A Roadmap for a Lightning Modeling Grand Challenge

v.1.0.0: 28 October 2024

Authors

Eric Bruning (lead), Texas Tech University
Amanda Back, NOAA Global Systems Laboratory
Sonja Behnke, Los Alamos National Laboratory
Steve Goodman, Thunderbolt Global Analytics, formerly NOAA and NASA
Chris Hogg, Sandia National Laboratory
Timothy Lang, NASA Marshall Space Flight Center
Julia Tilles, Sandia National Laboratory

Executive Summary

This document is a roadmap for building an interconnected model of the physical processes that produce a lightning discharge, and its observable optical and radio signals. We call this a Lightning Modeling Grand Challenge, recognizing that significant effort and coordination of human and financial resources is required to realize the capability. The roadmap serves to outline the coordination of resources necessary to enable stitching together existing knowledge and model components to make a lightning prediction, and to test these predictions with observations. Such a capability does not currently exist.

The roadmap is motivated not only by a spirit of scientific inquiry, but by practical challenges faced by US Federal and societal stakeholders. Advancements in lightning observations have outpaced our tests of integrated understanding, leaving many stakeholders unsure how to design their missions to properly detect and discriminate lightning, and unsure how to apply the sometimes-disagreeing lightning signals from diverse instruments. The time is right to connect existing theories and models to support stakeholders in understanding the signals they observe, for needs as diverse as climate monitoring, national security, weather forecasting, public safety, and protection of natural and built environments.

The roadmap's two main technical sections describe the components of a linked physical model, followed by a description of models of lightning signals and sensors that are driven by outputs from the physical model. The goal is to predict the time-varying physical properties of lightning that are self-consistent with the thunderstorm's structure and dynamics. These lightning signals then propagate through the storm, with realistic dispersion and attenuation, to receivers on the ground or in space. At a high level, the model begins with weather (cloud) model output, including explicit prediction of the electrification of cloud particles. The cloud's electrical structure drives a model of lightning physics, from initiation, through channel development, and discharges along those channels. Key lightning parameters, such as the temperature and currents in the channel, and their space and time distribution, are then used to produce optical and electromagnetic signal sources that propagate to modeled receivers. This architecture therefore generates a dataset suitable for comparison to existing and envisioned observing systems. The need for additional measurements and field campaigns to support model development is described.

In each model sub-component, inputs, outputs, uncertainties, evaluation methods, and next steps are summarized, interleaved with references to the scientific literature. Identifying boundaries between the model sub-components aids in segmenting an integrated, complex model into practical work packages and system sub-components, allowing a diverse team to contribute and maintain the system. We estimate that at least five years of effort and a $10M initial investment is necessary to make a significant step forward. Mechanisms to facilitate community coordination, including annual workshops and open-source code repositories, are described.

Table of Contents

1. Overview

Development of a holistic physical model for lightning is a grand challenge that relies on linking meteorological, chemical, plasma, optical, and radio physical process models across vast spatiotemporal scales ranging from molecular (sub-micrometer, sub-picosecond) to mesoscale (100s of kilometers, hours). Such a model would allow for improved lightning forecasting, most probable fire ignition determination, public safety, better climate variability and change assessment, more accurate lightning signal and background characterization, and up-to-date risk assessment for critical ground assets, including the electric grid and structure protection, and national security interests. The modeling system is envisioned to be modular, and to be developed for wide community use by those interested in modeling lightning from the sub-flash to global scales.

1.1 Motivation

In science, the gold standard for a theory is one which makes a specific numerical prediction that can be tested against observations. For lightning, observations now outpace the available theories for modeling the integrated whole of a lightning discharge. We are in need of a numerical test of extant theories to see if they allow us to understand observations, on the scale of full lightning flashes, and for many flashes within a thunderstorm.

