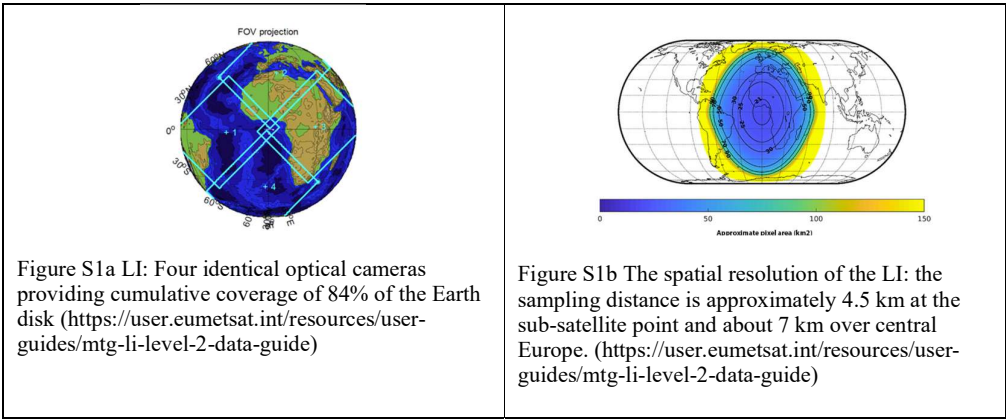


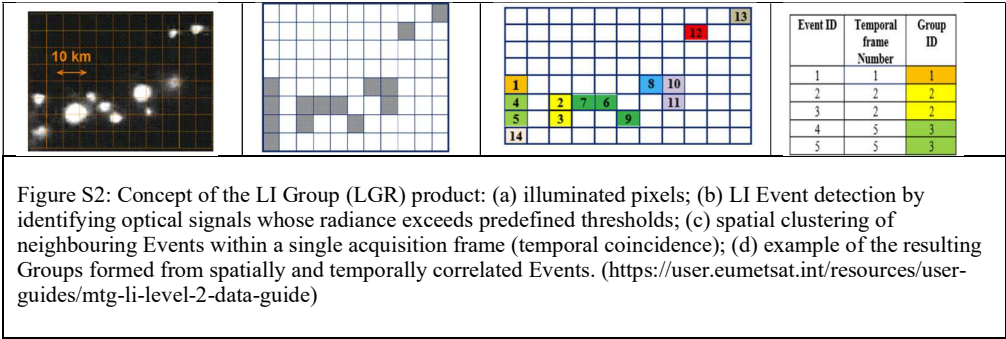
Supporting information LI

Section 2.2 Supporting Information

The LI is an imaging filter spectrometer comprising four identical optical cameras, each with a real-time pixel processor for on-board processing. The instrument detects lightning-related optical transients associated with total lightning activity and converts them into higher-level lightning products suitable for a wide range of applications. The LI field of view covers approximately 84% of the Earth's disk as seen from the geostationary position at 0° longitude (Figure S1). The spatial sampling at the sub-satellite point is 4.5 km, and the temporal sampling (integration time) is 1 ms. Figure S2 also illustrates how the spatial sampling increases with distance from the sub-satellite point; over central Europe, the effective spatial resolution is approximately 7 km.

