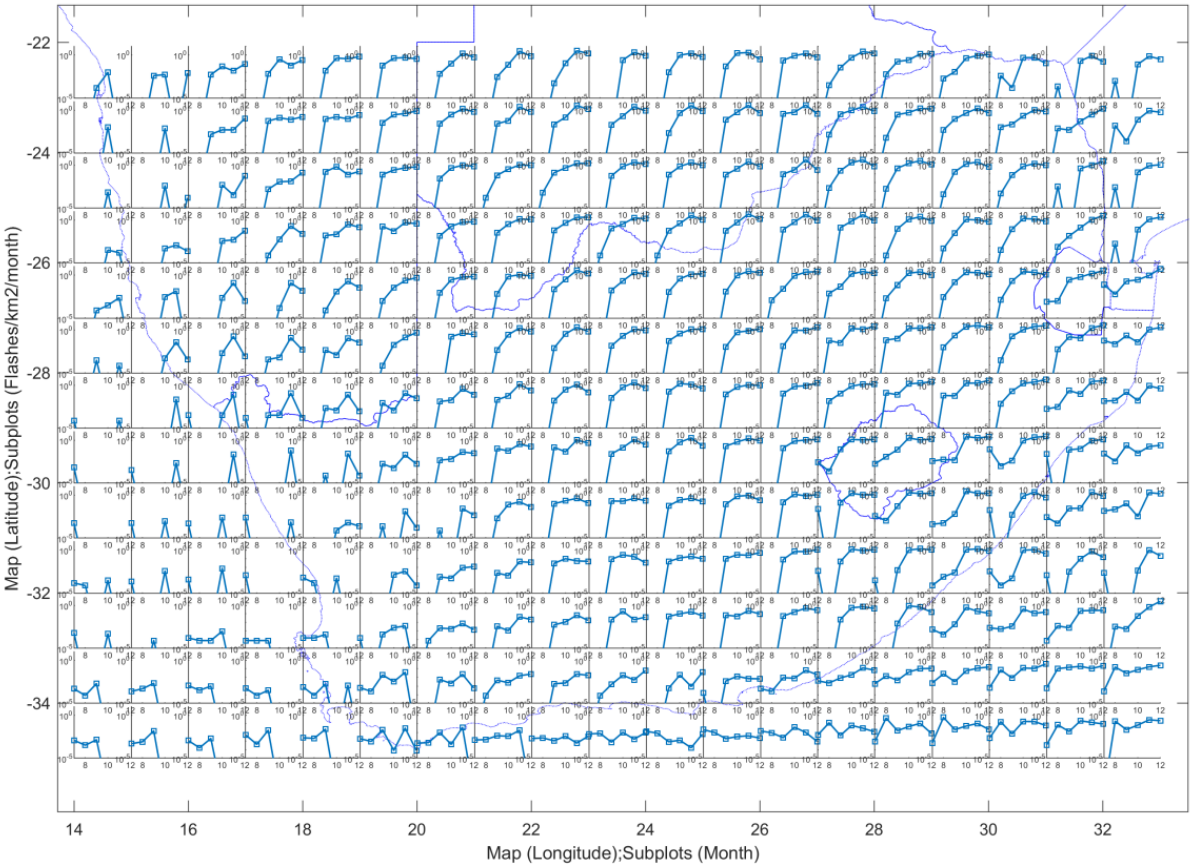


Fig.-3.4.55. GLD360 Monthly distribution for the Jul-Dec 2020 period.

Finally Table 3.4.3 synthesizes the main results in terms of period of storm occurrence and diurnal cycle. The period November-February appears the most interesting in terms of lightning activity over the three sub-regions of interest. Fig-3.4.56 shows the three geographical domains of interest that correspond to the hot spots identified in TRMM-LIS climatology. Comparison with SALDN lightning climatology should definitely consolidate that proposal.

Table 3.4.3. Summary of the period of convection during the year over South Africa as derived from SEVIRI, GLD360 (6 months) and TRMM-LIS climatologies. Red indicates for a given sensor the best period of the year. Orange gives the best period of the year identified in the 6 months of GLD360 dataset used in the present study. The other months of the year also analyzed independently from SEVIRI, GLD360 and TRMM-LIS are shown in grey. Occurrence of daytime convection/lightning activity is shown in green.

SEVIRI based period	J	F	M	A	M	J	J	A	S	O	N	D
SEVIRI diurnal cycle												

6-month GLD360 period	~~J~~	~~F~~	~~M~~	~~A~~	~~M~~	~~J~~	J	A	S	O	N	D
6-month GLD360 period												

TRMM-LIS based period	J	F	M	A	M	J	J	A	S	O	N	D
TRMM-LIS diurnal cycle												

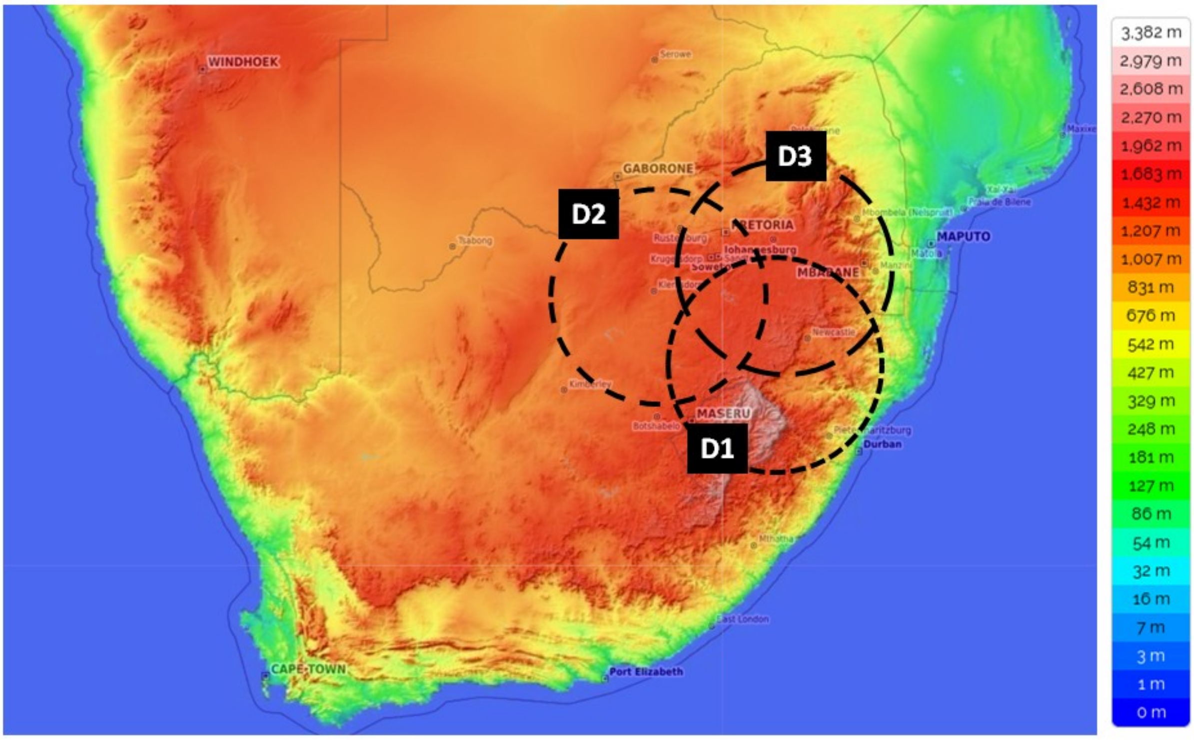


Fig.-3.4.56. Geographical domain that should be partially or totally covered with mainly a potential deployment at three sub-regions located in northeastern South Africa.

3.5 WP4 – Possible dedicated LMA campaign for LI Commissioning and Cal/Val.

It is planned to run the LMA network on a standalone mode (power delivered by solar panels and batteries). Such a way of operating requires either to ship all the equipment needed to build each station or to purchase at least the power equipment and station structures directly through the host Institute to limit the shipping. In the latter, the equipment would be reused by the host Institute at the end of the campaign. There is also the need for efficient mobile phone coverage (Machine-to-Machine M2M or basic connection if validated during the site surveys) for remote monitoring of all LMA stations.

Between 10 and 12 LMA stations will be deployed, meaning that 10 to 12 sites + 6 backup sites about ~20-30 km distant from each other should be identified and surveyed. The LMA stations must be deployed in electromagnetic quiet areas (e.g. away from power lines, away from any power supply): site survey (electromagnetic noise level, layout) will have to conduct prior deployment at least 1 year and few weeks before actual deployment for verification. All LMA stations should see around at 360° with ideally no obstacles at close range. LMA stations should be deployed in accessible, safe and secured areas (away from floods; thieves). No visit of the LMA stations will be conducted at night. The visit of all stations should be conducted every week for data recovery and maintenance. Local storage, technical and office (with internet) rooms will be needed. **All LMA stations have to be deployed in the same country to avoid border crossing**. Obviously, a referent of the host Institute will have to work closely with the LMA team, to locally keep contact with land owners and to handle paper works and issues with local authority. Finally there is definitively the need for local support for deployment, maintenance (with technical and science training), dismantlement, and logistics in general (including drivers). Regions also covered by additional instruments like radar, and with adequate lightning activity, should be considered as region of top interest.

Fig.-3.5.1 shows a preliminary timeline of the activities to conduct prior, during and after the field deployment with an arbitrary period for the LMA campaign. One major unknown is the duration of the shipping and in-bound custom operations. Shipping by air should be encouraged to limit preparation in advance. A part of the European team has to be in the field about 6 weeks prior the start of the LMA operation in order to survey a second time the LMA sites, to deploy and to test the equipment. The GO should be provided by EUMETSAT at least one year prior to the field deployment to conduct the 1st site survey at the expected time of the year that the campaign should be conducted the year after for verification. A preparation of the entire equipment will have to be performed before leaving Europe. Tests will have to be conducted during the 1st survey with one portable LMA station to at least verify the communications.