The authoring panel of this roadmap represents leaders in a variety of different research sectors in the United States, who came together out of a realization that a common community lightning model could solve shared problems. The National Science Foundation (NSF) has invested in the basic science of lightning through several flagship NSF CAREER awards in lightning-meteorology process coupling and holistic discharge modeling, and many more individual, small team, and field campaign investments in a golden age of lightning instrumentation and basic process understanding, but these efforts have not been brought together into a common framework. Lightning, as an indicator of the state of climate system (Aich et al. 2018), is relevant to the National Aeronautics and Space Administration's (NASA's) Decadal Surveys (National Academies 2017, Cohen et al. 2023), but updated designs for spaceborne monitoring of lightning lack a reference model for physics-based, observing system simulation. The National Oceanic and Atmospheric Administration's (NOAA's) Geostationary Lightning Mapper and next-gen lightning mapper (LMX) programs require the same measurement system characterization. NOAA's operational weather forecast missions to protect life and property through improved storm warnings would benefit from a meteorology-observation process understanding on par with that available for radar and satellite measurements, while NOAA's short-term numerical weather prediction efforts do not have a physical forward model of lightning processes matched to the many, varied kinds of lightning observations, each of which quantifies a different part of the lightning process. The Department of Energy (DOE) and its National Laboratories develop sensor technologies to further U.S. national security objectives through space-based Earth-observing platforms which deal with lightning as a near-constant background. As a result, DOE-developed sensor outputs have contributed to studies of lightning and other atmospheric phenomena, which in turn provide improvements for Space Situational Awareness modeling. Ongoing development of advanced sensing technologies, modeling and simulation tools is a key DOE national security objective to better inform DoD and other U.S. agencies of real-time environments and events occurring throughout the depth of the atmosphere. DOE Earth System Modeling efforts seek to understand the role of thunderstorms in the radiative budget of the atmosphere and shifts in hazards (such as lightning-initiated wildfires) in a changing climate, but lightning forecasts at the climate scale rely on statistical-empirical fits to large-scale weather parameters, with little capability to diagnose the underlying physical reasons for errors. The absence of a holistic model is a barrier to advancing the missions of each of these parties.

The current state of lightning science is fragmented: smaller model-theory-observation loops test sub-processes, but an integrated whole has not been pursued, and so at the most basic level lightning science suffers from not knowing if its constituent parts form a self-consistent whole. The global lightning observation capability, as well as detailed measurements and computational resources available to researchers, have now advanced to a stage where the time is right to pursue an end-to-end physical model, and linked to radio frequency and optical sensor models. National and international coordination of these efforts can drive progress. There is inspiration and pragmatic lessons to draw from the even wider range of processes addressed in building numerical models for weather prediction, linking physical theory to the global availability of coordinated weather observations in the 20th century.

The roadmap outlines how we might take existing, sometimes fragmented, lightning model components built on current theories, connect them to each other and to weather models (each with their own forecast uncertainties), make them communicate with each other, and compare modeled predictions with observations. This initial stitching and integrated testing of model components is the primary focus of this five-year roadmap.

1.2 Goals of this roadmap document:

- Identify inputs and outputs of major modeling system components
    - Allow for separable and independent development efforts by small/independent teams
    - Develop data structures for flexible communication among components
- Identify methods for practical model implementation
    - Connect common components between different models
    - Improve model components that currently lack connectivity
    - Evaluate model outputs against observations
- Identify where there are competing ideas about the essential physics
    - These will guide efforts at parallel evaluation of modeling approaches
- Recommend some initial, practical uses of existing model components
    - Not a goal to make binding decisions
- Indicate priorities and provide a year-by-year timeline
- In appendices, provide additional review of the state of the science

1.3 Overview of the major model components

This document outlines inputs and outputs of components of the modeling system, and a flowchart below shows connections between them. Weather forecast models can predict realistic clouds and precipitation rates for all three water phases, and electrification schemes exist to allow the cloud to charge as cloud particles collide. Initiation of lightning (a potentially relativistic process) in intensely electrified cloud regions leads to the development of initial plasma streamers, which convert to a larger-scale (10s of meters to 100s of kilometers) network of hot lightning leaders. Streamer and leader modeling sub-components require descriptions of local current flows and space charge distributions that drive chemistry and local electron density and produce radio frequency, optical, and even gamma emissions. Synthetic emissions from streamer and leader models must then be propagated through the clear and cloudy atmosphere, accounting for ground wave effects and the ionosphere, to observing system sensor models.

As such, major model components of a holistic physical model for lightning should include:

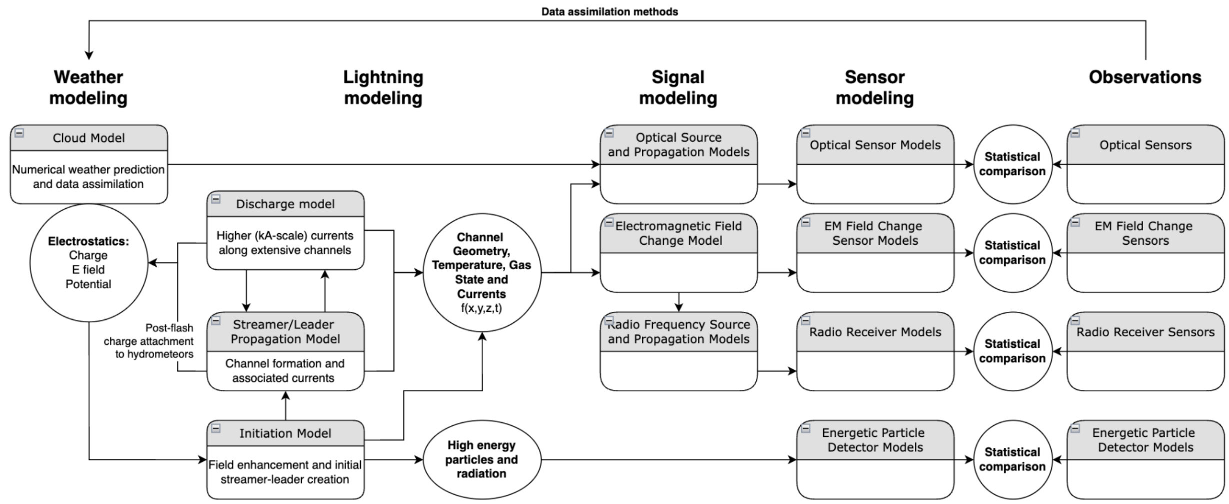
1. Cloud model
2. Initiation model
3. Streamer-leader development model
4. Lightning discharge model
5. Observable signals: production, propagation, and sensor detection models
6. Ancillary models
    - Chemistry
    - Effects of lightning on structures and vegetation