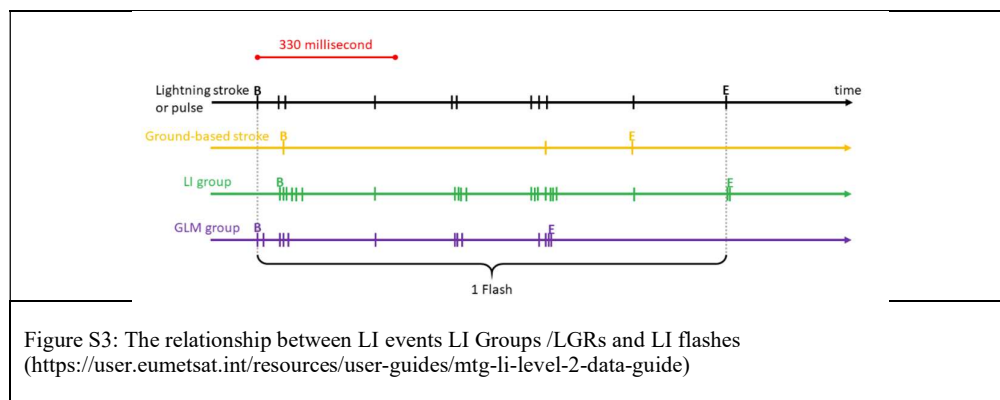


The LI primarily detects luminosity that escapes from clouds after scattering and absorption by cloud particles. Accordingly, the LI senses total lightning, including cloud-to-cloud CC, IC, and CG activity. It is therefore important to specify which LI data product is used in this paper and how it relates to the raw optical transients captured by the LI cameras. Here, we use the high-level product called the LI Group (LGR). Figure S2 illustrates how LGRs relate to lower-level measurements corresponding to optical transients that exceed a pixel-level detection threshold. Signals exceeding the detection threshold are identified as candidate lightning events (i.e., detected transients). A Group is a collection of spatially connected LI Events observed within a single acquisition frame. Figure S2c shows the detected Events, while Figure S2d illustrates which Events occurred within the same acquisition frame; Events that are also spatially correlated are shown in the same color, indicating that they belong to the same LGR. The LGR position is defined as the radiance-weighted centroid of the Event positions within the Group.



Furthermore, LI LGRs can be further temporally accumulated to produce a higher-level product, the LI Flash. The LI flash definition follows the same concept as that used by the GLM: a flash is a collection of Groups that are

correlated in space and time within windows of 330 ms (temporal) and 16.5 km (spatial), respectively. Although the LI Flash product is not used in this paper, it is useful for understanding how LI LGRs relate to GLM Groups and to ground-based LLS stroke detections and to overall lightning flash event, as illustrated in Figure S3.



For selected measured current waveforms, event-level analyses in this paper rely on three LI-group visualizations. A longitude-latitude map centered on the instrumented WT plots all LI groups at their geodetic coordinates; concentric circles with radii of 5, 10, 20, 30 and 40 km are drawn around the WT to indicate distance, and LI groups are colored according to whether they occurred before (shades of blue) or during/after (shades of red) the onset of the measured current, to emphasize preceding activity.

A time-distance plot of LI LGRs is also used, following the approach of van der Velde and Montanyà (2013) and Montanyà et al. (2024): each LI group is shown as a function of its occurrence time relative to the current onset at the instrumented WT (0 s reference) and its horizontal distance from the WT (0 km reference). Linear patterns in these time-distance plots may indicate positive or negative leader development, with the slope representing the apparent horizontal propagation speed. Dashed reference lines corresponding to typical negative and positive leader propagation speeds, as reported in the cited literature, are included in the relevant figures (e.g., Figure 16 in the main text) to aid interpretation.

Finally, an integrated optical radiance profile is calculated by summing the radiance of all LI groups within each 1 ms exposure frame (van der Velde et al., 2020). This profile is compared with the measured current and, when available, high-speed video observations, and is also used to identify continuous luminosity commonly associated with ICCs and CCs (e.g., Montanyà et al., 2014).

References cited in this section not already listed in the main manuscript reference list:

- Montanyà, J., et al., 2024. Upward flashes to wind turbines during winter observed from space by ISS-LIS and GLM. In: Proceedings of the 37th International Conference on Lightning Protection (ICLP 2024), Dresden, Germany, 1-7 Sept. 2024, pp. 1026-1031.
- van der Velde, O.A., Montanyà, J., 2013. Asymmetries in bidirectional leader development of lightning flashes. *J. Geophys. Res. Atmos.* 118. <https://doi.org/10.1002/2013JD020257>

Section 3.4 Supporting Information

Figure S4 shows, for each lightning flash case, the flash duration and the number of LGRs detected in the preceding window (first row of subfigures) and in the during-the-flash window (second row of subfigures). Each column corresponds to one split: positive vs. negative, ICC only positive vs. ICC only negative, and ICC only vs. non-ICC only flashes. The figure also enables inspection of flash-duration tendencies for the different categories. In particular, negative flashes (green) generally last longer than positive flashes (orange), which is consistent with the mean durations reported in Table 1 (table is located in the main manuscript).

