EWC Research & Development project progress report

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2024……..……
Project Title:	Long term analysis of mesoscale convective systems in Europe using MSG Rapid Scan Service
Principal Investigator(s):	Fiolleau Thomas……..…… Roca Remy …….……
Affiliation:	CNRS / LEGOS…… …..……
Start date of the project:	01/11/2023
Expected end date:	01/11/2026……

Summary of project objectives

(10 lines max)

The project aims to enhance the understanding and forecasting of Deep Convective Systems (DCS), which are crucial for climate and weather due to their role in precipitation and cloud cover. Using the MSG 20-year data record and the observation capabilities of the new MTG satellite, the project aims to build a long-term climatology of DCS life cycles over Europe. This will provide observational constraints to improve fine-scale numerical models used for weather prediction and climate forecasting. The TOOCAN cloud tracking algorithm will be applied to detect and track DCS, leveraging higher temporal frequency observations to refine the detection of small storms and improve existing DCS databases, especially in mid-latitude regions during winter.

In parallel, the project aims to extend the climatological databases of DCS from 1981 to present in Africa and the Atlantic Ocean using the long-term METEOSAT series, and to take advantage of METEOSAT-IODC data to establish a unique DCS database over the Indian region from 1998 to today.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)
(10 lines max)

During the first year of the project, several technical and logistical challenges were encountered, which hindered progress. One issue was related to the operating system: the initial CentOS environment, installed at the project's outset, reached its end of support in June 2024. This necessitated a migration to an Ubuntu environment, causing delays in system reconfiguration. Another major challenge was managing the large volumes of METEOSAT data. During the Use Cases phase, MSG data were easily accessible via the EUMETSAT Data Bucket. However, with the start of the EWC Research & Development project, it became necessary to download both MSG and MTG data from the EUMETSAT datastore to our virtual machine (VM). This process proved time-consuming and placed significant pressure on the VM's storage resources, which were not designed for such extensive data requirements.

Together, these challenges have impacted the project's efficiency and timelines.

Summary of plans for the continuation of the project

(10 lines max)

- Execution of the cloud tracking algorithm TOOCAN on the complete MSG dataset (2004 to present) over Europe.
- Correction of Parallax Shift Effects of clouds using cloud height data for geostationary satellite observations.
- Collocation of the precipitation from the OPERA radar network with the detected convective systems.
- Production of a 20-year DCS database spanning 2004 to the present over Europe.

List of publications/reports from the project with complete references

Roca, R., Fiolleau, T., John, V.O. *et al.* METEOSAT Long-Term Observations Reveal Changes in Convective Organization Over Tropical Africa and Atlantic Ocean. *Surv Geophys* (2024). https://doi.org/10.1007/s10712-024-09862-8

Summary of results

(A summary of the results so far. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document.)

1) Introduction:

The project seeks to advance the understanding and forecasting of Deep Convective Systems (DCS), which play a pivotal role in shaping weather and climate through their influence on precipitation and cloud cover both in tropical and mid-latitude regions.

First, by leveraging the 20-year data record from the serie of Meteosat Second Generation (MSG) satellites and the enhanced observation capabilities of the new Meteosat Third Generation (MTG) satellite, the project aims to construct a comprehensive long-term climatology of deep convective system (DCS) life cycles over Europe. Additionally, the project seeks to capitalize on the OPERA radar network and the Lightning Imager (LI) observations from MTG to further refine the analysis and understanding of these systems. Central to this effort is the application of the TOOCAN cloud tracking algorithm (Fiolleau and Roca, 2013) to detect and monitor DCS, utilizing the increased temporal resolution of newer satellite observations. This approach will enable the refinement of small storm detection and significantly enhance existing DCS databases, particularly in mid-latitude regions.

In parallel, the project aims to expand the climatological database of DCS across Africa and the Atlantic Ocean for the period 1981–2023, using the extensive METEOSAT series. Started during the Use Cases EWC phase project. Additionally, the integration of METEOSAT-IODC data will facilitate the creation of a unique, long-term DCS database for the Indian Ocean region, covering the period from 1998 to the present.

2) A 1981-2023 Deep Convective System database from METEOSAT Long-Term Observation over Tropical Africa and Atlantic Ocean

This work represents a continuation of the efforts initiated during the beta-testing phase of the use cases.