Subsequent sections will review each of these major components in turn. Components 1-5 are summarized in the flowchart below.

Outside the scope of the model envisioned in this roadmap but of interest are:

- Feedbacks of electrical energy on cloud microphysics
- Transient luminous events
- Planetary lightning
- Ball lightning

1.3.1 Flowchart: connections between major model components



A remark on modeling philosophy, which we expand upon in Appendix 1. There are two ways to build a physical model of lightning: working outward from physical first principles, leading to a hierarchy of processes that integrate into a complete picture of lightning. Alternatively, one can work from the outside in, using measures of energy conservation to avoid process detail and save computation time, while still preserving realism with high fidelity. Bearing in mind the value (for instance, in parameterization development) of first-principles, physics-based modeling efforts, which must continue in parallel, we construct this model with the outside-in approach, because practical models are often interested in just enough functionality to make a useful prediction, with additional complexity adopted as more process fidelity is required to match the fidelity of available observations.

1.4 Community coordination

1.4.1 Growing and sustaining a community of practice

Development of a practical numerical model of storm electrification, lightning physics, and related observing systems will require development of the numerous model components outlined in this document. Each requires knowledge of the underlying physics and how the physics are practically implemented in code.

From other examples (e.g., in numerical weather prediction) it is obvious that each major component will need at least one primary subject matter expert steward, and perhaps twice that number of people with general familiarity with the interfaces between the components and how the system is to be run as an integrated whole. Sustaining such a community of development and practice within the present lightning community is possible, though growth in this community of practice is likely needed (with sustaining funding) to ensure the system is holistically exercised and compared to observations with sufficient regularity to identify the necessary improvements and applications.

1.4.2 Workshops

Periodic workshops to gather the community for a focused review of the roadmap, including successes and challenges to date, will be needed. While ordinary professional conferences are another venue for discussing components of the work relevant to the roadmap, consolidation of results and synthesis into a practical working system is outside the scope of the kinds of discussion facilitated in typical general conference programs. These workshops might take place at a University, UCAR/NCAR, or other host institution, or held with the support of a professional society at a special meeting venue. Industry partners might also host, given their interests in power grid and structure protection, and in commercial lightning detection products and services. A meeting about once per year is expected. A summary of the April 2024 workshop that initiated the development of this roadmap is provided in Appendix 5. A second community workshop is planned for April, 2025 at Texas Tech University.

Prior to the next workshop, Town Hall discussions are scheduled for the American Geophysical Union and American Meteorological Society annual meetings in winter 2024-25 to solicit comments on the roadmap from the atmospheric and space electricity, atmospheric science, meteorological, and broader Earth science communities.

1.4.3 Open-source code and data repositories

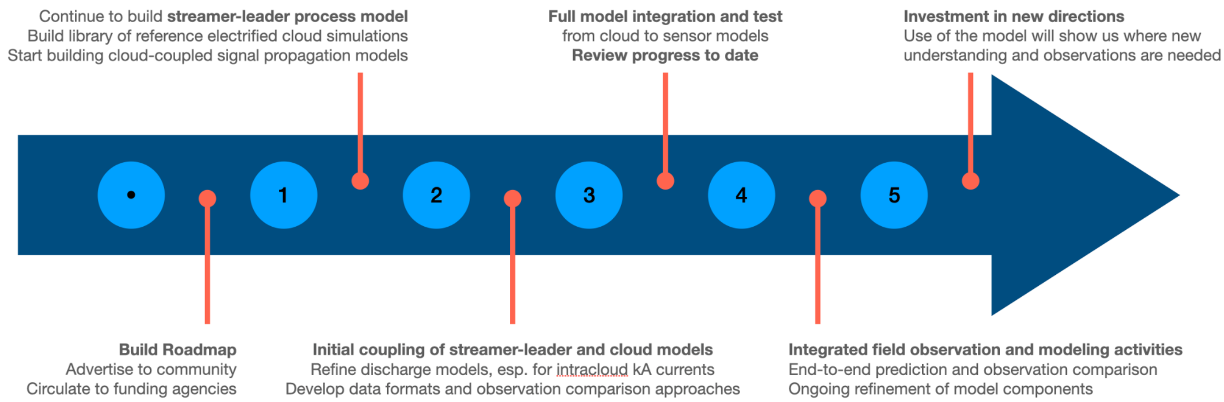
Community open-source models, like the one envisioned here, are developed in public on the internet using a commercial version control service. GitHub is commonly chosen because it facilitates not only tracking of code, but also public development discussion, delivery of documentation, and automation of testing of the code.