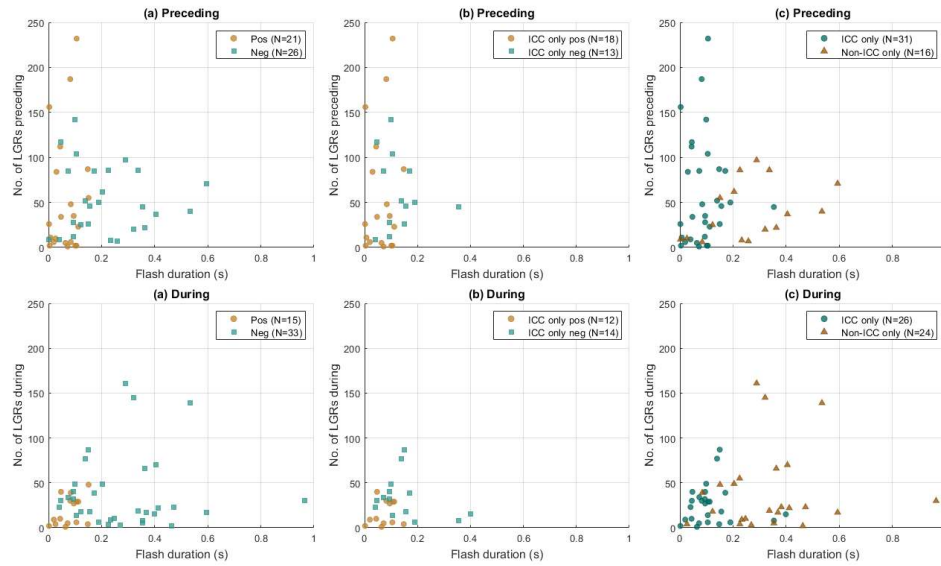


Figure S4 Flash duration versus number of LI LGRs in preceding and during-flash windows: positive vs. negative and ICC only positive vs. ICC only negative flashes.

Section 3.5 Supporting Information

Figure S5 shows, for each lightning flash case, the flash duration and associated median radiance of LGRs detected in the preceding window (first row of subfigures) and in the during-the-flash window (second row of subfigures). Each column corresponds to one split: positive vs. negative, ICC only positive vs. ICC only negative, and ICC only vs. non-ICC only flashes. Median radiances are used throughout the analysis because the LI radiance distributions are highly skewed and occasionally contain very high-radiance cases. Therefore, the median provides a more robust and representative measure of the typical radiance than the mean.

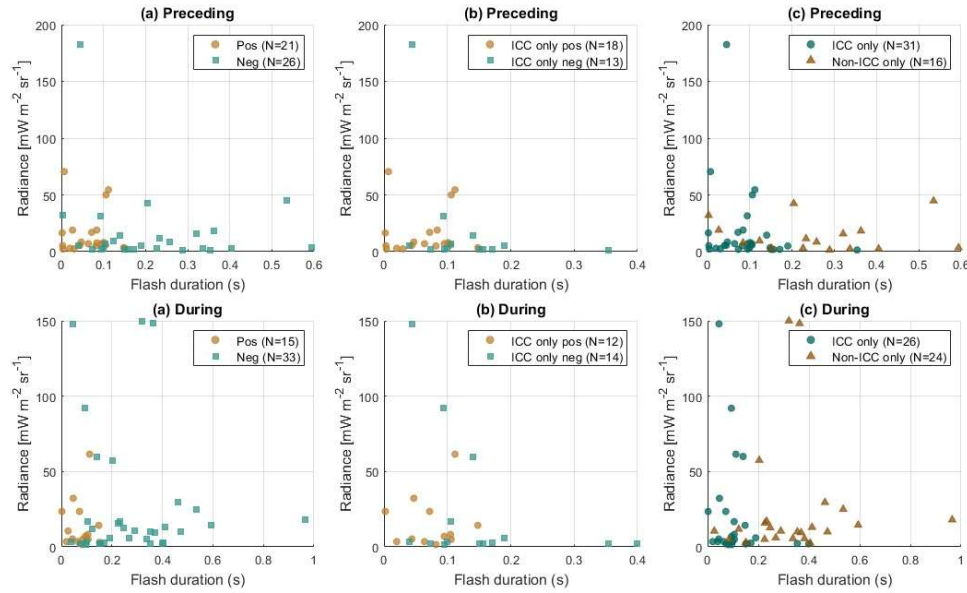


Figure S5 Flash duration versus median radiance of LI LGRs in preceding and during-flash windows: positive vs. negative and ICC only positive vs. ICC only negative flashes.

Section 3.6 Supporting Information

Figure S6 shows, for each flash detected in the preceding window, the earliest LI-detected LGRs plotted as detection time (Δt before onset) versus distance from the wind turbine. In Figure S6a, cases are colored by radiance, while Figures S6b–d show the same scatter using categorical coloring for (b) ICC only vs. non-ICC only, (c) positive vs. negative, and (d) ICC only positive vs. ICC only negative flashes.