To build a homogenized Deep Convective System (DCS) database over an extended period, a consistent and calibrated infrared (IR) dataset is essential. This effort leverages data from the first- and second-generation METEOSAT satellites, which share a broad thermal infrared channel. Despite this commonality, variations in spectral response functions, spatial resolutions, and temporal resolutions over the decades necessitate recalibration and homogenization for effective climate monitoring (Fiolleau et al., 2020). The Meteosat Visible Infra-Red Imager (MVIRI) and Spinning Enhanced Visible and Infrared Imager (SEVIRI) data have been systematically recalibrated following the approach outlined by John et al. (2019). Radiances from all instruments have been harmonized to match those of METEOSAT-5, ensuring consistency across the dataset. Quality control measures, as detailed by Liefhebber et al. (2020), have been applied to identify and flag corrupted images, enhancing data reliability. To maintain uniformity between the Meteosat First Generation (MFG) and Meteosat Second Generation (MSG) eras, the imagery has been re-gridded to a 0.04° regular grid. Additionally, brightness temperatures have been corrected for limb effects using the methodology described by Fiolleau et al. (2020).

In summary, the long-term METEOSAT observations have then been carefully homogenized over the length of the record, making them compliant with climate monitoring standards.

Deep Cloud Systems are identified using the Tracking Of Organized Convection Algorithm through a 3D segmentatioN (TOOCAN) algorithm (Fiolleau and Roca 2013). TOOCAN is designed to

overcome one major limitation of the traditional overlap-based tracking technique by analyzing the 3D (2D+time) imagery. It is based on a conceptual model of a convective system, where the cloud deck is composed of a convective and stratiform part clouds evolving in the space-time domain. To identify such a 3D cloud cluster, the TOOCAN algorithm analyzes a time sequence of IR images using a 3D region growing technique to segment the high cold cloud shield (BT $\leq$ 235 K) into individual DCSs in the spatio-temporal domain. This process begins by detecting convective seeds, defined by a brightness temperature threshold of 190 K. Seeds must meet criteria of a minimum lifetime of three frames (1.5 hours) and an area exceeding 625 km² per frame. Detected seeds are iteratively expanded in the spatio-temporal domain until reaching intermediate cold cloud shield boundaries defined by a 2 K warmer BT threshold. A second detection is performed at 192 K to capture convective seeds too warm to meet the initial 190 K threshold. All the detected seeds are then grown until reaching boundaries at 194 K. This detection and dilation procedure is repeated in 2 K increments, progressively incorporating warmer pixels, until all pixels with BT $\leq$ 235 K are assigned to a DCS. This iterative method ensures accurate segmentation of DCSs by systematically associating each pixel with its corresponding cluster in both space and time.

The TOOCAN algorithm has been applied on the homogenized long-term IR dataset of METEOSAT to produce a 1981-2023 DCS dataset. From one side, the dataset documents the integrated morphological parameters of each identified DCS (lifetime duration, maximum cloud surface, minimum brightness temperature…). On the other side, the morphological properties of each convective system are described every 30 minutes along their life cycles (evolution of the cloud surface ….). To analyze the general characteristics and behavior of tropical Deep Convective Systems (DCSs), it is crucial to exclude cloud systems influenced by tropical cyclones. For this purpose, the International Best Track Archive for Climate Stewardship (IBTrACS) version 4 dataset (Knapp et al., 2011) is used to flag DCSs associated with cyclonic circulations or classified as tropical cyclones. This flagging allows for selective inclusion or exclusion of these systems in the analysis, depending on the study objectives. Given the large volume of data, a data reduction step is implemented by projecting the raw DCS data onto a regular 1°×1°-1day grid. This grid preserves all relevant information about the systems while significantly reducing data complexity (see Methods section of Roca and Fiolleau 2020 for details). The reduced dataset, known as CACATOES, enables the computation of statistical metrics and facilitates a Eulerian analysis of DCSs. The CACATOES dataset is particularly useful for comparing DCS characteristics with auxiliary datasets, as it aligns all data on the same daily 1°×1° grid.

The four-decade-long DCS dataset has enabled a comprehensive analysis of convective organization, recently published in *Surveys in Geophysics* (Roca et al., 2024). This study reveals that while cold cloudiness has remained relatively stable with no significant trends over the past 30 years (Figure 1b), notable changes have occurred in the morphology of deep convective systems (DCSs).