Development of a governance model for this community code will be necessary over the five years of the roadmap. It is possible to obtain an organization-level GitHub account, under which individual model components can be aggregated, though initial development likely will proceed under individual or institutional repositories since linking to or up-streaming publicly developed code is technologically straightforward.

Repositories of reference and test datasets will be needed. For longer-term storage, use of public services capable of assigning a DOI are envisioned, whether open services like Zenodo or heavily managed and authenticated services like NASA EarthData.

1.5 Priorities for the Next Five Years and Notional Work Plan

Contingent on availability of funding, our priorities and work plan over the next five years are as follows.



Year 1 Synthetic signal propagation, including through realistic cloud models, and comparison to observation can begin immediately, to leverage existing lightning mapping (VHF) and simple electrostatic branched discharge numerical parametrizations to inform lightning channel geometry. Concurrently, development of streamer-leader models will continue. Development of a reference library of cloud simulations with electrification, and shared as a public dataset with supporting use tutorials. Begin development of data formats to connect model components and sensor models to enable observation comparison.

Year 2 Implement initial coupling of streamer-leader models to cloud models, and begin to refine the discharge models and connect them to streamer-leader models. Expertise in parameterization development and parallelization in high performance computing models will be needed. Especially needed is an approach to quantify and validate models of intracloud discharges like k-changes that are observed by both RF and optical remote sensors. Ongoing development of data formats to connect model components and sensor models to enable observation comparison..

Year 3 Continue to invest in the streamer-leader and discharge model development. Integration and test of all model components will continue. Carefully review progress to date and identify remaining gaps and priority investments for the final two years of effort.

Years 4-5 Alongside initial maturity of each of the model components, a significant jump in effort is expected in year 4 and continuing into year 5. Availability of outputs of each model component will enable additional investment in signal generation and comparison of those signals to observations will enable formal statistical validation of the model, including uncertainty characterization. Additional development and retesting will be guided by errors identified.

1.5.1 Table of effort and cost

Minimal effort estimates in each year are given in the table below, in grant-years at a university, typically 1-mo faculty time plus a doctoral student, conference/meeting travel, and research materials.

Some categories such as community coordination may split equivalent funds across more than one PI/staff scientist, and would also support an annual workshop. For the modeling pieces, efforts will benefit from splitting funding across a few research groups to help resolve scientific uncertainty and explore varied implementation ideas.

Costs associated with university grant-year efforts typically total $150K/yr, including overhead of about 50% at most universities, so the minimal plan below of 60 total grant-years is $9M over 5 yrs. Such costs put the lightning modeling effort into the funding class typically provided by NSF Science and Technology Centers and DOE Grand Challenges.

Task	**Yr1**	**Yr2**	**Yr3**	**Yr4**	**Yr5**	**Total**
Cloud	1	1	1	1	1	**5**
Lightning initiation	1	1	1	1	1	**5**
Streamer-leader	1	1	2	2	2	**8**
Discharge		1	2	2	2	**7**
Signal generation: E-field and RF		1	1	2	2	**6**
Signal generation: Optical		1	1	2	2	**6**
Signal propagation and observation: E-field and RF	1	1	1	1	1	**5**
Signal propagation and observation: Optical	1	1	1	1	1	**5**
Model integration and testing		1	1	2	2	**6**
Community coordination	1	1	1	1	1	**5**
Annual workshop	1 (next 3 yrs)			1 (next 3 yrs)		**2**
Estimated total (grant-years)	**7**	**10**	**12**	**16**	**15**	**60**
Estimated cost ($M)	**1.1**	**1.5**	**1.8**	**2.4**	**2.2**	**9.0**

2. Functional Description: Physical Process Models

In this section (focused on physical process models) and the next (focused on signal and sensor modeling), we walk through each of the major model components, and discuss concrete inputs, outputs, integration with other components, and uncertainties, methods for evaluation, and priorities for the next five years.

