Introducing a Grand Challenge for Lightning Modeling

Sonja A. Behnke,[a] Eric Bruning,[b] Amanda Back,[c] Steven J. Goodman,[d] Christopher Hogg,[e]
Timothy Lang,[f] Julia Tilles[e]

[a] *Los Alamos National Laboratories, Los Alamos, NM*
[b] *Texas Tech University, Lubbock, TX*
[c] *NOAA Global Systems Laboratory, Boulder, CO*
[d] *Thunderbolt Global Analytics, Huntsville, AL*
[e] *Sandia National Laboratories, Albuquerque, NM*
[f] *NASA Marshall Space Flight Center, Huntsville, AL*

Corresponding author: Sonja A. Behnke, sbehnke@lanl.gov

ABSTRACT: The atmospheric electricity discipline is overflowing with lightning observations across the electromagnetic spectrum – representing physical and chemical processes that span many orders of magnitude in spatial and temporal scales – but is lacking in integrated modeling capabilities to interpret these measurements. This gap limits our ability to synthesize knowledge from different types of lightning measurements and hinders our understanding of lightning in the broader context of thunderstorms, weather, and climate. To overcome this challenge, a framework for a holistic physical model of lightning has been developed to outline the current strengths and weaknesses in modeling capabilities and to envision how a modular end-to-end lightning model could be realized. The name of this proposed model is E2EL: the End-to-End Lightning Model. Application of E2EL to test theoretical predictions about lightning against observations will improve lightning forecasting, climate modeling, and our understanding of lightning-ignited wildfires, among other benefits for national security and the private sector. Achieving the first iteration of an integrated model requires significant investment from community stakeholders alongside careful coordination and copious effort among the lightning community, which we propose can be accomplished in a 5-year plan. This newly developed framework illuminates what was once unclear: that the task at hand is indeed within our scientific reach.

1. Introduction

A new effort is underway to develop an end-to-end model of a lightning discharge (named E2EL), starting from the inception of a cloud and ending with the observable electromagnetic signals produced by the discharge. This effort is organized and championed by a group of scientists representing academia, NOAA, NASA, and DOE National Laboratories who seek to catalyze collaborative effort and action within the atmospheric electricity community to realize such a model. The new model would be immediately impactful to a broad range of users spanning academia, government, and industry. We envision users will apply the model to gain new insight into lightning measurements, to plan new instrumentation or observing campaigns, to make predictions for lightning forecasting, to improve climate modeling, to improve our understanding of feedback processes between lightning and climate variables, and to study lightning-ignited wildfires. In addition to these practical use cases, the quantitative model outputs will enable rigorous testing of the fundamental theories of the lightning discharge across a large sample of data.

The creation of E2EL supports the missions of many U.S. federal research organizations, including NSF, NASA, NOAA, and DOE. An end-to-end physical model of lightning would be used to test theories founded on the numerous lightning observations funded by these agencies. A physics-based simulator of lightning will be used by NASA and NOAA to support the design of next-generation lightning sensors. For example, NASA Marshall Space Flight Center is developing an Observing System Simulation Experiment (OSSE) to demonstrate capabilities for a new space-based lightning mapping concept (Remington et al. 2024). The OSSE simulates lightning and the sensor responses (Gatlin et al. 2025) much as we envision E2EL will at higher fidelity. In addition, lightning predictions will have a direct impact on NOAA's operational weather forecasting models and can provide improved understanding of lightning's role in climate. In particular, the lightning parameterizations in global climate models are empirically based (Price and Rind 1992; Magi 2015; Verjans and Franzke 2025), and therefore lack physical explanatory power. E2EL could be used to develop physically based parameterizations that allow global models to link directly to fundamental lightning processes, which is important for quantifying lightning-produced nitrogen oxides. Lastly, a comprehensive model of lightning would support the national security missions of DOE, who develop sensors for space-based Earth-observing missions that contribute to increasing our understanding of lightning across the globe.

The effort behind the model originated with a workshop held in April 2024, funded and motivated by Sandia National Laboratories. About 60 meteorology and lightning scientists gathered both in person in Albuquerque, NM and online. They pooled their knowledge on the current state of the art of lightning modeling, from cloud electrification to signal detection. This workshop led to the creation of the Grand Challenge Roadmap (Bruning et al. 2024), a living document that describes the motivations, development plans, and model components, highlighting the state-of-the-art as well as the gaps and uncertainties in modeling capabilities. The initial workshop revealed that extensive modeling capabilities already exist that could be interconnected into one larger model. In 2025 a second workshop, funded by NSF, brought together about 60 scientists and students in-person at Texas Tech University in Lubbock and 20 participants online. Priorities for model development were identified and 16 individuals and research groups committed to making tangible advances in our capabilities over the next year. Moving forward, working groups will be established for each of the major model components, where the model design will be developed and model architecture will be refined. Working groups will communicate with each other to ensure compatibility among major components.

2. The End-to-End Lightning (E2EL) Model

There are four major components to E2EL: weather, lightning, signals, and sensors (Figure 1). The weather model will be derived from mature cloud and electrification models and will output the resulting electrical charge structure and electric fields in the cloud. The lightning model takes the outputs from the cloud model, producing the physical structure of a lightning flash and the currents produced by the discharge as a function of time. The signal model produces optical emissions and electric and magnetic fields from these output currents, which in turn are propagated and then received by sensor models and converted to data products commonly used by the community, making the signals readily verifiable against available observations.