Specifically, the analysis highlights a significant shift in the distribution of DCS characteristics. There has been a marked decrease in the frequency of large, short-lived systems, accompanied by an increase in the occurrence of smaller, longer-lived systems (Figure 1c). These findings underscore an evolving pattern in convective behavior, with implications for understanding long-term atmospheric dynamics and climate variability.

All datasets are publicly available and can be accessed via the following data repositories:

TOOCAN Database: https://user.eumetsat.int/catalogue/EO:EUM:DAT:0986

CACATOES Database: https://user.eumetsat.int/catalogue/EO:EUM:DAT:0987

These resources provide the necessary data for analyzing Deep Convective Systems and their characteristics.

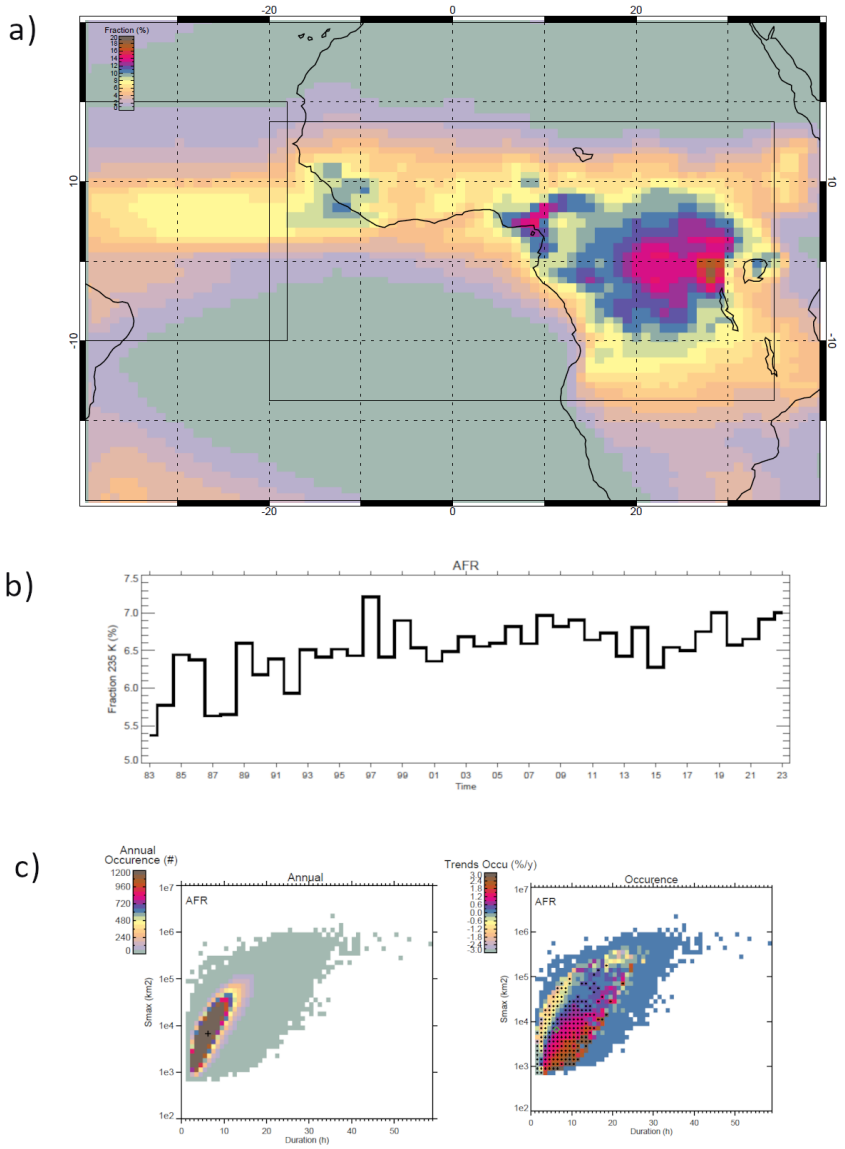


Figure1: a) The map of annual cold cloud fraction (in %) over 1983-2023 shows the active convective areas. b) Time series of the upper level cloudiness over Africa; c) (left) The 1983-2023 climatology of annual occurrence of DCS for Africa. Linear trend in the occurrence over the 1991-2023 period in %/year over Africa (right). Black dots mark the significant trends. (From Roca etal 2024)