2.1 Cloud Model

The cloud model encompasses adaptation of numerical weather prediction systems and other kinds of idealized cloud models used for more focused research experiments. Both are mature areas of science with robust capabilities and varied approaches (Tao and Moncrieff 2009; Khain and Pinsky et al. 2018).

Note that the simplest cloud electricity model has no cloud or meteorology at all. Simple slab-charge models have long been used in atmospheric electricity (e.g., Simpson and Scrase, 1937; Krehbiel et al., 2008), and even the most comprehensive, observationally consistent, and meteorologically coupled charge models (e.g., Stolzenburg et al. 1998) are idealized slabs of charge. These are useful for idealized tests and demonstrations of principles, but *do not allow for interaction of the electrical processes with the cloud processes and constituents*. Slab charge models offer no way to test whether the cloud influences the electrical structure (Saunders 2008, Mansell et al. 2010) or observed lightning signals (e.g., Peterson et al. 2017, Bruning and

MacGorman 2013) - an issue of great importance to optical lightning signals (Brunner and Bitzer 2020, Thomason and Krider 1982), for instance.

2.1.1 Inputs

1. Parameter list specifying model configuration (grid spacing, etc. See Appendix 2 on the internal components of cloud models and their configuration)
2. Initial and boundary conditions
    a. From regional or global model background, possibly coarser
        i. real-time operational forecasts (e.g., GFS, RAP, HRRR, ECMWF, AROME-France)
        ii. reanalysis (e.g., ERA5, NARR, Mesinger et al. 2004; CONUS404, Rasmussen et al. 2023)
    b. From uniform environment
        i. Minimally, a vertical profile of temperature, moisture, and wind
3. Simulated atmospheric state at later times: For retrospective simulations, model evolution can be constrained to tend toward reanalyses valid at later times (e.g., the "replay" reforecasts of Orbe et al. 2017).
4. Weather observations to be assimilated: For downscaling of a coarser model background, observations from, for example, surface weather observing stations and weather radars may increase the accuracy of the initial state and spur finer-scale processes.

2.1.2 Outputs

1. 3D Charge distribution and electric field as a function of time
    a. may need to be handed off to initiation, streamer-leader, and/or discharge models approximately continuously/in-line to couple storm-scale electrical feedbacks to the 3D cloud model grid.
    b. can also be saved at a time step of interest to experiment with discharge development (sample datasets already exist for this).
2. 3D cloud structure, including microphysics, kinematics, dynamics, aerosol/chemical distributions, and other features of the environment may need to be recorded when discharges occur, as these can impact downstream models (e.g., simulated lightning sensor observations, chemical process models).
3. Land surface model moisture content for use by the RF propagation component can be output at a regular cadence or when discharges occur.

2.1.3 Integration of lightning within cloud models

Outputs from the cloud model are fundamental to driving the rest of the discharge and observation models. The cloud model must include an electrification scheme (e.g., Mansell et al. 2005).

The lightning initiation, streamer-leader, and discharge models (which may include relativistic and plasma physics) must be able to feed back into the cloud model's evolving electrical structure, as they can significantly adjust charge distributions and electric fields on the cloud model grid after (e.g.) the discharge ends. Process details are left to those models, with the coupling envisioned as a simple update to the cloud model's electrostatic variables after the lightning processes have completed.

Existing cloud modeling systems with electrification:

- National Severe Storms Laboratory (NSSL) Collaborative Model for Multiscale Atmospheric Simulation (COMMAS)
    - COMMAS contains both electrification and a branched lightning scheme, but it is not public nor planned to be public.
        - Uses in-line Box-MG Poisson solver for charge-potential inversion
        - Electrification is coupled to a single microphysics scheme (NSSL 2-moment)
        - Uses either a branched lightning scheme or bulk simulation of lightning properties (e.g., flash extent density, FED)
- Weather Research and Forecasting (WRF) Electricity (ELEC) model
    - WRF-Elec has all the electrification capabilities of COMMAS except the branched lightning scheme, which other components of the holistic model can replace.
        - A branching scheme is planned to be implemented within the NASA Unified (NU) WRF, which includes the electricity scheme.
- Meso-NH (Lac et al. 2018)
    - freely available under CeCILL-C license agreement
    - uses CELLS cloud electrification and lightning scheme
    - simulates branching and NOx production

- Storm Electrification Model (Helsdon et al. 1992; Zhang et al. 2003)

    - Not publicly available, but has coupled microphysics, electrification, and chemistry

Other relevant /planned cloud modeling systems.

- NOAA Unified Forecast System (UFS) with Model for Prediction Across Scales (MPAS) dynamic core
    - Recent addition to UFS for operational convection-allowing models in the United States
- Department of Energy (DOE) Energy Exascale Earth System Model (E3SM)
    - Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) 3-km runs in support of the Dynamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) initiative.