Each major modeling component and – to the extent possible – its subcomponents will be designed to be modular with clearly defined data formats at component interfaces, allowing for compatible components to be interchanged and the intermediate outputs from each component to be available to a user. This is key for verification and validation of the model, particularly as it evolves over time and increases in sophistication. This also allows for increased utility from the model based on user needs. For example, there could be multiple models for a component (e.g., lightning channel physics) with varying degrees of sophistication and/or computational demands, which may be preferable depending on the desired granularity of the outputs. Or one may want to substitute an idealized cloud charge structure in place of the sophisticated cloud electrification model to test hypotheses about lightning behavior under idealized conditions. Such flexibility supports both focused and efficient operational modeling and deep inquiry to drive new scientific understanding.

a. The Weather Model

Modeling electrification within a cloud is a mature capability. Existing models include WRF-ELEC (Fierro et al. 2013), COMMAS (Mansell et al. 2010), and Méso-NH (Barthe and Pinty 2007). COMMAS and Méso-NH include stochastic lightning branching schemes, while WRF-ELEC simulates only bulk characteristics of lightning (e.g., flash extent density). None of these models can simulate detailed lightning physics. Currently, WRF-ELEC (https://github.com/MicroTed/wrf4-elec) and Méso-NH (http://mesonh.aero.obs-mip.fr/mesonh51) are open source.

Because these cloud models are mature, they could already be integrated today into an end-to-end model; thus, the priority for future work is model validation to understand boundaries on capabilities and to quantify uncertainties. For example, the electrification parameterizations, derived from laboratory studies of ice-ice collisional charging, play a primary role in controlling the charge structure of the storms, with significant sensitivities (Mansell et al. 2005). Further numerical modeling and rigorous assessment of storm cases and the lightning observables they produce, for a variety of meteorological environments, are needed to guide and test improvements within the current framework (Figure 2).

In contrast, modular links between physics-based lightning initiation/discharge models and cloud models need to be built. The primary variables to exchange between these models are the electric charge, field, and potential, which cloud models can simulate and lightning initiation/discharge models need to drive their explicit physical development. In turn, lightning alters the electrical structure of the cloud by depositing space charge and charging hydrometeors, forming a full feedback loop. The microphysics represented in cloud models also affects the scattering of optical signals from lightning (Brunner and Bitzer 2020) and may be responsible for local enhancements of electric fields that help initiate lightning (Babich et al. 2017).

Building on current cloud modeling infrastructure will most rapidly realize a working model. However, the next generation of weather modeling systems such as the MPAS-based RRFS prototype (Skamarock et al. 2012; Carley et al. 2023), are under active development to serve future needs of operational agencies and researchers. Early incorporation of electrification schemes in these weather models will ease the transition of E2EL to the post-WRF future.

b. The Lightning Model

Development of the lightning model will be the largest effort towards realizing E2EL. Model developers will need to address many unknowns about lightning physics, starting with how to model lightning initiation. It will be necessary to create defined interfaces among sub-modules in order for developers to test and compare various modeling options where there are competing physical theories.

Much of the prior work in lightning modeling has focused on the radiofrequency (RF) signals generated by current flowing in lightning channels and has almost exclusively relied upon transmission-line modeling (Rakov and Uman 1998) that ignores the underlying plasma dynamics, which is crucial to modeling the optical output of lightning. After initial optical modeling studies (Thomason and Krider 1982) in support of the Optical Transient Detector (OTD) and the Tropical Rainfall Measuring Mission (TRMM) in the mid-1990s, there was renewed interest in optical transport modeling as the next generation of optical sensors came online in the 2010s, such as the Geostationary Lightning Mapper (GLM) (Goodman et al. 2013), the Lightning Imaging Sensor on International Space Station (ISS-LIS) (Blakeslee et al. 2020), the Atmosphere-Space Interactions Monitor (ASIM) (Neubert et al. 2019), and the Global Lightning and Sprite Measurements on the Japanese Experiment Module (JEM-GLIMS) (Sato et al. 2014).

The physical mechanisms that comprise lightning (Figure 3) can simplify into plasma discharge processes that are either “hot”, which are modeled using local thermodynamic equilibrium (LTE) plasma dynamics (i.e., leader channels, Figure 3a-b), or “cold”, which are modeled by non-LTE plasma dynamics (i.e., streamers, Figure 3a). The interplay between LTE and non-LTE processes gives rise to complex processes along the leader channel, including current cutoff (Mazur and

Ruhnke 2014), needles (Hare et al. 2019), dart leaders (Jensen et al. 2023), leader stepping (Petersen and Beasley 2013), the leader corona sheath (Heckman and Williams 1989), and initial breakdown pulses (da Silva and Pasko 2015).

Lightning leader channels also produce high-flux, high-fluence gamma-ray bursts, known as terrestrial gamma ray flashes (TGFs) due to relativistic processes (Dwyer 2012), which can be observed from space (Briggs et al. 2013) and at ground level (Abbasi et al. 2024). Thunderstorms also regularly produce gamma ray glows in the absence of lightning (Marisaldi et al. 2024) and thunderstorm ground enhancements (Williams et al. 2022). Relativistic discharges can thus discharge clouds much in the same way that lightning does (Dwyer 2003), and this limits the bulk thunderstorm electric fields that can be reached (Marshall et al. 1995).

Historically lightning modeling has taken a modular approach due to lightning's complex phenomenology. Existing modeling capabilities include streamer and leader growth models with varying levels of plasma physics inclusion (da Silva et al. 2019; Liu and Pasko 2004; Luque et al. 2008), streamer-to-leader transition models (da Silva and Pasko 2015), fractal discharge models that generate large-scale geometries representative of realistic lightning channel morphology (Riousset et al. 2007) and relativistic models within thunderstorms and within proximity to lightning channels (Celestin et al. 2012). In addition, new modeling work addressing lightning initiation has been recently published (Pasko et al. 2025; Shao et al. 2025; Dwyer 2025), demonstrating gains in our understanding of one of the most troublesome aspects of modeling lightning.