3) A 1998-2023 IODC-METEOSAT Long-Term Observations over Indian region

The METEOSAT Indian Ocean Data Coverage (IODC) program is part of the EUMETSAT initiative to provide continuous meteorological observations over the Indian Ocean region. The IODC complements the primary METEOSAT observations over Europe and Africa, extending the observational coverage to include South Asia, the Middle East, and the Indian Ocean since June 1998. Initially, the program relied on the Meteosat First Generation (MFG) satellites, transitioning to the Meteosat Second Generation (MSG) in 2017. Using this harmonized IODC METEOSAT IR dataset, a homogeneous Deep Convective System (DCS) database for the Indian Ocean region has been constructed, spanning the period 1998–2023. The dataset provides a valuable resource for studying DCS behavior and trends in this tropical region. The dataset has been evaluated and figure2b shows the 1°x1° spatial distribution of the cold cloud fraction calculated from January 1999 to December 2023 over the Indian region. The geographical distribution of cold cloud fraction is consistent with previous DCS climatology. The Indian Ocean shows a large and zonally structured region, corresponding to the ITCZ. The convective systems extend to the foot of the Himalayas. Cold cloud fraction from DCS is also more important over the Indonesian region. The time series of upper-level cloudiness over the Indian Ocean from 1999 to 2023 (Figure 2a) shows relative stability with minor

interannual variability. The evolution of cold cloud fraction along time aligns closely with the time series of precipitation derived from the IMERG V07B product, which has been remapped onto a 1° × 1-day gridbox (Roca et al., 2020). This agreement underscores the coherence between cloudiness and precipitation patterns over the region.