2.1.4 Uncertainties

While numerical weather prediction (NWP) and cloud modeling are mature areas of science, innumerable uncertainties exist in cloud models. To state the obvious, weather forecasts are not perfect at the storm scale (e.g., Warn on Forecast; Stensrud et al. 2009). The ice-phase cloud microphysical parameterizations of great importance to electrification are among the largest uncertainties in cloud models, and impact many other processes that control storm dynamics (Morrison et al., 2015). Awareness of such uncertainties is crucial when applying cloud models for prediction of electrification, and subsequent remote sensor interpretation and diagnostics.

However, from the point of view of lightning modeling, routine application of the current state of the art in cloud prediction is rare, relying mostly on case studies and occasional efforts driven by observation campaigns and by a few individuals. Wider use of even the status quo in general-purpose cloud modeling would represent an advancement in lightning modeling, and ongoing efforts to align the lightning model's cloud component with widely used cloud modeling systems would enable those advancements to organically improve the basic cloud structure to which lightning responds. End-to-end exercise of the lightning model will likewise uncover characteristic sensitivities to the cloud structure, and these results should be reported back to the cloud-modeling community to drive mutual improvements.

Therefore, the uncertainties highlighted here are not those known to be of general interest in storm forecasting, but rather those of greatest significance to cloud electrification. It is these areas to which we expect an end-to-end lightning model would be most sensitive.

Of particular importance to an integrated lightning model are the prediction of ice and liquid phase hydrometeor concentrations, sizes, and process rates, as well as the performance of the modeling system as a whole in capturing the fluid physics of buoyant deep convection, with its characteristically high Reynolds number. Because thunderstorms develop and organize in response to the thermodynamic and moisture profiles, instability, and wind shear of their surrounding environment, regional variability is an important degree of freedom to explore when exercising a lightning model.

Cloud electrification schemes, as informed by laboratory experiments, remain a critical uncertainty, and there are few resources in the US to address aging capacity for doing the necessary experiments in laboratory settings, nor evaluating them at local, regional, or global scale. With the current state-of-the-art in electrified cloud modeling, it is possible to generate clouds with completely different electrical structures (e.g., normal vs. inverted tripole) simply by switching electrification schemes. Significant uncertainties still exist in laboratory studies of electrification of colliding ice particles, and in other secondary electrification mechanisms (Takahashi 1978, Emersic 2006, Bruning et al. 2014).

Any eventual operational implementation of a lightning model will require use of software packages aligned with and implementable in existing operational weather prediction systems. However, high-level, long-term agency plans shift over time and may be difficult to match for high-in-the-funnel development efforts. Therefore, close correspondence with operational model system planning will slow innovation, so some independence of implementation in more-flexible research cloud modeling systems is expected. Operational agency investments in ongoing proof-of-concept integrations of the lightning model with operational systems will be necessary to ensure the gap between research and operational modeling systems does not grow too large. Maintaining modularity and developing an interface description for the lightning model components, toward making them model-agnostic, will support research-to-operations transition but will require greater software engineering investment to support scientist-coder implementation of the physics.

2.1.5 Evaluation methods

Many methods to evaluate weather simulations already exist and are in use by operational centers and researchers. Evaluations performed for the purpose of lightning modeling should focus on aspects of cloud and thunderstorm representation.

Cloud simulations can be assessed against satellite and ceilometer observations of cloud top height, cloud fraction, and cloud base height, as well as cloud composition measurements recorded by field campaigns (e.g., ICICLE; Shakirova et al. 2022). Precipitating ice hydrometeors can be assessed against detections from the WSR-88D weather radar network, as well as against other ground-based research as well as satellite-based radars. NOAA's National Severe Storms Laboratory creates gridded products from WSR-88D (MRMS: Smith et al. 2016; Zhang et al. 2016), including column-maximum reflectivity, vertically-integrated liquid, echo top, and accumulated precipitation, that are used to validate NOAA's models and others. Further radar-based assessments with severe-storm focus can also be conducted, including presence of high differential reflectivity above the freezing level and area of 40 dBZ radar echo exceeding 9 km in height, which indicate strong updrafts and hail production respectively (Ryzhkov et al. 2020, Zipser and Liu 2021) and are also relevant to electrification (Buechler and Goodman 1990).

Measurements of the three-dimensional (3D), time-evolving electrostatic structure of storms are needed for verification of electrification processes. Innovative approaches must be developed to characterize 3D variability while working around challenges with sampling in 3D.

2.1.6 Summary of recommended next steps

Perform controlled comparisons of the candidate modeling systems listed above and quantify their ability to represent (non-electrified) cloud and thunderstorm meteorological processes accurately, exploring configuration options such as resolution, initial conditions, and physics parameterizations. Perform retrospective case studies spanning scenarios of lightning and severe storm interest with different regimes and drivers.