While including all these processes in the first model iteration may not be practical, the first iteration of a physics-informed lightning model must be able to realistically output time-resolved electric current on a spatially extended network of branched leader channels. This would be capable of producing realistic RF signals of lightning and include a realistic plasma composition to enable production of realistic optical signals. One approach might be to extend an existing model of single-leader current dynamics to operate on the extensive branched/forked channel morphology of existing fractal models in a realistic thunderstorm electrostatic background with parameterizations for lightning initiation.

This initial iteration of the lightning model would enable model validation studies that would lead to increased sophistication of the model. Using the optical signal outputs derived from the lightning model, the community could start to investigate the approximations that are reasonable for reproducing realistic, spectrally resolved optical signals of lightning, including both LTE and non-LTE processes. Similarly, streamer models could later be added, which would add additional optical and RF outputs for validation. The recent advances in understanding and modeling lightning initiation are exciting new developments that will benefit from the validation testing that E2EL enables. The additional inclusion of relativistic processes will provide more realistic charge composition feedback to the cloud models, and will provide an additional high-energy metric for observational validation of the model as a whole.

c. The Signal Model

Generation and propagation of optical and RF signals are a vital component of the model, because these signals will be used to validate the model against observational data (Figure 4). For both signals, there are either developed models in place and ready for integration into E2EL or established theory and methodologies ready to be implemented in code.

Electromagnetic fields can be calculated directly from the current density on streamer and leader channels (Shao 2016). Incorporating complexities of terrain into RF propagation over line-of-sight distances is commonly achieved with finite difference time domain (FDTD) methods (Li et al. 2019). Long distance propagation of low frequency RF signals can be modeled analytically with waveguide mode theory or computationally with finite element or FDTD methods (Cummer 2000).

For space-based RF detection, theory on propagation of radio waves through a magnetized plasma such as the ionosphere are well established (Budden 2010). One practical implementation of the theory has been realized by Light (2021), which includes the polarization of the magnetized wave. A small level of effort will be required to make the model open source.

Simulation of optical lightning spectra using LTE calculations for the concentrations of chemical species have been described by Pérez-Invernón et al. (2022). Models for optical scattering are mature (Brunner and Bitzer 2020) and exist for the two common wavelengths used by space-based optical sensors: 337 and 777 nm. The largest source of uncertainty for modeling optical scattering is knowledge of the hydrometeor particle distribution with a cloud.

d. The Sensor Model

A broad suite of possible sensor models is possible owing to the do-it-yourself nature of atmospheric electricity instrumentation. The initial version of the model requires a minimum set of sensors representing the most common observational systems that will be used in validation studies. These should include space-based optical sensors, ground-based lightning mapping arrays, short-range electric field change sensors, and long-range electromagnetic lightning detection sensors. Modularity of E2EL will allow users to extract propagated signals for input into their own sensor models.

3. The Path Forward

With the strong support that has been demonstrated in the atmospheric electricity community and the foundational modeling work that already exists, we propose that the first iteration of E2EL can be achieved in the next 5 years. A framework must be established that interfaces the model components and allows access to intermediate model outputs for validation. A top priority is to develop a functional, but limited lightning model that goes beyond extant fractal, quasi-electrostatic models. Signal source and propagation models need to be established from existing theory.

Validation plans need to be developed in parallel with the model, with validation addressed at intermediate stages as well as for the full capability. The next step is to establish requirements for model performance so that future field campaigns could be designed for validation. Historical data sets will also play a key role in validation, and thus centralization of common data types will be needed. Possible performance metrics will include the spatial extent of a flash, flash rates, the ratio of intracloud to cloud-to-ground flashes, and the accuracy of measureable electromagnetic signal outputs. We have begun to solicit validation datasets from the community.

Completion of the E2EL model will require sustained investment and growth of a strong community involved in model development, in conversation with meteorological modeling communities to prevent disciplinary siloing. Atmospheric electricity is an observationally dominant field, and though robust observational capabilities will be a boon to verification and validation of the model, there is a need to grow expertise in computational techniques as a concrete implementation of theories of lightning physics. This represents a fruitful entry point into the field of atmospheric electricity for new Ph.D. students or experienced modelers from other parts of atmospheric science at time when lightning research and its applications are expanding (Ng and Chou 2025).