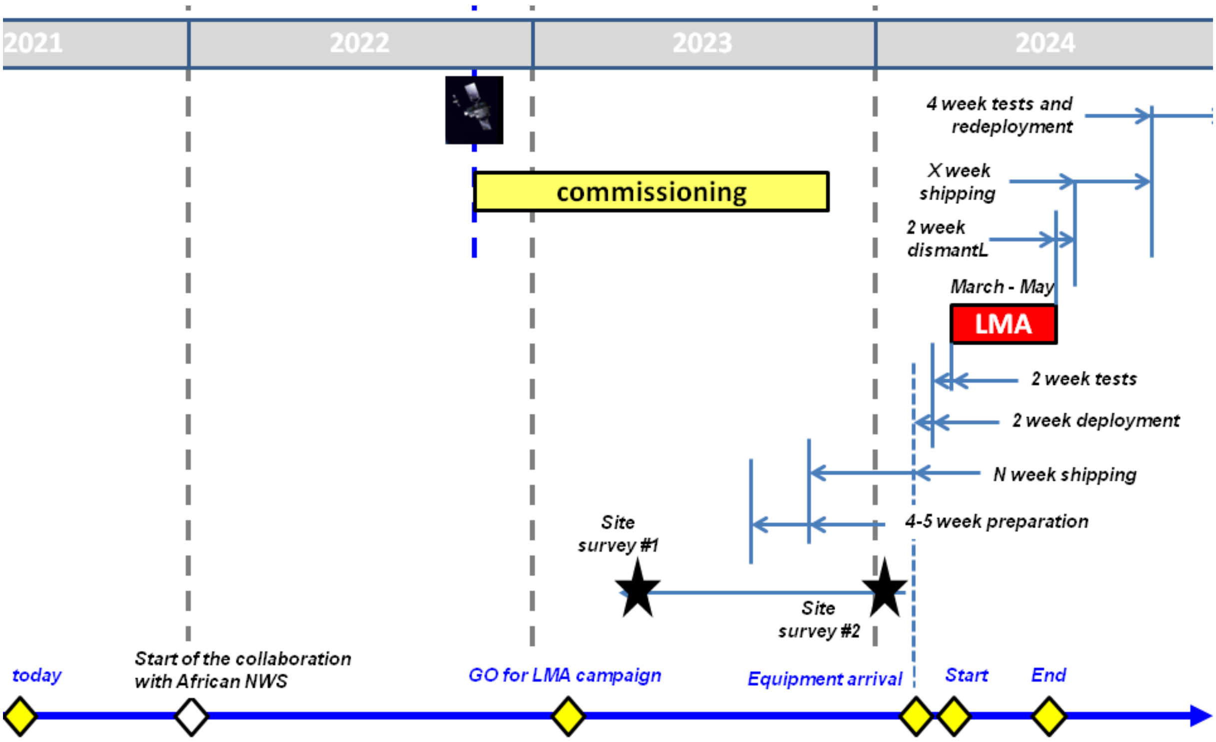


Fig.-3.5.1. Timeline for pre-deployment, operations and post-deployment of the LMA network.

Before the field deployment and the 1st visit, it is important to associate the team of the host Institute through a common training and science plan to contribute to the science and technical objectives. Such interactions should rely on exchanges between staff and on scientific studies conducted between all teams. Local universities should also be invited to join the team.

Fig.-3.5.2, Fig.-3.5.3 and Fig.-3.5.4 present three or four different scenarios for the three countries of interest. In those figures, the LMA coverage area is represented by 1-km altitude increment concentric circles showing the ranges at which the Earth curvature limits the lightning detection at low altitude. The larger circle has a radius of about 175 km. Note that the LMA coverage area, copy of the Corsica LMA coverage area, might differ according to the actual configuration of the network. New coverage area will have to be plotted according to the potential LMA station sites and then according to the actual sites of the LMA stations when finally known.

Scenario #1.1

- *Host country : Tanzania (Musoma region)*
- *Coverage area : North of Tanzania, West of Kenya, East part of Lake Victoria*
- *Period : FMA*

Scenario #1.2

- *Host country : Kenya (Kisumi region)*
- *Coverage area : North of Tanzania, West of Kenya, East part of Lake Victoria*
- *Period : FMA*

Scenario #1.3

- *Uganda (Mayuge region)*
- *Coverage area : South Uganda, West Kenya, North Victoria Lake*
- *Period : FMA*

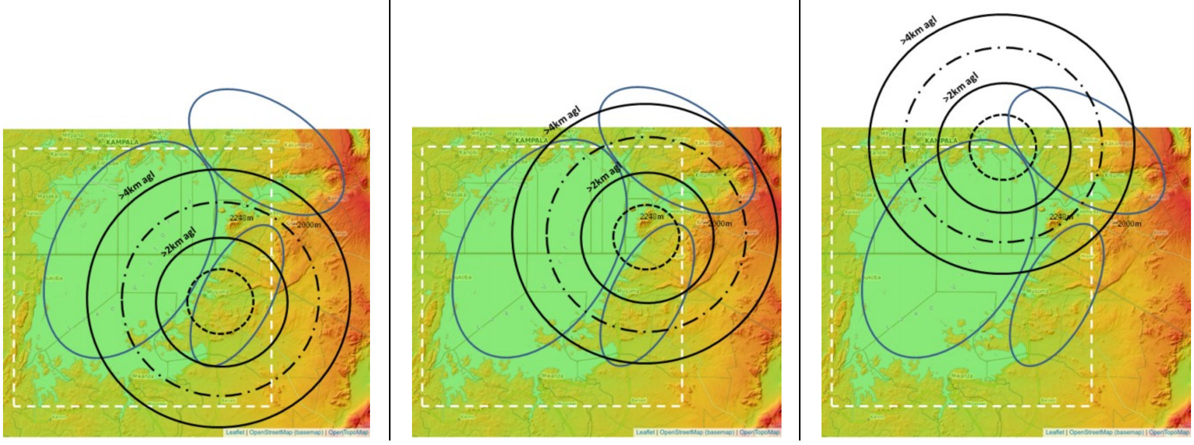
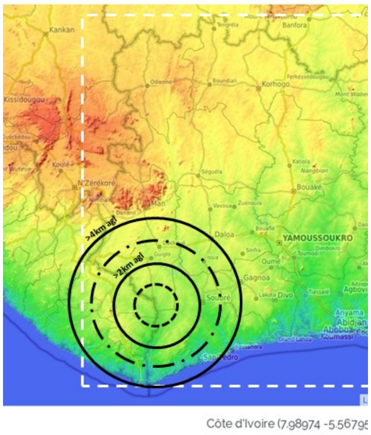


Fig.-3.5.2. Three scenarios for a deployment in Kenya/Uganda/Lake Victoria.

Scenario #2.1

- *Host country : Ivory Coast (Soubré region)*
- *Coverage area : SW Ivory Coast, Liberia*

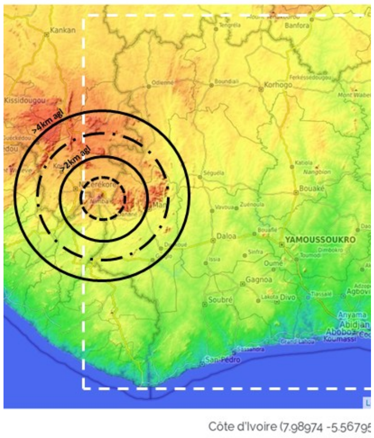
- *Period : MAM*



Scenario #2.2

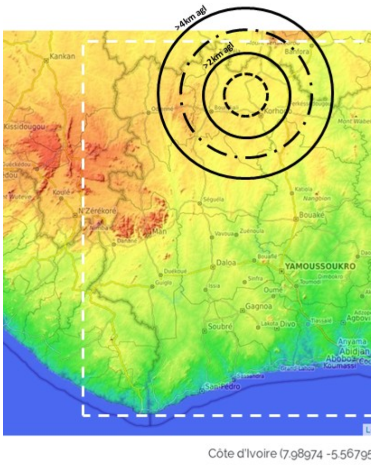
- *Host country : Ivory Coast (Man region)*
- *Coverage area : E Ivory Coast, Liberia*

- *Period : MAM*



Scenario #2.3

- *Host country : Ivory Coast (Korhogo region)*
- *Coverage area : N Ivory Coast, S Mali, SW Burkina Faso*
- *Period : MJJ*



Scenario #2.4

- *Host country : Ivory Coast (Abidjan region)*
- *Coverage area : South of Ivory Coast*

- *Period : MAM*

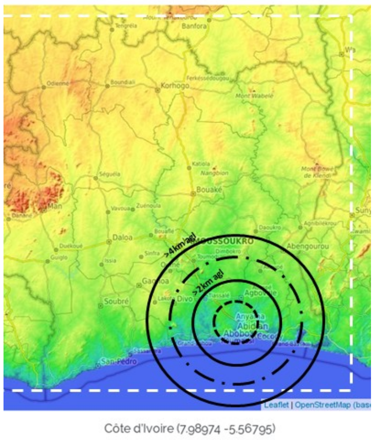
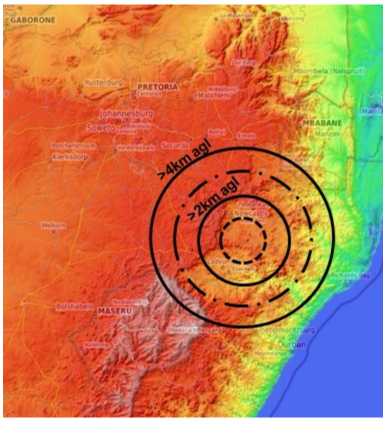


Fig.-3.5.3. Four scenarios for a deployment in Côte d'Ivoire.

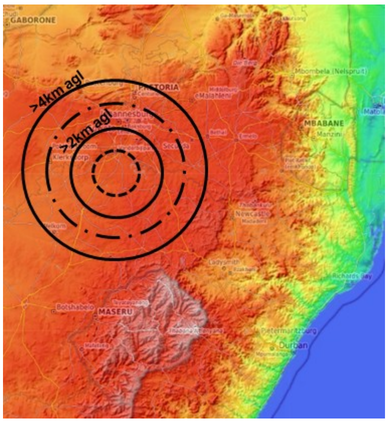
Scenario #3.1

- *Host country : South Africa (Colenso region, 28S 30E)*
- *Coverage area : Northeast of South Africa*
- *Period : NDJF*



Scenario #3.2

- *Host country : South Africa (Klerksdorp region, 27S 26E)*
- *Coverage area : Northeast of South Africa*
- *Period : NDJF*



Scenario #3.3

- *Host country : South Africa (Ermelo region, 26.5S 30E)*
- *Coverage area : Northeast of South Africa*
- *Period : NDJF*

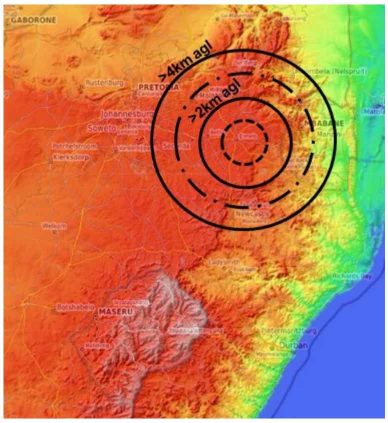


Fig.-3.5.4. Three scenarios for a deployment in South Africa.