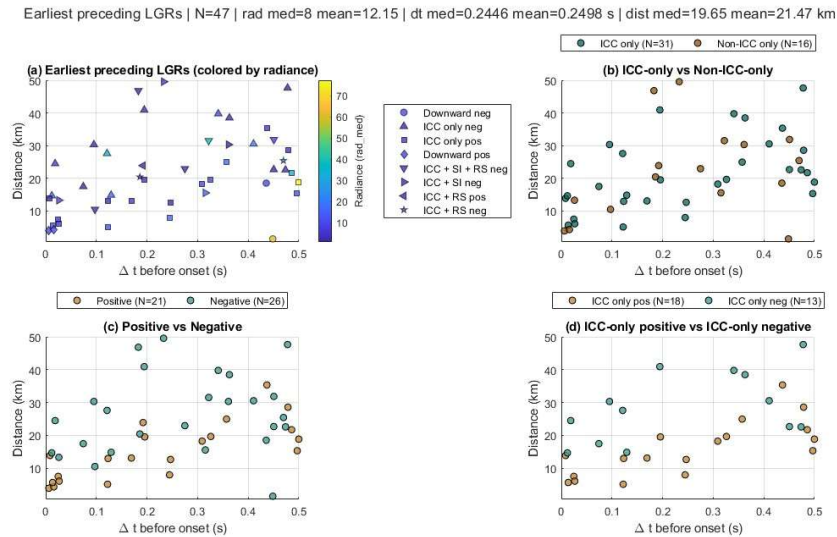


Figure S6 Earliest LI-detected LGRs in the preceding window: detection time versus distance from the wind turbine for positive vs. negative, ICC only positive vs. ICC only negative, and ICC only vs. non-ICC only flashes.

Figure S7, for each flash detected in the preceding window, the closest LI-detected LGRs plotted as detection time (Δt before onset) versus distance from the wind turbine. In Figure S7a, cases are colored by radiance, while Figures S7b–d show the same scatter using categorical coloring for (b) ICC only vs. non-ICC only, (c) positive vs. negative, and (d) ICC only positive vs. ICC only negative flashes.

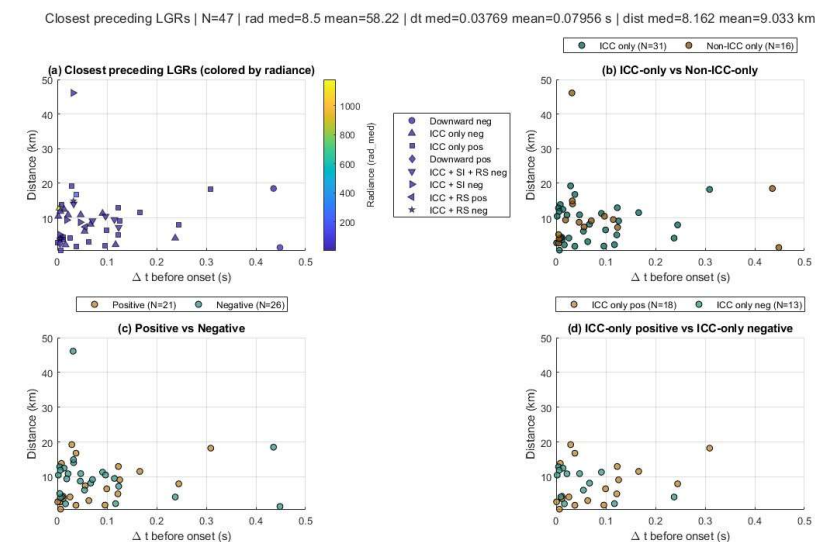


Figure S7 Closest LI-detected LGRs in the preceding window: detection time versus distance from the wind turbine for positive vs. negative, ICC only positive vs. ICC only negative, and ICC only vs. non-ICC only flashes.

Section 3.7 Supporting Information

Figure S8 shows the day/night dependence of preceding-window LI activity restricted to ICC-only flashes, comparing ICC-only positive and ICC-only negative flashes. Panels (a) and (b) show the number of LGRs detected in the preceding window as a function of flash duration for daytime and nighttime events, respectively, while panels (c) and (d) show the corresponding median LGR radiance in the preceding window for daytime and nighttime events.

Figure S9 shows the equivalent day/night comparison for the during-flash window, restricted to ICC-only positive and ICC-only negative flashes. Panels (a) and (b) show the number of LGRs detected during the flash as a function of flash duration for daytime and nighttime events, respectively, while panels (c) and (d) show the corresponding median LGR radiance during the flash for daytime and nighttime events.