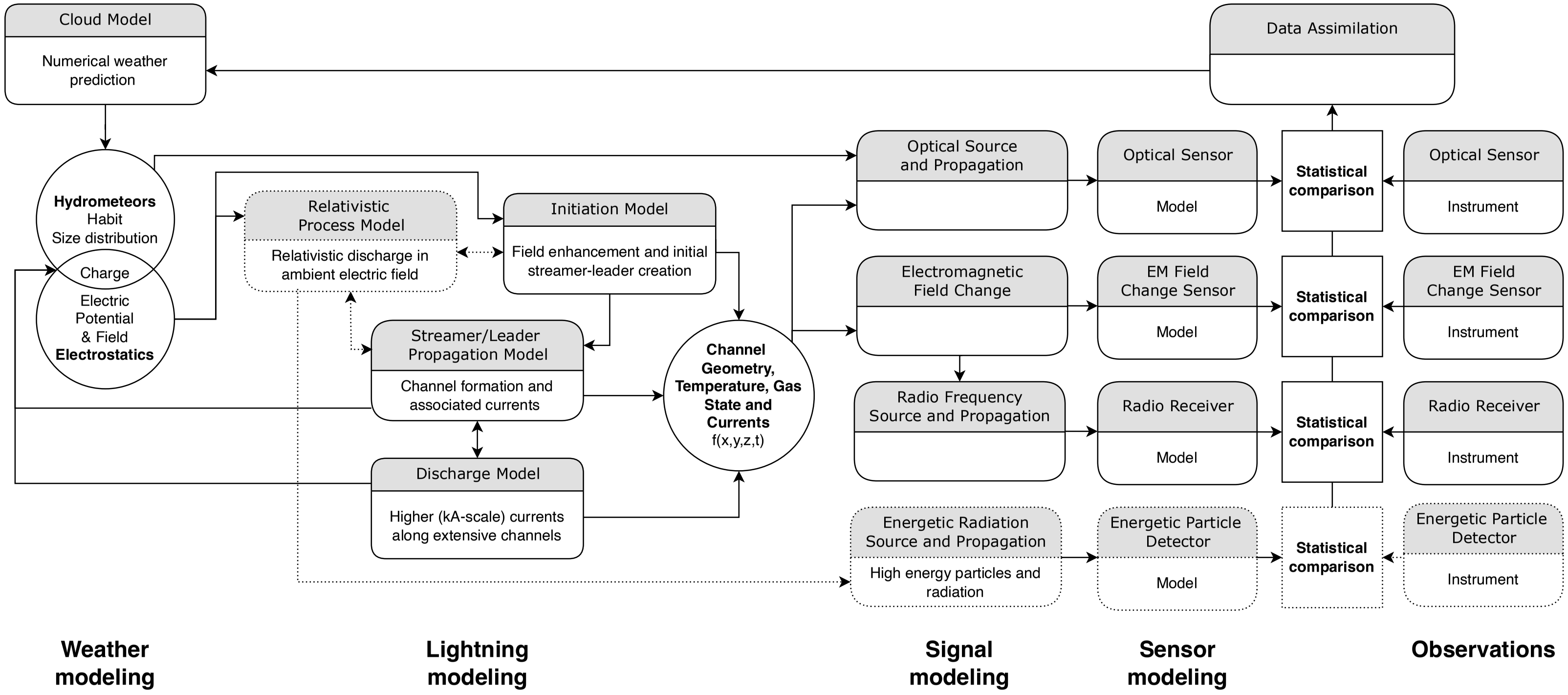

FIG. 1. E2EL components (rounded rectangles) including modular sub-models and observations, outputs for key physical parameters (circles), interconnectivity (arrows), and validation steps (squares). Dotted lines and boxes indicate components and interfaces that are considered optional for the first iteration of E2EL. Unidirectional arrows indicate uncoupled outputs as input to another component, and bidirectional arrows indicate coupled modeling.