Select the best-performing model or models to form the environment in which electrification components are enabled, if they are not already (e.g., port capabilities in WRF-ELEC to MPAS if MPAS outperforms WRF in initial retrospective simulations). Any necessary development and implementation of electrification schemes should be conducted in a manner consistent with the goal of code portability discussed above.

Develop interfaces for integration of various lightning initiation, streamer-leader, and discharge schemes within electrified cloud models.

Develop a public library of canonical, observationally validated reference simulations of clouds at the km and LES scales, with a guide to data structures that can be used to drive other lightning models.

2.2 Lightning Initiation Model

Lightning initiation is hypothesized to require local enhancement of the ambient electric field because there is a lack of in-situ observations demonstrating that electric fields caused by normal thunderstorm charging mechanisms ever reach magnitudes required to initiate the electrical breakdown of air (Winn et al. 1974, Marshall et al. 1991, Marshall et al. 1995, Stolzenburg et al. 2007; the field seems to maximize at the so-called relativistic runaway electron avalanche, or RREA, threshold). If the electric field is sufficiently increased by a secondary means, streamers may be launched – potentially from hydrometeors – which further enhances the electric field at the origin of the streamer network and creates the conditions for negative breakdown to occur. Thus, one paradigm for a lightning initiation model would be a two-step process: (i) initial electric field enhancement leading to production of streamers followed by (ii) networks of streamers enhancing the field for negative polarity breakdown.

(i) Initial electric field enhancement

Two methods for initial electric field enhancement are hypothesized: cosmic ray showers without runaway processes and runaway relativistic electron avalanches.

(a) Cosmic ray showers without runaway processes: A cosmic ray shower propagates through a region of a thunderstorm where the electric field is near the critical breakdown threshold for relativistic runaway breakdown. The cosmic ray shower creates low-energy secondary electrons that enhance the electric field to the threshold required for fast positive breakdown. A secondary effect of the cosmic ray shower is a detectable RF signal produced by the low energy electrons drifting in the thunderstorm electric field (Shao et al. 2020).

(b) Runaway relativistic electron avalanches: Similar to method (a), a cosmic ray shower propagates through a region of a thunderstorm where the electric field is near the critical breakdown threshold for relativistic runaway breakdown. Runaway relativistic electron avalanches (RREA) occur, potentially with relativistic feedback mechanisms (Dwyer 2003). RREAs effectively discharge the large-scale field, producing a sub-region of localized electric field that is shifting in altitude and increases in intensity over tenths of a second. This electric field enhancement is also required to create terrestrial gamma ray flashes and glows from accelerating electrons (Marisaldi et al. 2024).

It has also been proposed that turbulence in clouds plays a role in locally enhancing the electric field streamers (Kostinsky et al. 2020; Souza and Bruning, 2021; Salinas et al. 2022, Bruning and MacGorman 2013), perhaps supporting the mechanisms above.

2.2.1 Inputs - initial field enhancement:

1) 3D, time varying electric field on scales of 100s of meters

2) Background cosmic ray flux

2.2.2 Outputs - initial field enhancement:

1) Local region of enhanced electric field

2) Process-dependent output signals:

(a) RF signal from cosmic ray shower
(b) gamma ray emissions

(ii) Positive streamer networks leading to negative electrical breakdown

Once the electric field is sufficiently enhanced, positive streamers may be launched from a hydrometeor, and will further encounter the large number concentrations of hydrometeors in clouds. Exponential growth of these positive streamers leads to additional electric field enhancement sufficient for negative electrical breakdown to occur. The network of positive streamers creates the RF signature of narrow bipolar events (NBEs; Griffiths and Phelps 1976, Attanasio et al. 2019, Attanasio et al. 2021).

Following the development of the positive streamer network, negative breakdown eventually happens in response, generally in the opposite direction of the positive streamers, producing an initial streamer-leader segment that is suitable for bidirectional propagation at each end.

We note that there have been many studies examining the relationship between external electric field and hydrometeor geometry both experimentally (Petersen et al. 2006, 2014), and through modeling (Liu et al. 2012, Sadighi et al. 2015, Shi et al. 2016), some of which suggest that fields less than the RREA threshold could launch positive streamers, thus negating the need for the initial electric field enhancement from cosmic-ray driven processes. An alternative model could circumvent the high-energy processes and create streamer networks in the ambient electric field in the presence of hydrometeors."

2.2.3 Inputs - hydrometeor streamer production:

1) 3D, time-varying electric field or electric potential

2) Distribution of hydrometeors shapes and sizes

2.2.4 Outputs - hydrometeor streamer production:

1) Positive streamer (i.e., NBE) currents

2) Initial bidirectional streamer-leader segment, including its location and other properties suitable for further streamer-leader modeling.