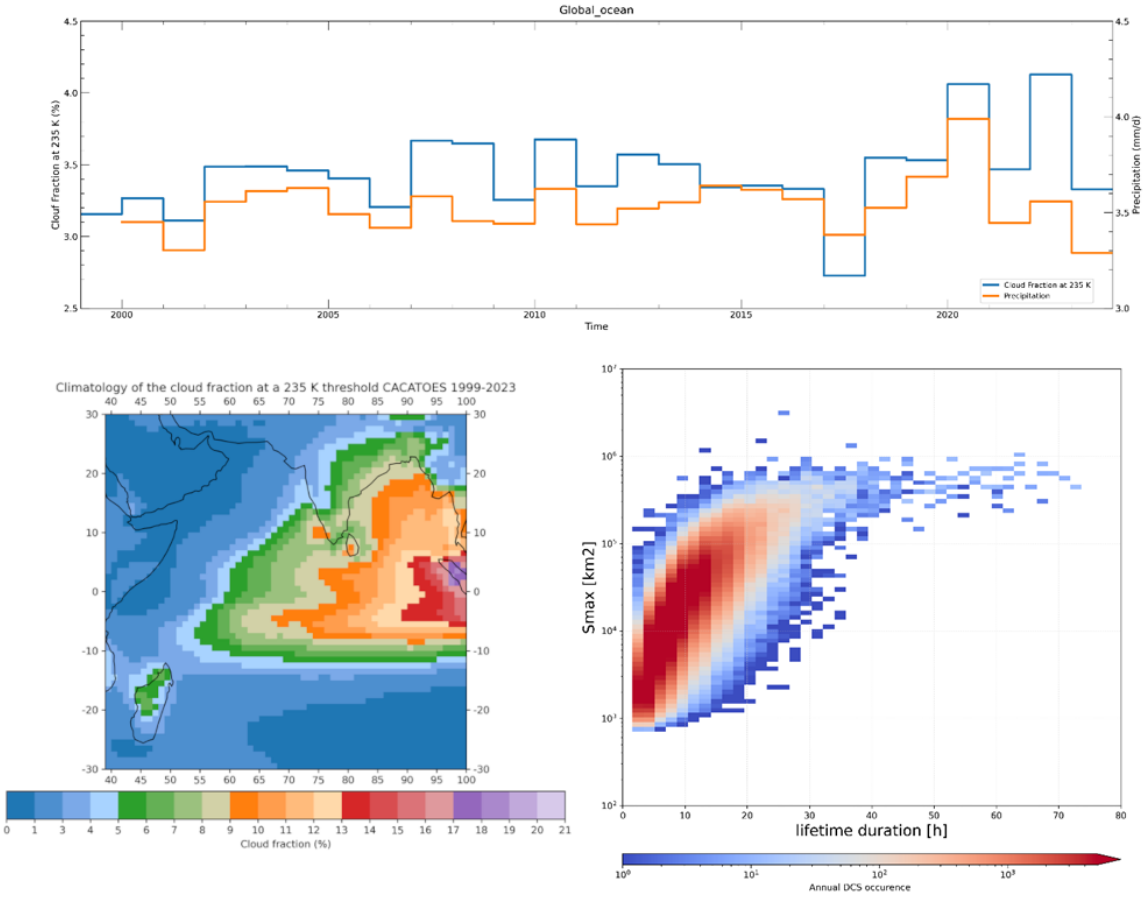


Figure2: a) Time series of the upper level cloudiness over Indian global ocean and of the precipitation from IMERG V07B gridded into a 1°x1°-1day gridbox (Roca etal 2020) b) The map of annual cold cloud fraction (in %) over 1999-2023 shows the active convective areas. c) (left) The 1999-2023 climatology of annual occurrence of DCS for Indian global ocean.

4) Development of advanced tools for monitoring and tracking Convective Systems Over Europe

We have started developing tools for tracking convective systems over Europe, with the ultimate goal of building a long-term climatology of deep convective system life cycles in the region.

To achieve this, we initially relied on infrared observations from the 10.5 µm channel of the new Meteosat Third Generation (MTG) Flexible Combined Imager (FCI) Level 1c High-Resolution Image (HRFI) data, which provides rectified full-disc images with high spatial (1 km) and temporal (10 minutes) resolution. The TOOCAN algorithm has been applied to the MTG-FCI 10.5 µm infrared observations at their full spatial and temporal resolution for the period of August 1 to September 30, 2024, as well as from October 29 to October 31, 2024 to focus on convective system "Dana" responsible for the flash floods in the Valencia region on October 29, 2024.

Prior to that, the TOOCAN algorithm, initially designed for DCS in tropical regions, has been adapted to better suit mid-latitude conditions:

- The first detection threshold for brightness temperatures has been adjusted from 190 K to 210 K to align with the typically lower tropopause altitude in mid-latitudes.
- The detection threshold for upper cold cloudiness remains unchanged at 235 K.

- The criteria for identifying convective "seeds" have been modified: the required area has been reduced from 625 km² per frame to 200 km², while the minimum lifetime criterion remains three frames (1.5 hours).

These adjustments ensure that the algorithm is more representative of mid-latitude convective characteristics, enabling more accurate tracking and analysis of convective systems in this region.
In the tropics, temperatures below 235 K typically indicate deep convection accompanied by stratiform anvil clouds. In contrast, mid-latitude systems detected using such brightness temperature thresholds on infrared (IR) observations may include a variety of cloud types with less vertical development but equally cold cloud tops due to their altitude. However, these clouds are not exclusively associated with convective systems. For example, the upper layers of frontal systems can reach high altitudes, resulting in cloud-top temperatures below 235 K even in the absence of strong convection. Similarly, the jet stream often facilitates the formation of cirrus clouds at high altitudes, which can also be detected with a 235 K threshold. The Lightning Imager (LI) instrument onboard Meteosat Third Generation (MTG) satellites offers the ability to detect the optical signals of total lightning activity, providing a valuable tool to differentiate convective clouds from other types of high-altitude clouds. Moreover, the LI data helps identify the more actively convective cores within convective systems in mid-latitude regions.
We have implemented a collocation procedure between observations from the LI Level 2 Accumulated Flashes (AF) product and the cloud systems identified by the TOOCAN algorithm from the IR imagery of MTG. This procedure serves two primary purposes: first, to distinguish convective systems from other types of clouds, and second, to characterize convective activity within the identified convective systems. This approach then improves the ability to analyze and monitor convective systems across Europe.
Out of a total of 20123 cloud systems identified by TOOCAN, only 42.4% are associated with lightning and can therefore be classified as convective systems.