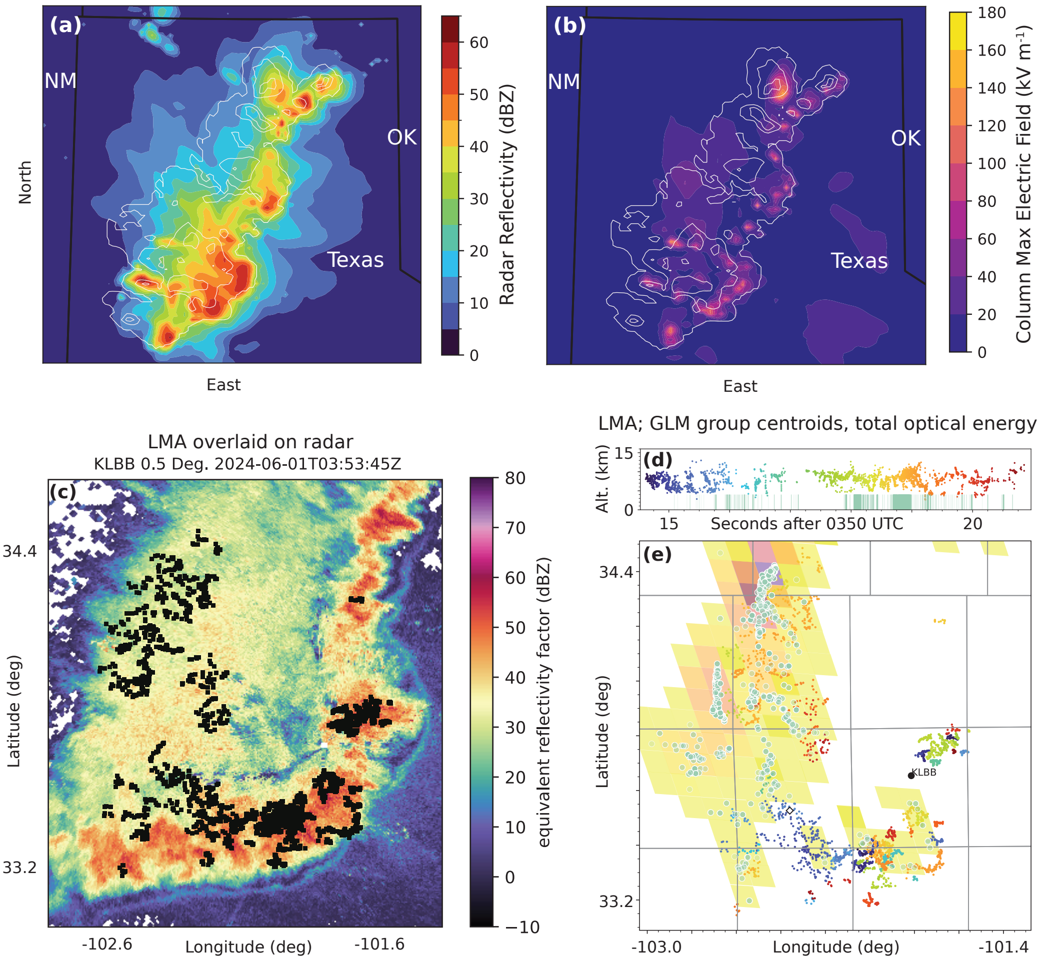

Fig. 2. WRF-ELEC model output (a-b) and observations (c-d) of a mesoscale convective system on 1 June 2024 at 4 UTC. Plan view of WRF-ELEC (a) radar reflectivity and (b) column maximum electric field (shaded) with flash rates of 1, 2, 4 min^{-1} shown as white contours. Observed radar reflectivity from KLBB (c) at 0.5° elevation angle overlaid with lightning mapping sources (black circles). (d) Time-height and (e) plan view of 6 seconds of lightning mapping sources (colored dots) and GLM group centroids (green lines in d, green-white circles in e) along with color-shaded GLM total optical energy (e, yellow (lower optical energy) to purple (higher optical energy)).

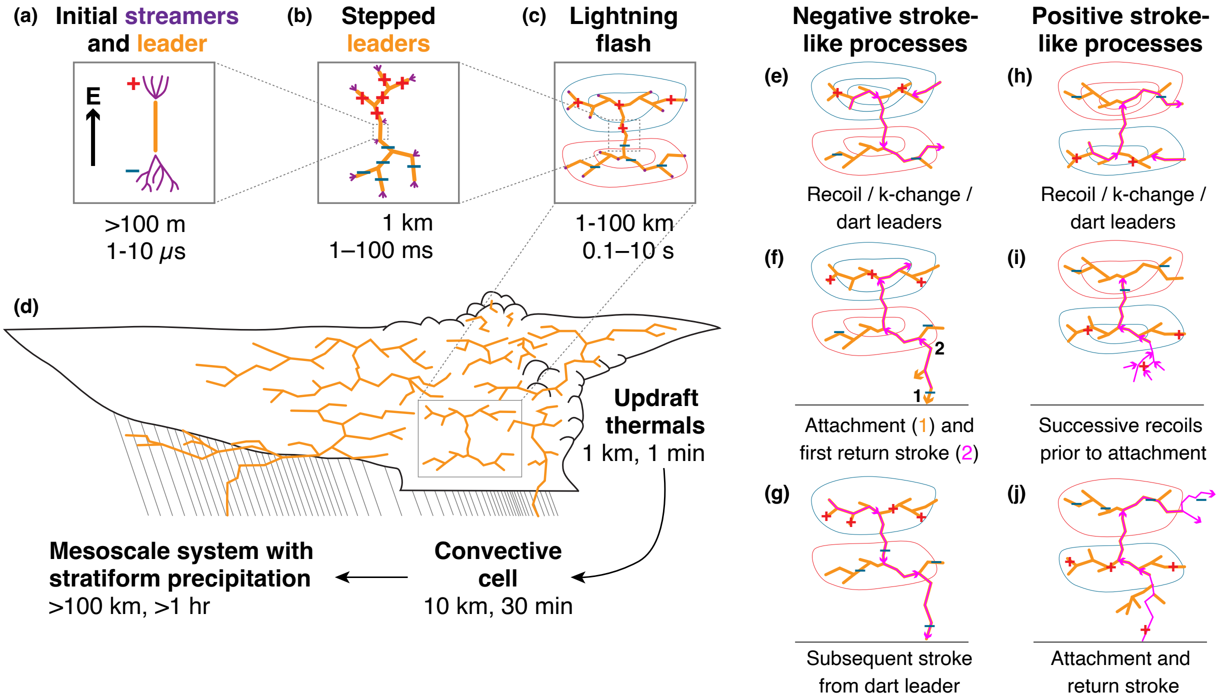

Fig. 3. Time and space scales of key lightning and meteorological phenomena and their relationship to one another. (a) After lightning is initiated in a large initial electric field E, streamers (purple) ionize the air and are heated, becoming leaders (orange) that develop bidirectionally into (b) a fractal discharge tree. The polarity of each channel is indicated as red plus marks for a positively charged channel and blue minus signs for a negatively charged channel. (c) Eventually, the channels branch horizontally into regions of electric potential, and is called a lightning flash. Red and blue contours indicate positive and negative electric potential produced by charge of the same polarity. (d) Storm charge is produced and transported by meteorological processes in updraft thermal bubbles aggregating into convective cells, which sometimes organize as mesoscale systems and produce the largest and longest-lived lightning flashes. Negative (e-g) and positive (h-j) stroke-like processes (e-j, magenta lines, with propagation directions indicated by arrows) occur along the existing discharge tree (orange lines), with impulsive currents lasting about 0.1 ms.