Key information including lightning rate is given for each scenario in Table 3.5.1. The following paragraphs detail the different scenarios based on preliminary discussions with Kenya, South Africa and Côte d'Ivoire NWSs and on the main conclusions of the study. These discussions provide the material to give the level of feasibility of each campaign and a priority level of each scenario and reported in the last column of Table 3.5.1. The priority level is argued in the table but Kenya and South Africa scenarios present similar ranges of lightning activity (as deduced from TRMM-LIS climatology), suggesting that those two regions might be considered first.

Kenya Weather Service has indicated its interest to contribute to the LMA-based LI validation campaign. Scenario #1.2 has been identified as a potential deployment scenario with the support of the Kenya Weather Service. Deployment of some LMA stations at the locations of the weather stations of Kenya Weather Service will be possible.

South Africa Weather Service confirmed its interest to help during the LMA-based LI validation campaign. Scenario #3.3 has been identified as the best scenario considering the lightning activity. South Africa Weather Service operates an operational lightning locating system and several weather radars that cover Scenario #3.3 area.

SODEXAM (Côte d'Ivoire Weather Service) provided climatology of precipitation based on 30 years of measurements from weather stations that confirms the main results discussed in Section 3.4.4. A deployment in the southwest area of Côte d'Ivoire (Scenario #3.1) will benefit from the future deployment of weather radar in 2023. Scenario #3.4 could also be a backup possibility but the electromagnetic noise level will have to assess first. SODEXAM confirms its interest to support the LMA team during the LI validation campaign and has offered the possibility to position the LMA stations at the locations of their weather stations.

Table 3.5.1. Key information on the different sites of interests, with P1, P2, P3 standing for priority from high to low.

Region	Domain	Host country	Period during the year	Period during the day	Expected range of lightning activity based on TRMM-LIS climatology	Science interest	Validation interest	LMA network	Hosts	Facilities and services	Operation interest
Kenya/Uganda/Lake Victoria	1.1	Tanzania (Musoma region)	FMA	Over land during daytime Over the lake during nighttimes	Range of annual flash rate *[mean annual flash rate]* (flash/km^2/year): 1.61-52.13 *[22.31]* Range of monthly flash rate *[mean monthly flash rate]* (flash/km^2/day): 0.004-0.154 *[0.102]*	P1 (low and high flash rate expected, day and night activities, hot spot over land and fresh water)	P1 (1 camera only; high probability for day and night validation)	Coverage area : North of Tanzania, West of Kenya, East par of Lake Victoria	Tanzania Weather Service	-No analog TV -GSM -Hardware: https://www.prosolar.co.tz -Weather radar coverage	P2
	1.2	Kenya (Kisumi region)	FMA	Over land during daytime Over the lake during nighttimes	Range of annual flash rate *[mean annual flash rate]* (flash/km^2/year): 3.12-49.78 *[24.72]* Range of monthly flash rate *[mean monthly flash rate]* (flash/km^2/day): 0.054-0.155 *[0.107]*	P1 (low and high flash rate expected, day and night activities, hot spot over land and fresh water)	P1 (1 camera only; high probability for day and night validation)	Coverage area : North of Tanzania, West of Kenya, East part of Lake Victoria	Kenya Weather Service Discussions held during the study	-No analog TV -GSM -Hardware: https://www.prosolar.co.tz -Support from the Kenya Weather Service	P1 (support of Kenya Weather Service)
	1.3	Uganda (Mayuge region)	FMA	Over land during daytime Over the lake during nighttimes	Range of annual flash rate *[mean annual flash rate]* (flash/km^2/year): 6.86-42.49 *[19.76]* Range of monthly flash rate *[mean monthly flash rate]* (flash/km^2/day): 0.024-0.132 *[0.089]*	P1 (low and high flash rate expected, day and night activities, hot spot over land and fresh water)	P1 (1 camera only; high probability for day and night validation)	Coverage area : South Uganda, West Kenya, North Victoria Lake	Uganda Weather Service	-No analog TV -GSM -Hardware: https://www.prosolar.co.tz -Ground – based Lightning Locating System	P2

Côte d'Ivoire	**2.1**	**Ivory Coast (Soubré region)**	**MAM**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km²/year): 0.50-43.44 *[11.79]***	**P2 (lower flash rate expected than in Lake Victoria)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views)**	**Coverage area : SW Ivory Coast, Liberia**	**SODEXAM**	**- GSM -Hardware: https://www.jumia.ci/ -Weather radar in 2023**	**P1**
					Range of monthly flash rate *[mean monthly flash rate]* (flash/km²/day): 0.007-0.141 *[0.049]*				**Discussions held during the study**		
	2.2	**Ivory Coast (Man region)**	**MAM**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km²/year): 1.70-57.23 *[18.38]***	**P2 (lower flash rate expected than in Lake Victoria)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views)**	**Coverage area : E Ivory Coast, Liberia**	**SODEXAM**	**- GSM -Hardware: https://www.jumia.ci/**	**P2**
					Range of monthly flash rate *[mean monthly flash rate]* (flash/km²/day): 0.022-0.187 *[0.085]*				**Discussions held during the study**		
	2.3	**Ivory Coast (Korhogo region)**	**MJJ**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km²/year): 2.49-53.30 *[17.23]***	**P2 (lower flash rate expected than in Lake Victoria)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views)**	**Coverage area : N Ivory Coast, S Mali, SW Burkina Faso**	**SODEXAM**	**- GSM -Hardware: https://www.jumia.ci/**	**P3**
					Range of monthly flash rate *[mean monthly flash rate]* (flash/km²/day): 0.012-0.174 *[0.067]*				**Discussions held during the study**		
	2.4	**Ivory Coast (Abidjan region)**	**MMA**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km²/year): 1.01-45.07 *[13.51]***	**P2 (lower flash rate expected than in Lake Victoria)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views)**	**Coverage area : Abidjan, South Central Ivory Coast**	**SODEXAM**	**- GSM -Hardware: https://www.jumia.ci/ -Weather radar in 2023**	**P2**
					Range of monthly flash rate *[mean monthly flash rate]* (flash/km²/day): 0.025-0.181 *[0.080]*				**Discussions held during the study**		

South Africa	**3.1**	**South Africa (Colenso region, 28S 30E)**	**NDJF**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km^2/year): 7.68-38.95 *[20.86]*** **Range of monthly flash rate *[mean monthly flash rate]* (flash/km^2/day): 0.038-0.210 *[0.134]***	**P2 (lower chances of deep convection)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views; edge of LI FOV)**	**Coverage area : Colenso region, Lesotho**	**SA Weather Service** **Discussions held during the study**	**-Ground-based Lightning locating System -radar S-band -Still today analog TV. -3G /4G**	**P2 (based on SA Weather Service feedback)**
	3.2	**South Africa (Klerksdorp region, 27S 26E)**	**NDJF**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km^2/year): 8.33-41.08 *[20.49]*** **Range of monthly flash rate *[mean monthly flash rate]* (flash/km^2/day): 0.058-0.212 *[0.138]***	**P2 (lower chances of deep convection)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views; edge of LI FOV)**	**Coverage area : Klerksdorp region**	**SA Weather Service** **Discussions held during the study**	**-Ground-based Lightning locating System -radar S-band -Still today analog TV. -3G /4G**	**P2 (based on SA Weather Service feedback)**
	3.3	**South Africa (Ermelo region, 26.5S 30E)**	**NDJF**	**Over land during daytime**	**Range of annual flash rate *[mean annual flash rate]* (flash/km^2/year): 7.46-46.76 *[19.03]*** **Range of monthly flash rate *[mean monthly flash rate]* (flash/km^2/day): 0.044-0.164 *[0.104]***	**P1 (hail storms)**	**P1 (2 cameras could be validated but to be confirmed according to actual LI Optical Camera field of views; edge of LI FOV)**	**Coverage area : Ermelo region, Swaziland**	**SA Weather Service** **Discussions held during the study**	**-Ground-based Lightning locating System -radar S-band -Still today analog TV. -3G /4G**	**P1 (based on SA Weather Service feedback)**

4. Conclusions

The present study aimed at proposing scenarios of LMA-based LI validation campaigns in Africa. Four main items have been addressed:

1. Which are the dedicated LMA campaigns that have been run or being run providing data for comparisons against space-borne lightning optical imagers? Which are their key characteristics and results?
2. What type of dedicated campaign(s), with intellectual/human resources needed, could be performed by relocating the European LMA networks, as we know them today?
3. What are the best sites over African territory to run a dedicated LMA campaign? What is the lightning activity in such sites?
4. What are the possible examples of dedicated campaigns that EUMETSAT could consider to run after the launch of LI?

To address the 1st item, a literature review has been conducted. Judging that the information in the literature was only partially describing the requirements of the campaigns, the issues faced during the campaigns and the lessons learned, a specific survey has been sent out to the Principal Investigators of the LMA-based campaigns. The topics of the survey cover the pre and post-campaign activities and the operations during the campaign. However one should be very careful in drawing conclusions from field campaigns in American countries for a validation campaign in sub-Saharan Africa as local reality is very much different. Interaction with local hosts should help set up plans and mitigation for not only the site survey, but also the deployment, the operation, the security of the equipment and the team, and the dismantlement.