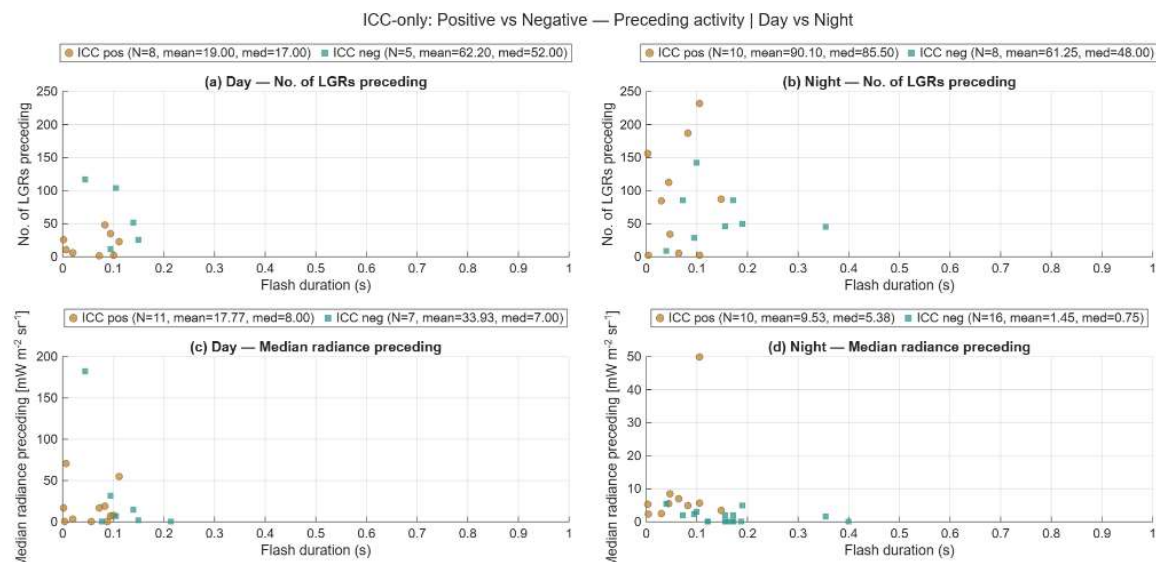


Figure S8 Day/night comparison of preceding-window LI activity for ICC-only positive vs. ICC-only negative flashes: (a) number of LGRs during the day; (b) number of LGRs at night; (c) median radiance during the day; (d) median radiance at night.

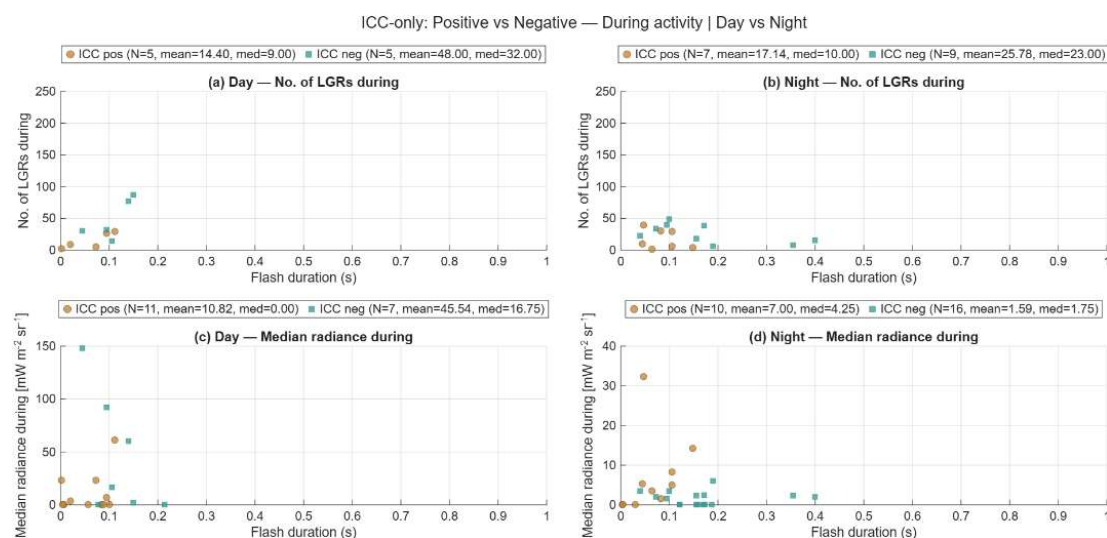


Figure S9 Day/night comparison of during-flash LI activity for ICC-only positive vs. ICC-only negative flashes: (a) number of LGRs during the day; (b) number of LGRs at night; (c) median radiance during the day; (d) median radiance at night.