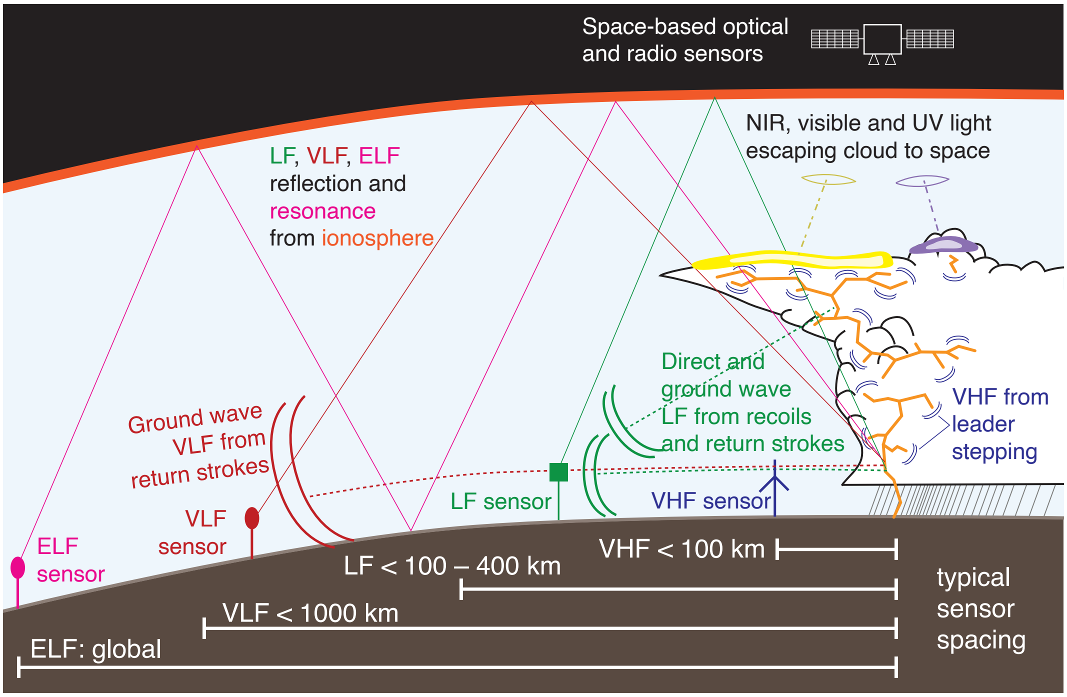

Fig. 4. RF and optical lightning emissions can be measured at various ranges with different techniques. Impulsive very high frequency (VHF; 30-300 MHz) radiation can be detected with VHF lightning mapping sensors, typically at ranges of 100 km or less from the source. VHF emissions will also propagate through the ionosphere and can be detected by space-based RF sensors. Low frequency (LF; 30-300 kHz) and very low frequency (VLF; 3-30 kHz) sensors detect electromagnetic fields from current pulses along lightning channels, like return strokes. At ranges of 100-400 km the direct ground wave is detectable, whereas at longer ranges (1000 km) sensors detect radiation that is reflected off the ionosphere. Extremely low frequency (ELF, 3-30 Hz) sensors detect Schumann resonances within the Earth-ionosphere waveguide. Optical emissions at the near-infrared (NIR), visible, and ultraviolet (UV) wavelengths are detectable by space-borne sensors.

Acknowledgments. E. Bruning was supported by NSF AGS 2513065. T. Lang was supported by the NASA Earth from ISS program. S. Goodman was supported by Sandia National Laboratories PO 2267224. The 2025 workshop in Lubbock, TX was funded by NSF AGS 2513065. The 2024 workshop was funded by Sandia National Laboratories. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC (NTESS), a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA) under contract DE-NA0003525. This written work is authored by an employee of NTESS. The employee, not NTESS, owns the right, title and interest in and to the written work and is responsible for its contents. Any subjective views or opinions that might be expressed in the written work do not necessarily represent the views of the U.S. Government. The publisher acknowledges that the U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this written work or allow others to do so, for U.S. Government purposes. The DOE will provide public access to results of federally sponsored research in accordance with the DOE Public Access Plan. Los Alamos National Laboratory is operated by Triad National Security, LLC, under contract number 89233218CNA000001. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the Department of Commerce.

References

Abbasi, R. U., and Coauthors, 2024: Intermediate Fluence Downward Terrestrial Gamma Ray Flashes as Observed by the Telescope Array Surface Detector. *J. Geophys. Res. Atmos.*, **129 (e2024JD041260)**, https://doi.org/10.1029/2024JD041260.

Babich, L. P., E. I. Bochkov, and T. Neubert, 2017: The role of charged ice hydrometeors in lightning initiation. *J. Atmos. Solar-Terr. Phys.*, **154**, 43–46, https://doi.org/10.1016/j.astp.2016.12.010.

Barthe, C., and J. P. Pinty, 2007: Simulation of a supercellular storm using a three-dimensional mesoscale model with an explicit lightning flash scheme. *J. Geophys. Res.*, **112 (D06210)**, https://doi.org/10.1029/2006JD007484.

Blakeslee, R. J., T. J. Lang, W. J. Koshak, D. Buechler, P. Gatlin, and e. a. Mach, D. M., 2020: Three yearsof the Lightning Imaging Sensor on board the International Space Station: Expanded global coverage andenhanced applications. *J. Geophys. Res. Atmos.*, **125 (e2020JD032918)**, https://doi.org/doi:10.1029/2020JD032918.

Briggs, M. S., and Coauthors, 2013: Terrestrial gamma-ray flashes in the Fermi era: Improved observations and analysis methods. *J. Geophys. Res. Space Physics*, **118**, 3805–3830, https://doi.org/10.1002/jgra/50205.

Bruning, E. C., S. A. Behnke, A. Back, S. Goodman, C. Hogg, T. Lang, and J. Tilles, 2024: A Roadmap for a Lightning Modeling Grand Challenge. Tech. rep., Texas Tech University. https://doi.org/10.5281/zenodo.14624043.

Brunner, K. N., and P. M. Bitzer, 2020: A first look at cloud inhomogeneity and its effect on lightning optical emission. *Geophys. Res. Lett.*, **47 (e2020GL087094)**, https://doi.org/10.1029/2020GL087094.

Budden, K. G., 2010: *The Propagation of Radio Waves: The Theory of Radio Waves of Low Power in the Ionosphere and Magnetosphere*. Cambridge University Press, https://doi.org/10.1017/CBO9780511564321.