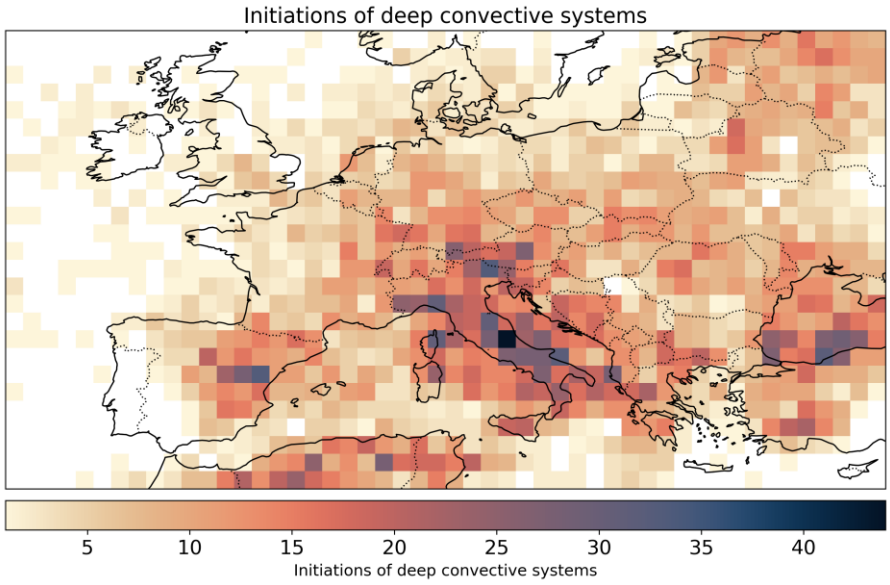


Figure 3: Map of convective system Initiation occurrences in a 1°x1° grid over Europe and the Mediterranean region for August–September 2024.

Figure 3 shows the map of convective initiation occurrences over Europe and the Mediterranean region for August-September 2024 period. It shows that convective system are observed mainly over Southern Europe, including regions like Italy, Spain, Greece, and the Balkans and over North Africa.

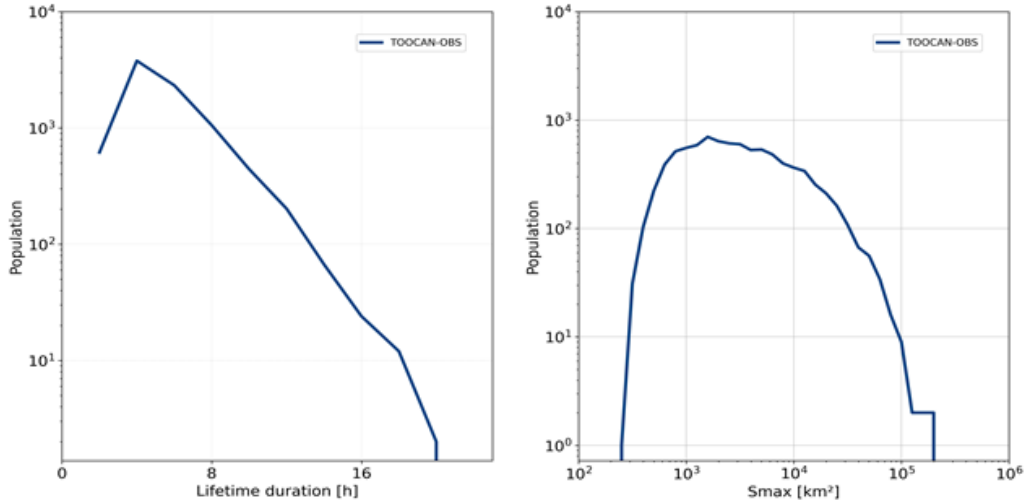


Figure 4: a) Distribution of convective systems lifetime duration; b) Distribution of Maximum surface reached by convective systems over a 15°W:35°E; 30°N:60°N region and for August-September 2024

Distribution of lifetime duration (figure 4) shows that convective systems are maximum for a 5h duration and they do not last more than 20h for a maximum spatial extent of 245000km².
Figure 6 shows a time series of the TOOCAN segmented images from the MTG IR data between 29 October 2024 at 10h00 UTC and 19 October 2024 20h30 UTC over Valencia region. The high cold cloud shield defined by a 235 K threshold on the infrared imagery is decomposed into several deep convective systems whose anvil clouds touch each other. The deep convective system called "Dana" and highlighted in red, which was responsible for the flash flooding event over Valencia, is shown during its growth phase. The system starts at 11h40 UTC and dissipates at 04h00, lasting then 16h20. The System is described by a symmetric evolution of its cold cloud surface. It grows during 8h up to reaching ~80000km², before decaying. A maximum of ~28000 lightnings has been produced by the system during its whole lifetime duration.