When addressing the 2nd item, the analysis of the survey responses reveals that the UT3/UPC Consortium has faced the same issues when operating their LMAs either in Colombia or in Corsica. The UT3 and UPC LMAs have successively demonstrated their capability to measure lightning activity on the stand alone from their bases and remotely. The observations of the two LMA networks have contributed to ISS-LIS, ISS-ASIM and GLM cal/val activities. The UPC and UT3 LMAs are 10 and 7 year old, respectively. The two groups have equipment spares of all sub-systems. UT3 and UPC are currently running their networks through national and European projects of more or less short duration. Even if UT3 and UPC have access to a pool of Master and PhD students and possibility to host EUMETSAT post-docs, there will be a need to define a Human Resources strategy for the years to come to keep current personal working on soft money, to get recruitment of new permanent staff, and to define as well a more general project UT3-UPC strategy at national, European and international levels, and an upgrade will have to be investigated in support to long term operations, including MTG-LI validation in Africa and in Europe.

To address the 3rd item, the team has built multiple-source storm climatology based on 10-year SEVIRI, 16-year TRMM-LI and 6-month GLD360 records. The climatology has been analyzed in terms of location and severity over the whole African continent through seasonal and diurnal cycles of the convection. Three regions – Kenya/Uganda/Lake Victoria, Côte d’Ivoire and South Africa - have then been investigated based on EUMETSAT demand. Geographical distributions of the lightning activity and convection at different decade, yearly, monthly temporal resolution have been documented. Properties of the lightning activity in terms of flash rate and flash density have also been investigated. For each of the three regions of interest, three scenarios of LMA campaign have been proposed, each scenario corresponding to a specific regional coverage at either the same period of the year (Kenya/Uganda/Lake Victoria and South Africa) or at different times during the year (Côte d'Ivoire).

Those different scenarios have been used as a basis to address the 4th item. Interactions with Kenya, Côte d'Ivoire and South Africa national weather services help consolidate and at ranking these scenarios according to their feasibility, their scientific relevance and their benefits relative to MTG-LI validation. Based on the exchanged with the Kenya, Côte d'Ivoire and South Africa national weather services, the following scenarios are proposed from higher to lower validation/science interests: Scenario #1.2 for the region of Lake Victoria (*annual flash rate [mean annual flash rate] : 3.12-49.78 [24.72] flash/km^2/year; monthly flash rate [mean monthly flash rate] : 0.054-0.155 [0.107] flash/km^2/day*), Scenario #3.3 for the region of South Africa (*annual flash rate [mean annual flash rate] : 7.46-46.76 [19.03] flash/km^2/year; monthly flash rate [mean monthly flash rate] : 0.044-0.164 [0.104] flash/km^2/day*), and Scenario #2.1 for the region of Côte d'Ivoire (*annual flash rate [mean annual flash rate] : 0.50-43.44 [11.79] flash/km^2/year; monthly flash rate [mean monthly flash rate] : 0.007-0.141 [0.049] flash/km^2/day*). Note that Scenario #2.1 and Scenario #3.3 might provide observations that would help validate two different LI optical cameras (OC1 & OC2, and OC3 & OC4, respectively) because of overlaps of LMA and LI coverage areas.

The Consortium strongly recommends conducting the site survey with electromagnetic noise level measurements in the LMA VHF band at all potential regions of interest, prior to any decision on the actual location of the campaign. Staff of the host institutes could be trained to conduct such field activities. Their travel and subsistence expenses should be covered by EUMETSAT. The Consortium suggests to EUMETSAT to consider the possibility to conduct several LMA-based campaigns in Africa during the years to come either through dedicated EUMETSAT-funded campaigns or through contribution to scientific campaigns that could be organized in Africa. EUMETSAT should also support any initiative in Africa related to the deployment of new ground-based lightning detection networks.

It is planned to run the LMA network on a standalone operation (power delivered by solar panels and batteries). There is also the need for efficient mobile phone coverage for remote monitoring of all LMA stations. Between 10 and 12 LMA stations will be deployed, meaning that 10 to 12 sites + 6 backup sites about ~20-30 km distant from each other should be identified and surveyed. The LMA stations must be deployed in electromagnetic quiet areas, so site surveys (electromagnetic noise level, layout) will have to conduct prior deployment at least 1 year and a few weeks before actual deployment for verification. All LMA stations should see around at 360° with ideally no obstacles at close range. LMA stations should be deployed in accessible, safe and secured areas (away from floods; thieves). The visit of all stations should be conducted every week for data recovery and maintenance. Local storage, technical and office (with internet) rooms will be needed. Obviously, a referent of the host Institute will have to work closely with the LMA team, to locally keep contact with land owners and to handle paper works and issues with local authority. Finally there is definitively the need for local support for deployment, maintenance (with technical and science training), dismantlement, and logistics in general (including drivers).

It is important to associate quite before the field deployment and the 1st visit the team of the host Institute through a common training and science plan to contribute to the science and technical objectives of the MTG-LI validation. Such interactions should rely on exchanges between staffs and scientific studies conducted between all teams, and their costs should be included either in the budget of the campaign or through a dedicated Europe-Africa project including science, technology and operational applications. Local African universities should also be invited to participate to the campaign during its different phases.

Finally the objectives, requirements and milestones of the field campaign should be clearly defined. This includes the definition of a science plan in collaboration with the African NWS host, the definition of an observational (and modeling) plan and the definition of a data processing plan. Associated risk analysis should be investigated in order to propose mitigation plans as uncertainties (sanitary conditions, national and international issues) will be present during the periods before, during and after the campaign. The preparation of the campaign should start as soon as possible and one might need to contact other governmental and international organizations to ease the processes. Finally the campaign should be advertised to the scientific community for additional contribution on self funding and bigger scientific returns.

A preliminary campaign cost has been assessed that includes instrument preparation, shipping, missions (pre-campaign and campaign related), running costs, spares of instrument sub-systems, data processing and first data analysis, and salary of European and African teams. This cost is not is not given in this report.

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The French AERIS/ICARE data center provided the SEVIRI data, and computing and storage resources to produce the 10-year SEVIRI climatology over Africa. EUMETSAT provided the 6-month GLD360 dataset. TRMM-LIS 0.1 Degree Very High Resolution Gridded Climatology data collection (http://dx.doi.org/10.5067/LIS/LIS/DATA306) was used to complete the study.

Annex 1. Survey sent to the lightning community that has been involved in abroad field campaigns

Survey on LMA deployment and operation in support GLM and LIS cal/val activities	
Teams:	**Eric Defer (UT3/LA) & Joan Montanya (UPC/LRG)**
Document reference:	**UT3/2021/EUM/CO/20/4600002481/BV/SURVEY01**
Date:	**16 February 2021**
Expected return:	**02 March 2021**

UT3/LA (E. Defer) and UPC/LRG (J. Montanya) are currently running a study for EUMETSAT to investigate the possibility to deploy and operate a LMA in Africa in support to MTG (Meteosat Third Generation) LI (Lightning Imager) cal/val activities.

Based on your involvement in (TRMM and ISS) LIS and GLM validation, we would like to ask you a series of questions to help us consolidate the observational strategy that needs to be applied based on your experience and the lessons learned. The (rather long) survey includes questions on the instrument itself, on site survey, on the preparation of the instrument, on the shipping, the installation, the operation, the dismantlement, the data processing during the campaign(s), and the exploitation of the LMA data during the campaign(s) and post-campaign.

Please provide as much as you want details in your answer if you want.

Name	
Institute	
Email address	
Summary of your involvement in the LIS and/or GLM validation	*[LMAs operated from their bases and involved in any cal/val activity are also eligible.]*
Involvement in field campaign	YES – NO *[if yes give the name of the campaign(s) and geographical locations. LMAs operated from their bases and involved in any cal/val activity are also eligible.]*
Involvement in cal/val data analysis	YES – NO *[if yes give the name of the campaign(s) and geographical locations. LMAs operated from their bases and involved in any cal/val activity are also eligible.]*

1 - Team (LMA campaign)
1.a How many people were involved in total? 1.b How many people were involved for LMA installation? 1.c How many people were involved for LMA operation in the field? 1.d How many people were involved for LMA operation at your institute? 1.e How many people were involved for LMA dismantlement? 1.f How many people were involved for data processing? 1.g How many people were involved for data quality control? 1.h How many people were involved for data analysis? 1.i Did you hire personnel? How many? Which tasks? 1.j <u>Free comments</u> :

2 - LMA sensors
2.a Who owned the LMA sensors/network? How many sensors? 2.b Did you buy/borrow LMA sensors for the campaign? How many? From who? 2.c Which type of LMA sensors? (old versions installed in cooler-box, version with 75 Ohm and operating system in CF, newer versions with 50 Ohm) 2.d What was the average age of the sensors? 2.e Did you conduct a risk analysis, and, if yes, on which topics? 2.f <u>Free comments</u> :

3** - **Before shipping and installation
3.a Did you perform a site survey? Could you please describe the methodology you applied? 3.b How much time in advance the survey was conducted? And how long lasted the survey? 3.c Who performed the site survey? 3.d How many candidate sites were surveyed? 3.e How many sites were rejected? 3.f How many potential sites were identified to host one of your LMA stations? 3.g Did you conduct a risk analysis, and, if yes, on which topics? 3.h <u>Free comments</u> :

4 – Shipping
4.a How were the LMA stations shipped to the destination? 4.b How did you manage customs (temporal export, ATA carnet, ...)? 4.c Did you pay customs? How much? 4.d Any problems related to customs (bringing in and out of the country)? 4.e Did you take any insurance? 4.f Please list all the equipment shipped (toolboxes…). 4.g How long did the shipping last? 4.h Did you conduct a risk analysis, and, if yes, on which topics? 4.i <u>Free comments</u> :

5 - Description of the LMA sites
5.a Installation in private properties or public areas? 5.b What type of energy was available ? Power (mains) available? Solar? Swap batteries? 5.c What type of communication did you use? No online communications with the stations? Host ethernet? Using GPRS/3G/4G communications? Using satellite communications? 5.d How did you contact the host(s)? How were made the arrangement with the host(s)? 5.e Did you pay the host(s)? If yes, if not confidential, how much? 5.f Were there any access restrictions (security, driving)? If yes, how long did the access procedure take for a visit? 5.g Please provide a map with the instrument setup. And describe as well the relief where the LMA network was deployed. 5.h Please discuss the spatial distribution of the LMA stations relatively to the scientific and technical objectives. 5.i Did you conduct a risk analysis, and, if yes, on which topics? 5.j <u>Free comments</u> :