Carley, J., C. Alexander, L. Wicker, C. Jablonowski, A. Clark, J. Nelson, I. Jirak, and K. Viner, 2023: Mitigation Efforts to Address Rapid Refresh Forecast System (RRFS) v1 Dynamical Core Performance Issues and Recommendations for RRFS v2. Office note (National Centers for Environmental Prediction (U.S.)); 516, https://doi.org/10.25923/ccgj-7140.

Celestin, S., X. W., and V. P. Pasko, 2012: Terrestrial gamma ray flashes with energies up to 100 MeV produced by nonequilibrium acceleration of electrons in lightning. *J. Geophys. Res.*, **117 (A05315)**, https://doi.org/10.1029/2012JA017535.

Cummer, S. A., 2000: Modeling electromagnetic propagation in the Earth-ionosphere waveguide. *IEEE Transactions on Antennas and Propagation*, **48 (9)**, https://doi.org/10.1109/8.898776.

da Silva, C. L., and V. P. Pasko, 2015: Physical mechanism of initial breakdown pulses and narrow bipolar events in lightning discharges. *J. Geophys. Res. Atmos.*, **120**, 4989–5009, https://doi.org/10.1002/2015JD023209.

da Silva, C. L., R. G. Sonnenfeld, H. E. Edens, P. R. Krehbiel, M. G. Quick, and W. Koshak, 2019: The plasma nature of lightning channels and the resulting nonlinear resistance. *J. Geophys. Res. Atmos.*, **124**, 9442–9463, https://doi.org/10.1029/2019JD030693.

Dwyer, J. R., 2003: A fundamental limit on electric fields in air. *Geophys. Res. Lett.*, **30 (20)**, https://doi.org/10.1029/2003GL017781.

Dwyer, J. R., 2012: The relativistic feedback discharge model of terrestrial gamma ray flashes. *J. Geophys. Res.*, **117**, https://doi.org/10.1029/2011JA017160.

Dwyer, J. R., 2025: Energetic particles produced by thunderstorm electric fields. *J. Geophys. Res. Atmos.*, **130 (e2024JD042193)**, https://doi.org/10.1029/2024JD042193.

Fierro, A. O., E. R. Mansell, D. R. MacGorman, and C. L. Ziegler, 2013: The Implementation of an Explicit Charging and Discharge Lightning Scheme within the WRF-ARW Model: Benchmark Simulations of a Continental Squall Line, a Tropical Cyclone, and a Winter Storm. *Mon. Wea. Rev.*, **141**, 2390–2415, https://doi.org/10.1175/MWR-D-12-00278.1.

Gatlin, P., P. M. Bitzer, J. Burchfield, Y. Wu, and M. Bateman, 2025: Updates on Developing a Satellite-Based Lightning OSSE. URL https://ntrs.nasa.gov/api/citations/20250003427/downloads/Gatlin_LtngOSSE_Apr2025_Ltng_Workshop_final.pdf, 2025 Lightning Modeling Workshop, Texas Tech University, Lubbock, TX.

Goodman, S., and Coauthors, 2013: The GOES-R Geostationary Lightning Mapper (GLM). *Atmospheric Research*, **125-126**, 34–49, https://doi.org/doi:10.1016/j.atmosres.2013.01.006.

Hare, B. M., O. Scholten, J. R. Dwyer, and et al., 2019: Needle-like structures discovered on positively charged lightning branches. *Nature*, **568**, 360–363, https://doi.org/10.1038/s41586-019-1086-6.

Heckman, S., and E. R. Williams, 1989: Corona envelopes and lightning currents. *J. Geophys. Res.*, **94 (D11)**, 13,287–13,294, https://doi.org/doi:10.1029/JD094iD11p13287.

Jensen, D. P., X. M. Shao, and R. G. Sonnenfeld, 2023: Insights into lightning K-leader initiation and development from three dimensional broadband interferometric observations. *J. Geophys. Res. Atmos.*, **128 (e2023JD039104)**, https://doi.org/10.1029/2023JD039104.

Li, D., F. Rachidi, and M. Rubenstein, 2019: FDTD Modeling of Lightning Electromagnetic Field Propagation Over Mountainous Terrain. *2019 International Applied Computational Electromagnetics Society Symposium (ACES)*, Miami, FL, USA, 1-2.

Light, M., 2021: Trans-ionospheric signal polarization. Tech. Rep. LA-UR-21-20674, Los Alamos National Laboratory. https://doi.org/10.2172/1762727.

Liu, N., and V. P. Pasko, 2004: Effects of photoionization on propagation and branching of positive and negative streamers in sprites. *J. Geophys. Res. Space Physics*, **109 (A09311)**, https://doi.org/10.1029/2003JA010064.

Luque, A., V. Ratushnaya, and U. Ebert, 2008: Positive and negative streamers in ambient air: modelling evolution and velocities. *J. Phys. D: Appl. Phys.*, **41 (234005)**, https://doi.org/10.1088/0022-3727/41/23/234005.

Magi, B., 2015: Global lightning parameterization from cmip5 climate model output. *J. Atmos. Oceanic Technol.*, **32**, 434–452, https://doi.org/doi:10.1175/JTECH-D-13-00261.1.

Mansell, E. R., D. R. MacGorman, and C. L. Ziegler, 2005: Charge structure and lightning sensitivity in a simulated multicell thunderstorm. *J. Geophys. Res.*, **110 (D12101)**, https://doi.org/10.1029/2004JD005287.

Mansell, E. R., C. L. Ziegler, and E. C. Bruning, 2010: Simulated Electrification of a Small Thunderstorm with Two-Moment Bulk Microphysics. *J. Atmos. Sci.*, **67**, 171–194, https://doi.org/10.1175/2009JAS2965.1.