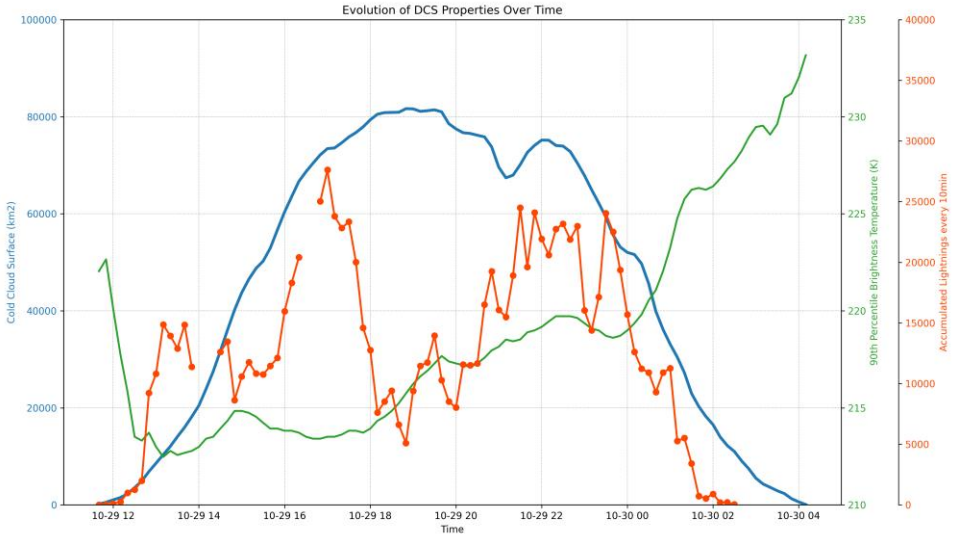


Figure 5: Evolution of the cold cloud surface at 235 K for the convective system "Dana" during its life cycle, responsible for flash flooding in Valencia on 29 October 2024 (blue curve). The red curve represents the evolution of the accumulated lightning flashes produced by the system, while the green curve shows the evolution of the 90th percentile of the brightness temperature within the convective system.