6 - Installation
6.a Who installed the sensors? How many people worked on the installations? 6.b Did you hired people or companies to help with the installation? If yes please describe? How much? 6.c For how long was the LMA deployed? 6.d Were your LMA stations operated on the stand alone or hooked to the power grid or/and phone lines? 6.e Who paid the (power, phone) bills? What was the total cost of the power bill? And the phone bill? 6.f Were the LMA stations built before shipping or built from scratch with material purchased locally? In the latter did you have to redesign the structure of the station to mitigate the fact that you did not find the required material? 6.g Can you describe the installation strategy (each station set up successively or several teams working in parallel)? 6.h Can you discuss if you had to buy some items locally and which items (e.g. masts, cables…)? 6.i Average time required to install each station? 6.j Minor problems related to the installation? 6.k Major problems related to the installation? 6.l Unexpected costs related to the installation? 6.m What did you have to install to secure each LMA sites (fences against wild animals; thieves; lightning protection)? 6.n Could you provide representative pictures of your LMA stations as deployed in the field? 6.o How did you secure your LMA stations against flash flood? 6.p Did you conduct a risk analysis, and, if yes, on which topics? 6.q Free comments :

7 - Operation
7.a How did you monitor the stations during the campaign(s)? 7.b How often did you visit the stations? 7.c Was the real time of the LMA used as decision and planning tool? Was the LMA real time source/flash display required in real time to support the cal/val activities? 7.d Did the LMA real time data used for live or near real time data analysis, and/or post-campaign studies? 7.e Did you get some timeliness requirements to deliver the LMA data in real time? Please list those requirements and how those requirements were or not met. 7.f Please remind the time resolution of the LMA network? And the time resolution of the real time of the LMA network? 7.g Did you need to adapt the setup of your LMA stations (cooling systems, additional fans,...) to be able to run nominally in extreme conditions (temperature, heavy rain, strong wind)? Please detail as much as possible what you did. 7.h How often the data from LMA sensors were collected? 7.i In average, how many LMA sensor were operating? And for how long? What were the main causes of the LMA sensor malfunctions? 7.j Were human resources continuously available to keep the LMA stations working during the campaign? Could you please describe what were the activities conducted by either local support, or the people from your institution, or hired personnel? 7.k What was the average time required to fix problems? Did you conduct some operation at sites during the night? 7.l Did you have a maintenance plan before arriving in the field or did you just fix the problems when they happened? 7.m Could you please list the minor problems you faced during the LMA operation during the campaign? (e.g. preamplifiers damaged, GPS damages, LMA operating system problems, ...) Did you bring enough spares with you? 7.n Could you please list the minor problems you faced during the LMA operation during the campaign? 7.o Did you conduct a risk analysis, and, if yes, on which topics? 7.p <u>Free comments</u> :

8 – Data processing
8.a What were the requirements in terms of data delivery? Did you have to deliver real time data and under which timeliness, operation requirements? 8.b How was conducting the real time data processing? 8.c Did you deploy specific computing resources locally? Or did you transfer the LMA data to your premises? 8.d What were the temporal and quality control requirements to deliver your LMA data for the analysis? 8.e Did you conduct a risk analysis, and, if yes, on which topics? 8.f <u>Free comments</u> :

9 – Personnel
9.a Did you contract personnel for the campaign? How many people were hired? (only human resources related to LMA installation, maintenance, operation, ...) Please describe. 9.b Did you contract any local company to provide local support to keep the LMA in operation? 9.c Did you conduct a risk analysis, and, if yes, on which topics? 9.d <u>Free comments</u> :

10 – *Costs*
10.a Which was your main source/s of funding for the campaign? 10.b How much funding it was related to the LMA (all aspects)? 10.c Can you provide, when not confidential, some amounts of costs related to: - buying new sensors or necessary hardware. - Shipping of the sensors (in and out, including customs......) - Installation - Operation (hosts, communications, spares, data collection...) - Removal of the sensors - Hired personnel necessary for the campaign. - Data analysis. 10.d Did you conduct a risk analysis, and, if yes, on which topics? 10.e <u>Free comments</u> :

11 – *Auxiliary data*
11.a What are the auxiliary atmospheric electricity measurements that have been collected during the campaign in addition to the LMA observations to support the cal/val activities? 11.b What are the auxiliary atmospheric (e.g. cloud, rain) measurements that have been collected during the campaign in addition to the LMA observations to support the cal/val activities? 11.c Were any other auxiliary measurements or model outputs collected during the campaign(s) to support the cal/val activities? 11.d <u>Free comments</u> :

12 – *Lessons learned and advices*
12.a What are main successes of the LMA campaign(s)?   12.b What are the main failures of the LMA campaign(s)?   12.c Any advice?   12.d What are the lessons learned?

13 – *Missing items*
[please feel free to discuss missing items]

Annex 2. Map of Africa

Annex 3. Site survey: Analog TV switch-off and communications

A3.1 Status of Analog TV channel-switch off

The LMA operates in the VHF frequencies allocated for analog TV broadcasting. These analog TV VHF channels are not used by the Digital TV broadcasting (DTV) so the LMA can be conveniently allocated in one of these channels. Typically, the LMA uses Channel 3: 60-66 MHz. In this section we investigate the status of the analog TV switch-off in each of the candidate countries. The data is obtained from the web and documents edited by telecommunications agencies in the countries.

Country	**Site survey:** Digital TV (analog switch-off)
Kenya	No-analog TV broadcast, early switch-off 2012-15
Uganda	No-analog TV broadcast, 2018
Tanzania	No-analog TV broadcast, early switch-off in 2012
Côte d’Ivoire	Expected analog switch-off by 2020.
South Africa	Analog switch-off completed in all the country by March 2022. From the meeting with the SAWS we conclude that South Africa is still in process (50%) to finalize the transition.

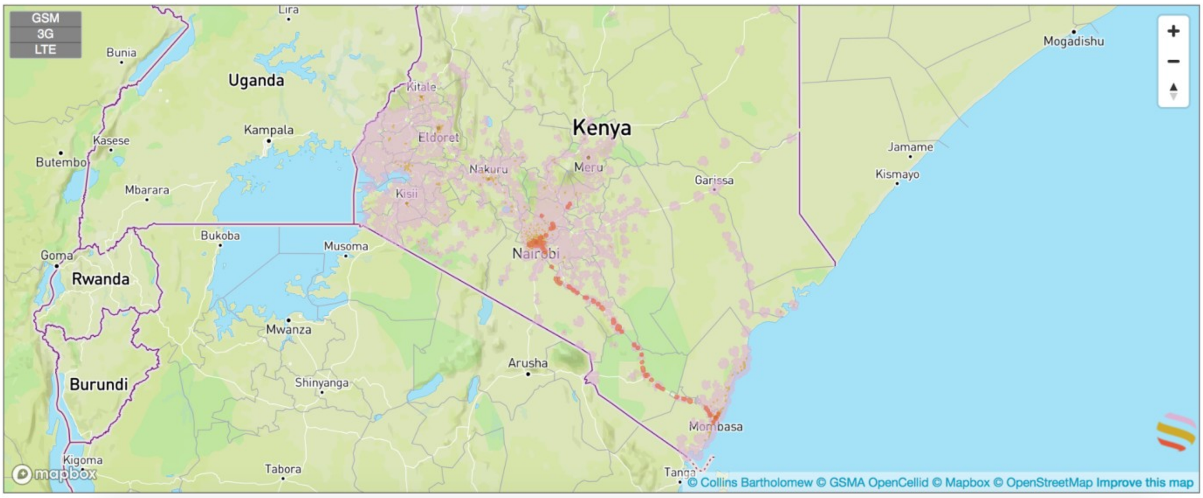
A3.2 Cellular coverage

The second important aspect is the GSM/3G/4G coverage in the different proposed regions. This determines the capacity of remote management of the sensors and, if possible, data transferring.

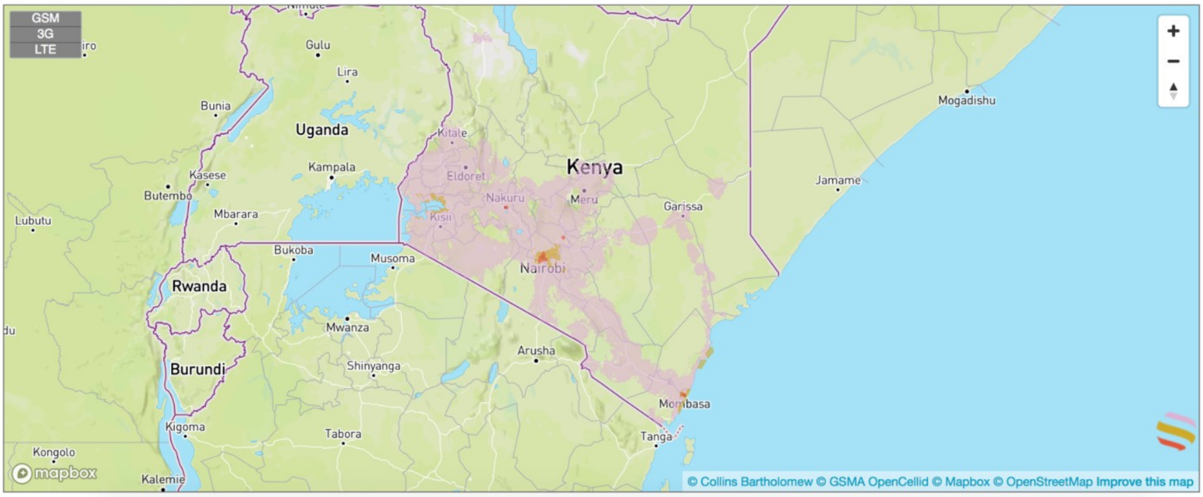
Kenya

The region of interest in Kenya is covered by GSM but 3G is almost unavailable.