Marisaldi, M., and Coauthors, 2024: Highly dynamic gamma-ray emissions are common in tropical thunderclouds. *Nature*, https://doi.org/10.1038/s41586-024-07936-6.

Marshall, T. C., M. McCarthy, and W. Rust, 1995: Electric field magnitudes and lightning initiation in thunderstorms. *J. Geophys. Res.*, **100**, 7097–7103.

Mazur, V., and L. H. Ruhnke, 2014: The physical processes of current cutoff in lightning leaders. *J. Geophys. Res. Atmos.*, **119**, 2796–2810, https://doi.org/10.1002/2013JD020494.

Neubert, T., N. Ostgaard, V. Reglero, and et al., 2019: A terrestrial gamma-ray flash and ionospheric ultraviolet emissions powered by lightning. *Science*, **367**, https://doi.org/doi:10.1126/science.aax3872.

Ng, S.-L., and K.-H. Chou, 2025: Development, Structure, and Trends in Lightning Research: A Comprehensive Bibliometric Analysis. *Bull. Amer. Meteo. Soc.*, https://doi.org/10.1175/BAMS-D-25-0029.1.

Pasko, V. P., S. Celestin, A. Bourdon, R. Janalizadeh, Z. Pervez, J. Jansky, and P. Gourbin, 2025: Photoelectric effect in air explains lightning initiation and terrestrial gamma ray flashes. *J. Geophys. Res. Atmos.*, **130 (e2025JD043897)**, https://doi.org/10.1029/2025JD043897.

Pérez-Invernón, F. J., F. J. Gordillo-Vázquez, M. Passas-Varo, T. Neubert, O. Chanrion, V. Reglero, and N. Østgaard, 2022: Multispectral Optical Diagnostics of Lightning from Space. *Remote Sensing*, **14 (9)**, https://doi.org/10.3390/rs14092057.

Petersen, D. A., and W. H. Beasley, 2013: High-speed video observations of a natural negative stepped leader and subsequent dart-stepped leader. *J. Geophys. Res. Atmos.*, **118**, 12,110–12,119, https://doi.org/10.1002/2013JD019910.

Price, C. G., and D. Rind, 1992: simple lightning parameterization for calculating global lightning distributions. *J. Geophys. Res.*, **97 (D9)**, 9919–9933, https://doi.org/doi:10.1029/92JD00719.

Rakov, V. A., and M. A. Uman, 1998: Review and evaluation of lightning return stroke models including some aspects of their application. *IEEE Transactions on Electromagnetic Compatibility*, **40 (4)**, 403–426, https://doi.org/10.1109/15.736202.

Remington, J. R., P. N. Gatlin, S. M. Stough, N. Pailoor, S. A. Behnke, T. J. Lang, and H. E. Edens, 2024: Simulated feasibility of 3-D lightning mapping from space. *IEEE Transactions on Geoscience and Remote Sensing*, **62**, 1–9, https://doi.org/10.1109/tgrs.2024.3398508.

Riousset, J. A., V. P. Pasko, P. R. Krehbiel, R. J. Thomas, and W. Rison, 2007: Three-dimensional fractal modeling of intracloud lightning discharge in a New Mexico thunderstorm and comparison with lightning mapping observations. *J. Geophys. Res.*, **112 (D15203)**, https://doi.org/10.1029/2006JD007621.

Sato, M., T. Ushio, T. Morimoto, M. Kikuchi, H. Kikuchi, T. Adachi, and et al., 2014: Overview and early results of the Global Lightning and Sprite Measurements mission. *J. Geophys. Res. Atmos.*, **120**, 3822–3851, https://doi.org/doi:10.1002/2014JD022428.

Shao, X. M., 2016: Generalization of the lightning electromagnetic equations of Uman, McLain, and Krider based on Jefimenko equations. *J. Geophys. Res. Atmos.*, **121**, 3363–3371, https://doi.org/10.1002/2015JD024717.

Shao, X. M., D. P. Jensen, C. Ho, M. P. Caffrey, E. Y. Raby, P. S. Graham, W. B. Haynes, and W. G. Blaine, 2025: 3D radio frequency mapping and polarization observations show lightning flashes were ignited by cosmic-ray showers. *J. Geophys. Res. Atmos.*, **130 (e2024JD042549)**, https://doi.org/10.1029/2024JD042549.

Skamarock, J. B., W. C. aand Klemp, M. G. Duda, L. Fowler, S.-H. Park, and T. D. Ringler, 2012: A Multi-scale Nonhydrostatic Atmospheric Model Using Centroidal Voronoi Tesselations and C-Grid Staggering. *Mon. Wea. Rev.*, **240**, 3090–3105, https://doi.org/10.1175/MWR-D-11-00215.1.

Thomason, L. W., and E. P. Krider, 1982: The effects of clouds on the light produced by lightning. *J. Atmos. Sci.*, **29**, 2051–2065, https://doi.org/10.1175/1520-0469(1982)039⟨2051:TEOCOT⟩2.0.CO;2.

Verjans, V., and C. Franzke, 2025: Development of a data-driven lightning scheme for implementation in global climate models. *Journal of Advances in Modeling Earth Systems*, **17 (e2024S004464)**, https://doi.org/doi:10.1029/2024MS004464.

Williams, E. R., H. Mkrtchyan, B. Mailyan, G. Karapetyan, and S. Hovakimyan, 2022: Radar diagnosis of the thundercloud electron accelerator. *J. Geophys. Res. Atmos.*, **127 (e2021JD035957)**, https://doi.org/doi:10.1029/2021JD035957.