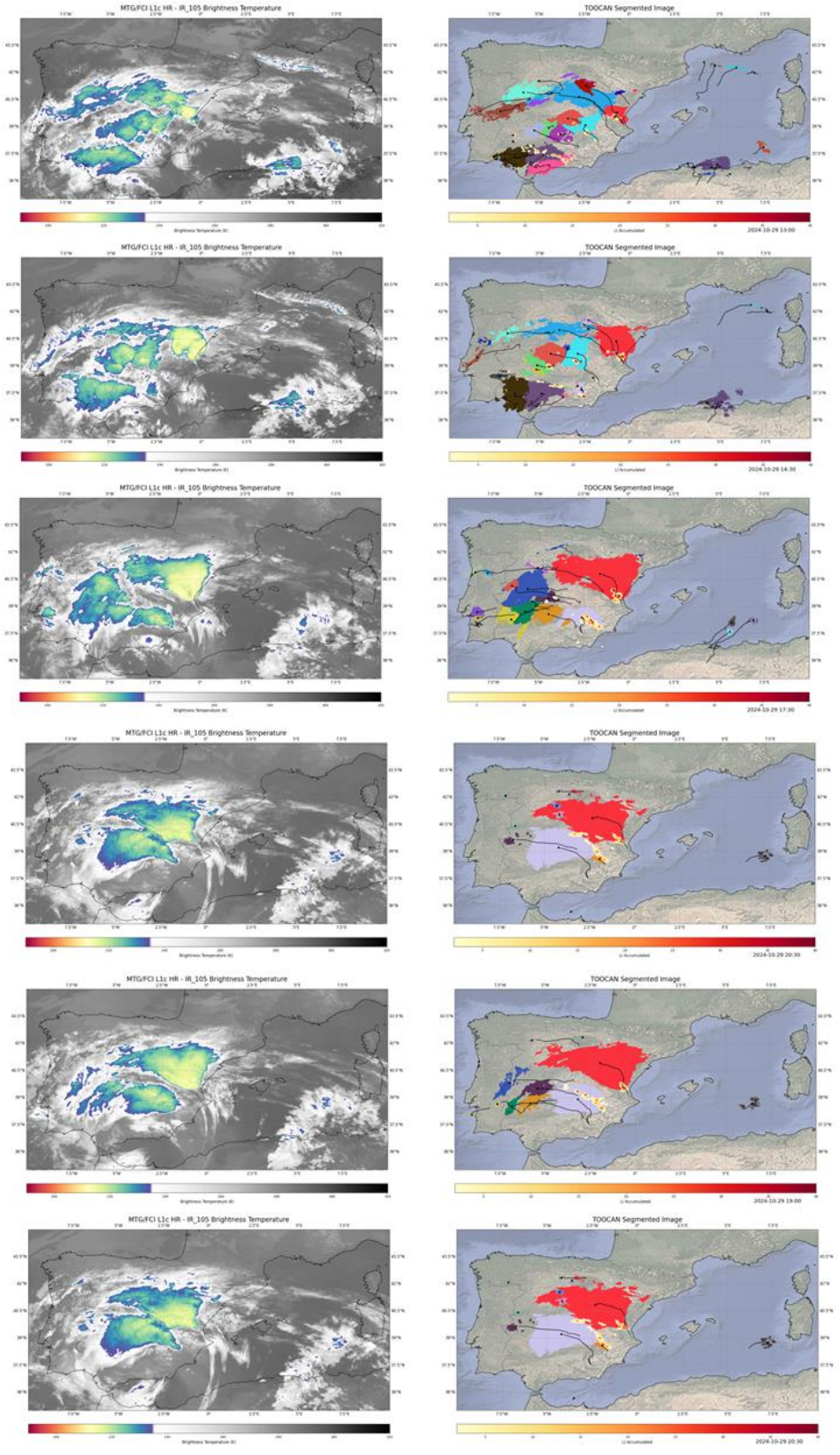


Figure 6: Illustration of the TOOCAN segmentations for a convective situation which occurred in 29, October 2024, over Valencia region. (a) Infrared observation of MTG-FCI from 29 October 2024 at 13:00 UTC to 29 October 2024 at 20:30 UTC; (b) DCS segmented by the TOOCAN algorithm. Each color corresponds to a unique deep convective system. The black lines indicate the trajectories of their centers of mass since initiation. Overlaid on the map, the yellow-to-dark red color scale represents the accumulated lightning occurrences, with darker shades indicating higher lightning density.

- *Fiolleau, T. and Roca, R.: An algorithm for the detection and tracking of tropical mesoscale convective systems using infrared images from geostationary satellite, IEEE Transactions on Geoscience and Remote Sensing, 51, https://doi.org/10.1109/TGRS.2012.2227762, 2013a.*
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- *John, V. O., T. Tabata, F. Rüthrich, R. Roebeling, and T. Hewison, 2019: On the Methods for Recalibrating Geostationary Longwave Channels Using Polar Orbiting Infrared Sounders.*
- *Liefhebber, F., and Coauthors, 2020: Automatic quality control of the Meteosat First Generation measurements. Atmos. Meas. Tech., **13**, 1167–1179, 626 https://doi.org/10.5194/amt-13-1167-2020.*
- *Roca, R., Alexander, L. V., Potter, G., Bador, M., Jucá, R., Contractor, S., Bosilovich, M. G., and Cloché, S.: FROGS: a daily 1° × 1° gridded precipitation database of rain gauge, satellite and reanalysis products, Earth Syst. Sci. Data, 11, 1017-1035, https://doi.org/10.5194/essd-11-1017-2019, **2019**. PDF*
- *Roca, R., Fiolleau, T., John, V.O. et al. METEOSAT Long-Term Observations Reveal Changes in Convective Organization Over Tropical Africa and Atlantic Ocean. Surv Geophys (2024). https://doi.org/10.1007/s10712-024-09862-8*