Operator: Airtel (Bharti Airtel)



Operator: Orange (Telkom Kenya)

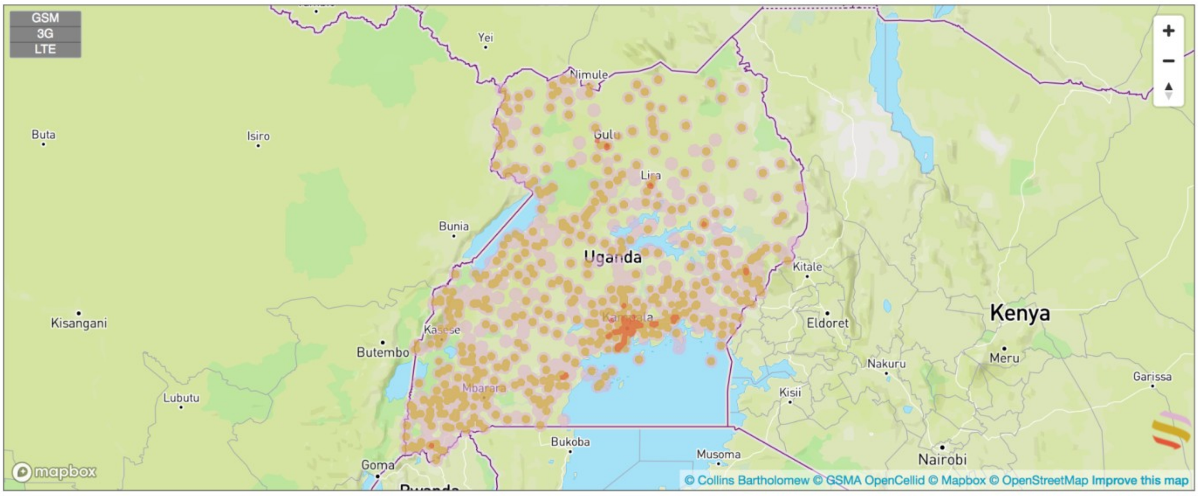


Standards: GSM 900 / GSM 1800 / UMTS 2100 / LTE 800

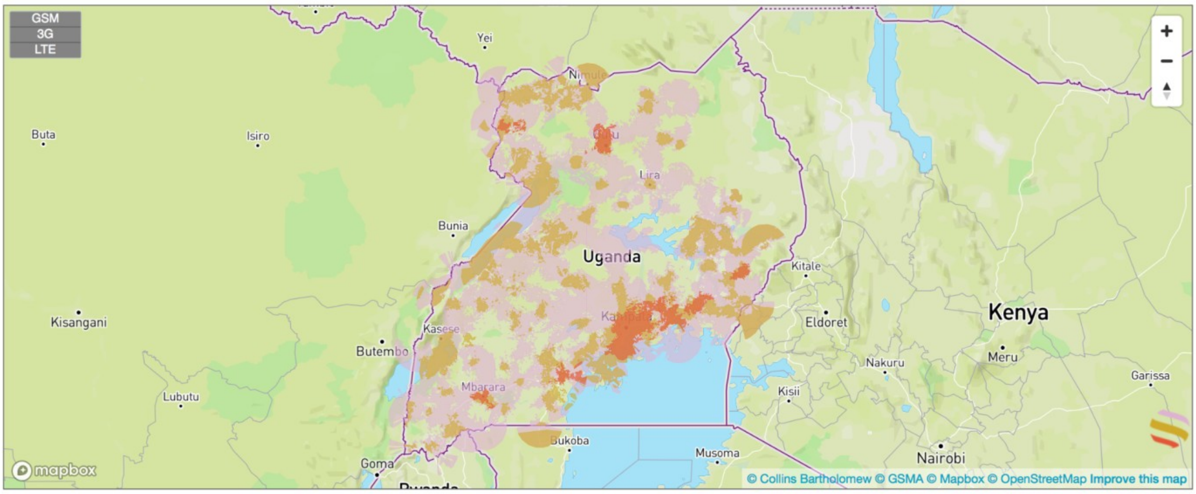
Uganda

GSM and, in some areas, 3G are available in the area of interest. But it will be difficult to expect 3G available in all the sites.

Operator: MTN



Operator: Africell (Lintel)

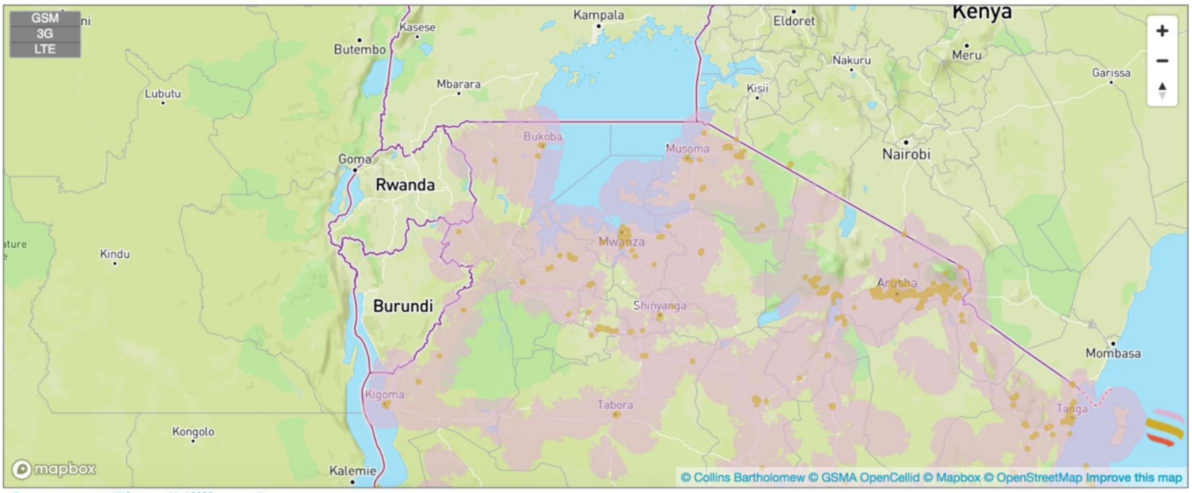


Standards: GSM 900 / UMTS 900 / UMTS 2100 / LTE 2600
GSM 900 / GSM 1800 / UMTS / LTE 800

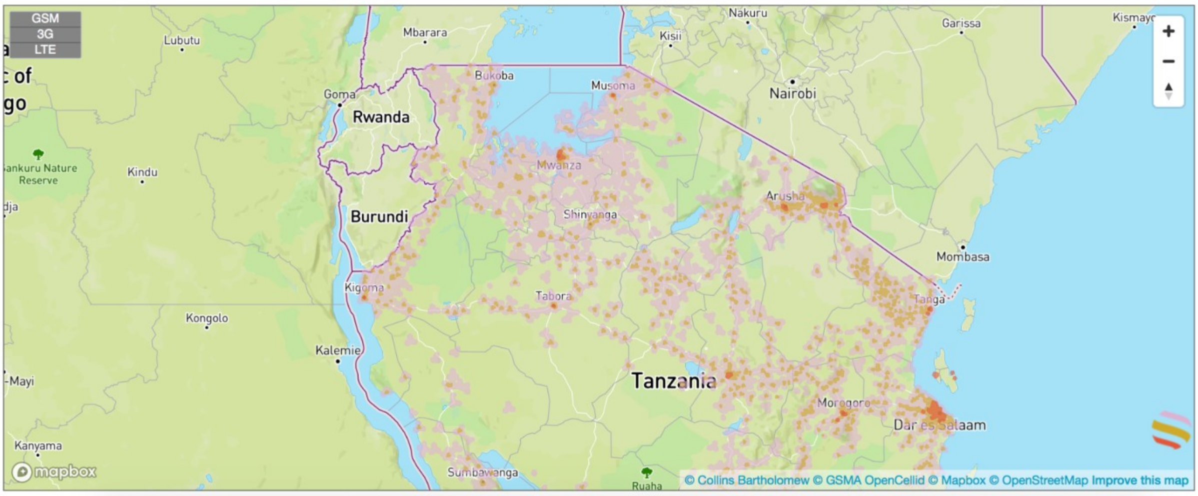
Tanzania

The area of interest is well covered by GSM but 3G is very limited.

Operator: Vodacom



Operator: Tigo (Millicom)

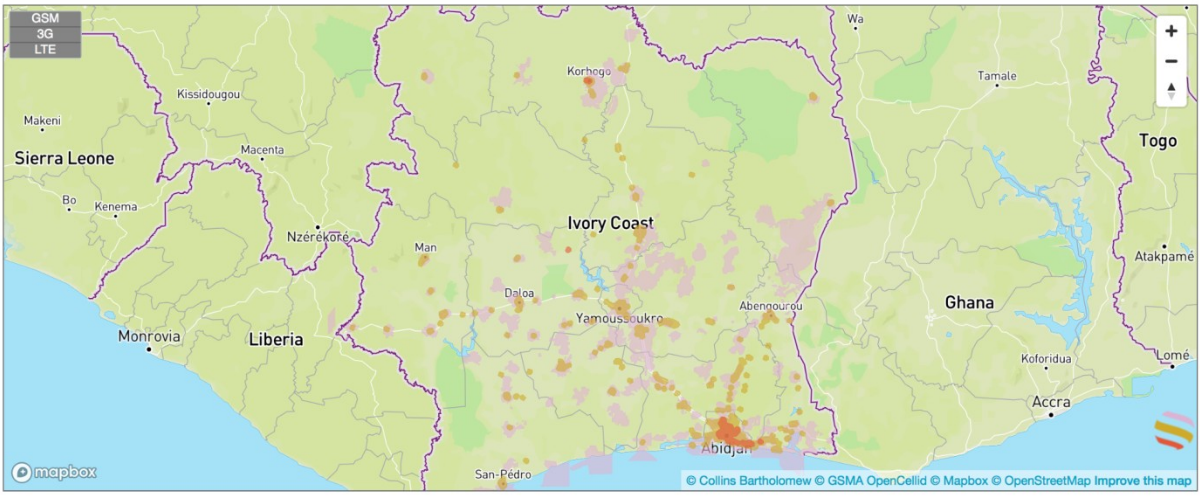


Standards: GSM 900 / GSM 1800 / UMTS 2100 / LTE 1800

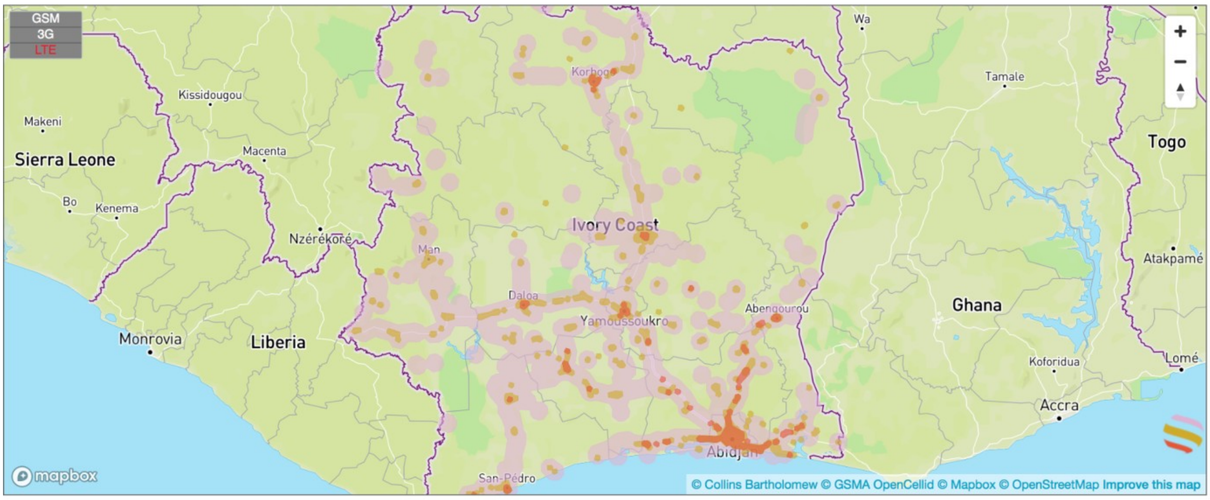
Côte d'Ivoire

The areas of interest are almost uncovered by GSM and much less by 3G.

Operator: MTN



Operator: Orange

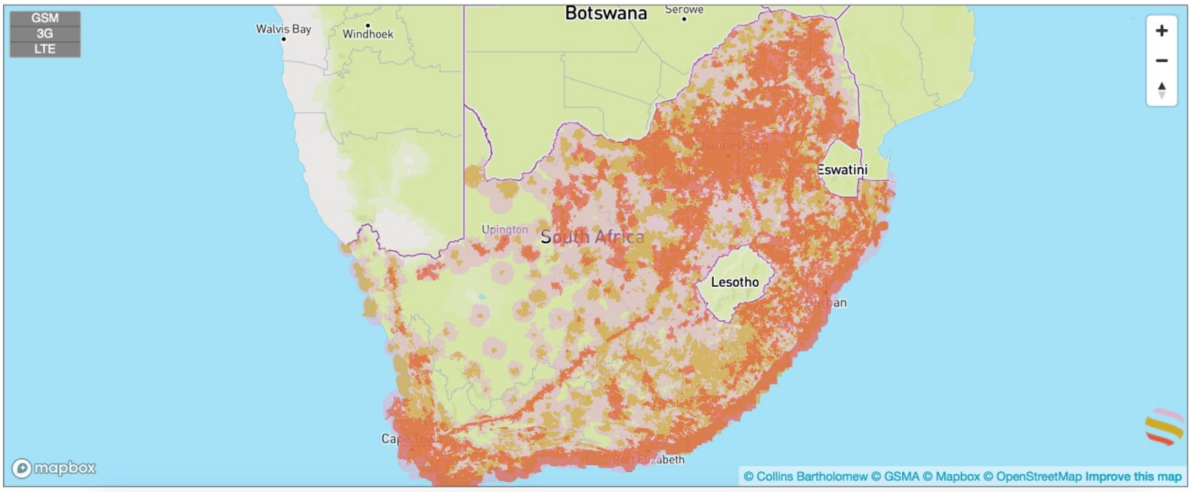


Standards: GSM 900 / UMTS 2100 / LTE 800 / LTE 2600

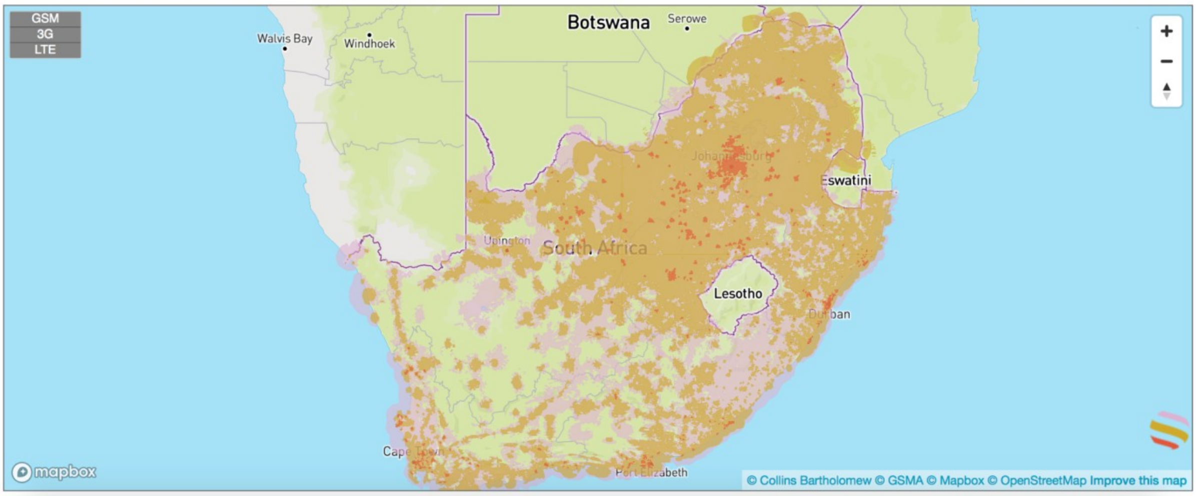
South Africa

The areas of interest are well covered by GSM and 3G.

Operator: Vodacom



Operator: MTN

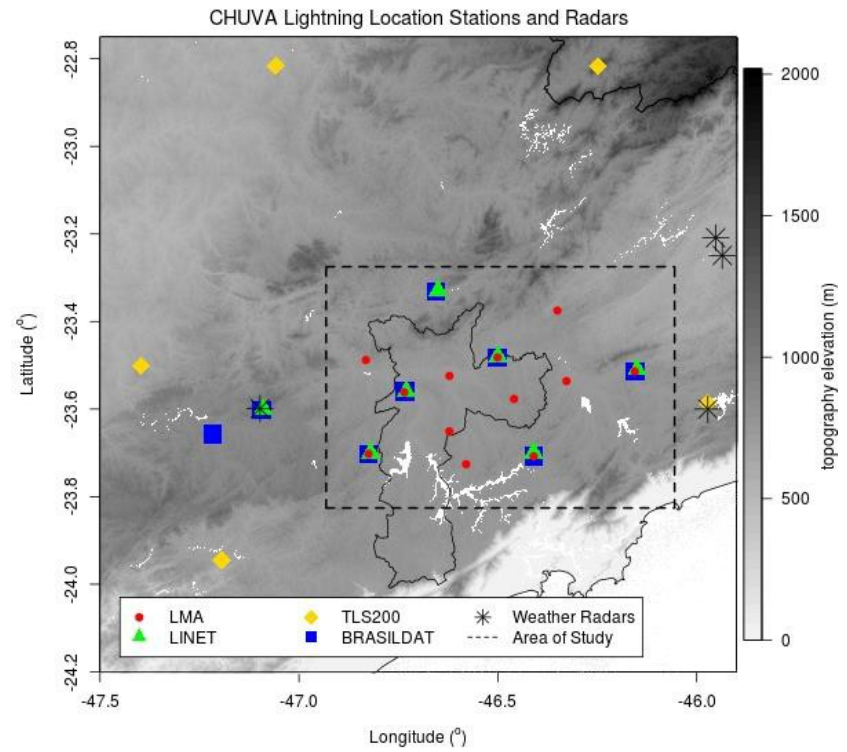


Standards:
GSM 900 / GSM 1800 / UMTS 2100 / LTE 900 / LTE 1800 / LTE 2100 / LTE 5200 / LTE 5800 / 5G 700 / 5G 3500
GSM 900 / UMTS 900 / UMTS 2100 / LTE 900 / LTE 1800 / LTE 2100 / 5G 700 / 5G 1800 / 5G 2100 / 5G 3500 / 5G 28000

Annex 4. Maps of LMA networks operated during LIS/GLM validation

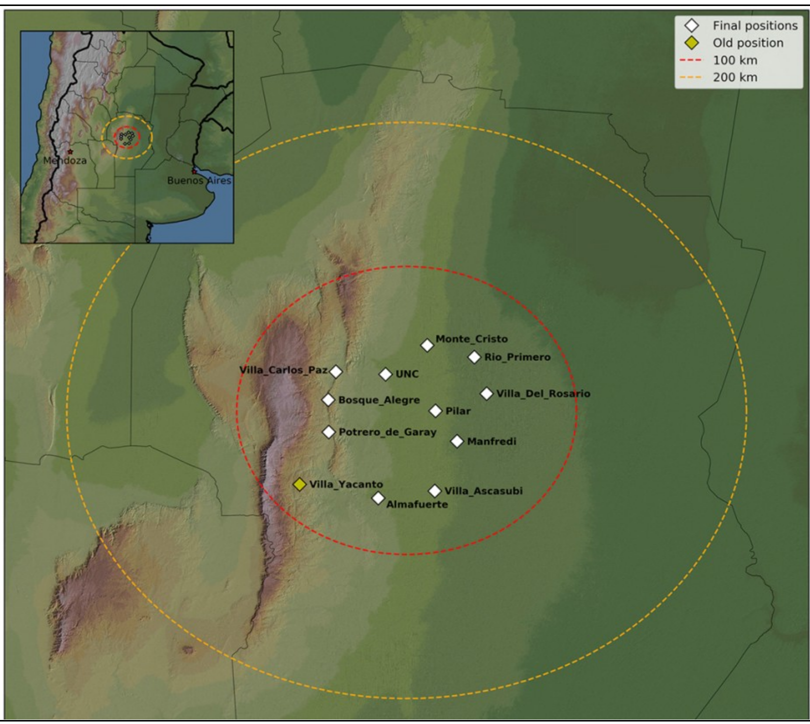
Campaign: **CHUVA**

Reference:
Albrecht et al., ICAE conference (2014)

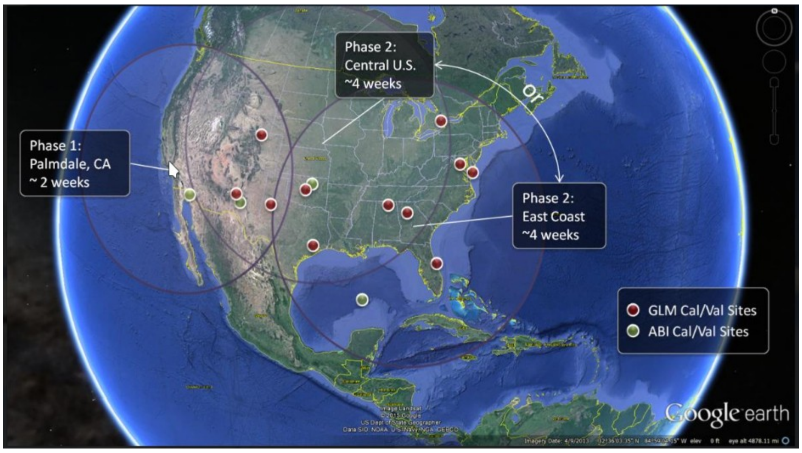


Campaign: **RELAMPAGO**

Reference:
Lang et al. (2020)
10.1175/JTECH-D-20-0005.1

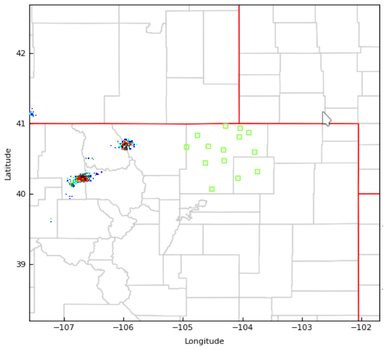


Campaign: **GOES-R PLT**

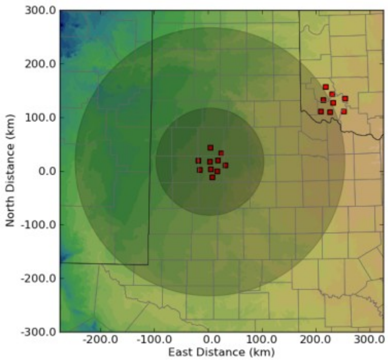


(Reference: Padula et al., CALCON, 2015)

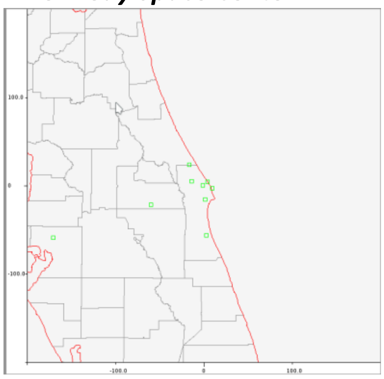
Colorado LMA



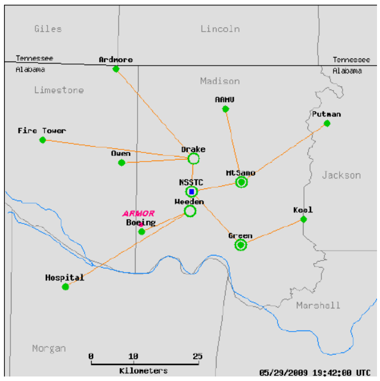
West Texas LMA



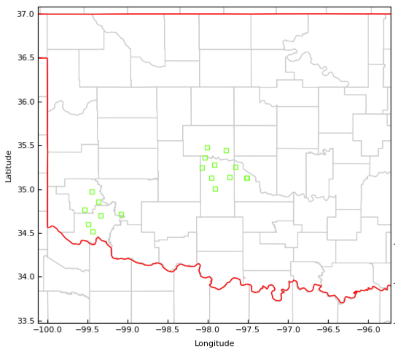
Kennedy Space Center LMA



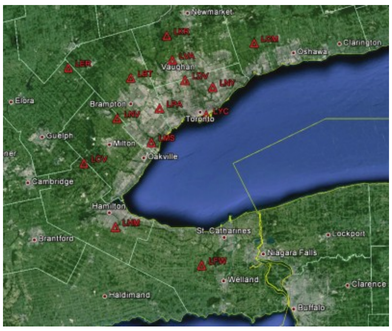
North Alabama LMA



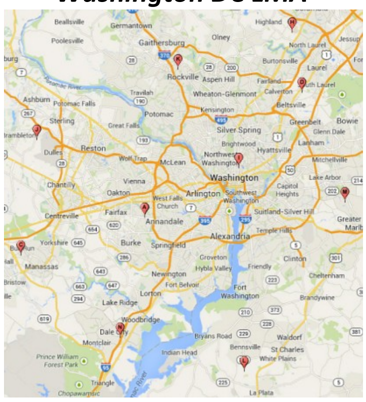
Oklahoma LMA



Southern Ontario LMA

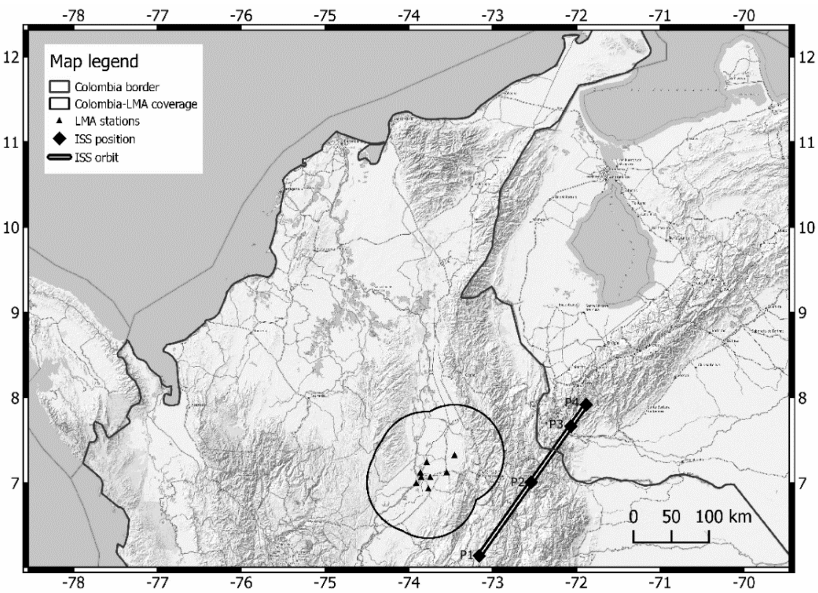


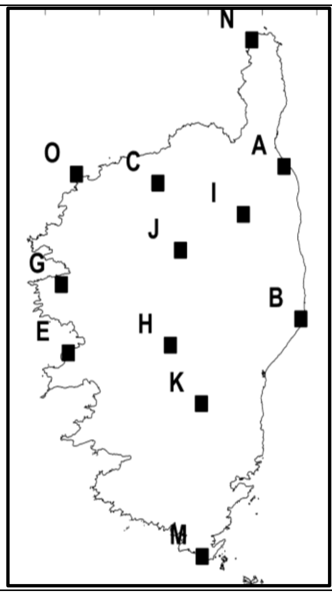
Washington DC LMA



Campaign: **Colombia ASIM**

Reference:
López et al., JGR (2019)
Montanya et al., JGR (2021)



Corsica SAETTA LMA	
Reference: *Coquillat et al., AMT (2019)*	

Annex 5. Acronym list

AF-IWP	Above Flash precipitation Ice Water Path
AMMA	African Monsoon Multidiscplinary Analysis
ASIM	Atmosphere-Space Interactions Monitor
ATDNET	UK Met Office Arrival-Time-Difference lightning detection network
BLESKA	Broadband Lightning Electromagnetic Signal Keeper Analyzer
BRAMS	Brazilian developments on the Regional Atmospheric Modelling System
CACTI	Clouds, Aerosols, and Complex Terrain Interactions
CAMMA	Córdoba Argentina Marx Meter Array
CHUVA	Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud-Resolving Modeling and to the Global Precipitation Measurement (GPM)
CNES	Centre National d'Etudes Spatiales
CNRS	Centre national de la recherche scientifique
COLMA	Colorado LMA
CSU	Colorado State University
DE	Detection Efficiency
DLR	German Aerospace Center
DOE	Department of Energy
ENTLN	Earth Networks Total Lightning Network
EPFL	Swiss Federal Institute of Technology Lausanne
FAPESP	Fundação de Amparo à Pesquisa do Estado de São Paulo
GHRC	NASA's Global Hydrometeorology Resource Center
GLD360	Global Lightning Dataset 360
GLM	Geostationary Lightning Mapper
GOES-R	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
HAMMA	Huntsville Alabama Marx Meter Array
INPE	Instituto Nacional de Pesquisas Espaciais
IPA	DLR Institut für Physik der Atmosphäre
ISS	International Space Station
IWC	Ice Water Content
KSC	Kennedy Space Center
LEETCHIE	Les Echanges Et Transformations d'espèces CHImiques et d'Energie (France)
LF	Low Frequency
LI	Lightning Imager
LINET	Lightning detection network by nowcast GmbH
LIS	Lightning Imaging Sensor
LLS	Lightning Locating System
LMA	Lightning Mapping Array
LRG	Lightning Research Group
MTG	Meteosat Third Generation
MSFC	Marshall Space Flight Center
NALMA	North Alabama LMA
NASA	National Aeronautics and Space Administration (USA)
NMT	New Mexico Tech (New Mexico Institute of Mining and Technology)

NOAA	National Oceanic and Atmospheric Administration (USA)
NSF	National Science Foundation (USA)
NSSL	National Severe Storms Laboratory (USA)
NWS	National Weather Service
OC	Optical Camera
OTD	Optical Transient Detector
PLT	Post-Launch Test
PVC	Polyvinyl chloride
RELAMPAGO	Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations
RINDAT	Brazil's national lightning detection network
SDA-2	Short Dipole Antenna
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SSD	Solid State Drive
TGF	Terrestrial Gamma-ray Flash
TLE	Transient Luminous Event
TLS	Vaisala Total Lightning Sensor
TRMM	Tropical Rainfall Measuring Mission
TTU	Texas Tech University (USA)
TV	Television
UPC	Universitat Politècnica de Catalunya
USP	Universidade de São Paulo
UT3	Université Toulouse 3 Paul Sabatier
VHF	Very High Frequency
VLF	Very Low Frequency
WP	Work Package
WRF	Weather Research and Forecasting model
XPOL	X-Band Polarimetric Doppler Weather Radar