2.2.5 Uncertainties:

- Modeling the effects of cosmic ray showers depends on the background state of the ambient thunderstorm electric field. Thus, faithfully representing the background electric field is critical.
- Direct observational evidence of cosmic ray showers correlating with lightning initiation is lacking.
- The mechanism by which positive streamers launch a negative streamer-leader system in the opposite direction.

2.2.6 Evaluation methods

Direct observations of the relativistic mechanisms and their short term enhancement of the electric field are difficult or impossible to make. Shao et al. (2020) demonstrates an observational link between a measurable RF cosmic ray signature and the initiation of lightning, which could be compared to modeling outputs. Modeling of the RF emissions of NBEs can be compared to observations (Watson and Marshall, 2007; Nag and Rakov, 2010a;b).

2.2.7 Summary of recommended next steps

Models for relativistic electric field enhancement, initiation of streamers off of hydrometeors, and NBES from an initial streamer currently exist. The models need to be examined to determine what improvements or simplifications need to be made to make the models tractable in the larger simulation framework and work with each other. A model of the electric field enhancement from non-relativistic cosmic ray processes needs to be created. Dependencies of streamer formation on the number concentration and size distribution of particles reported by cloud models need to be assessed.

2.3 Streamer-Leader Model

The streamer-leader model follows after lightning initiation, and it creates a network of (relatively) low resistance and electrically charged streamers and leader channels. This network has these properties:

- Following the development of an initial leader channel, growth can occur at both ends of the leader.
- Leaders appear as straight-line segments: distinct leaders start at points where the channel changes direction or branches into 2 or more new leaders.
- Leader channels have a hot (3000-5000 K) and conductive core with a radius of about 1 cm.
- Leader channels have a coronal sheath, with a radius of several meters, where charge is stored (~1 Coulomb/kilometer)
- A leader channel has these attributes:
    - A pair, initial and terminal endpoints, of 3D positions
    - Core temperature and radius
    - Ambient air state (temperature, pressure, density, constituent molecules, etc.)
    - Coronal sheath state (temperature, pressure, density, molecular species, charge, etc. as functions of distance from the core.
    - Integrated or total charge
    - Intrinsic capacitance and impedance
    - Electric field at terminal endpoints

The set of leader endpoints constitutes a set of nodes (or vertices) for a mathematical graph. Edges in this graph are in 1-1 correspondence with the leaders. A notional “root” node represents the point where lightning initiation occurs. Growth may occur at all terminal endpoints, where streamer processes form one or more new leaders, or where a high-current discharge reaches a leader tip and stimulates significant new channel development.

A model component must also indicate when a connection to ground is made.

2.3.1 Inputs:

- Neutral air/gas chemistry, and variability with altitude
- Pre-flash electrostatic field
- Location and plasma properties of the initial streamer-leader segment seeded by the last stage of initiation

2.3.2 Outputs:

- Streamer and leader morphology
  - Locations of leader channel segments
  - Locations of streamer segments (e.g., on tips of leaders)
  - Locations of ground connections
  - Time sequence of streamer-leader conversion events that add nodes and ground connections
- Currents, time-varying (broken out due to different RF and optical behavior)
  - in streamer zones
    - especially those during streamer-leader conversion
  - along leaders
    - Ionization levels within leaders (especially important for optical and chemical models)
- Charge distribution as a function of time and space
  - Within streamer zones
  - In leader sheath
- Ionization levels
- Space charge remaining after all leader channels decay

Leader development and associated current flows drive feedbacks in new streamer development, and larger-scale discharges like return strokes can spur extensive new leader development, so there is some expected coupling/feedback during the discharge process itself. High electric fields at the extremities of the leader network induce reaction fields in the ambient environment while the leader network is active..

2.3.3 Uncertainties:

In a streamer-leader model uncoupled to a discharge model, it is not known whether there is a way to produce self-consistent current flows along a generic fully conductive leader channel. The dynamics of streamers as they collectively propagate away from the leader tip make this the hardest part of the leader to model, and there are known asymmetries in the propagation of the positive and negative leader ends (Williams 2006).

Extant large-scale fractal discharge models (e.g., Riousset et al. 2007) do not include decay of channel conductivity, which is thought to be necessary to obtain dart leaders and k-changes. Adding such capability will be necessary to properly initiate discharges and couple the streamer-leader and discharge models. A reasonable model should also capture the fact that positive leaders produce relatively low-amplitude radio pulses in the VHF band as they propagate forward, and much larger ones on the negative end.

2.3.4 Evaluation methods

Since they are rarely observed directly (except for current measurements on instrumented towers) the currents generated by the streamer-leader model must be fed to the RF and signal source models, and then propagated onward to specific sensor models for comparison to observations. Another, relatively simple, test is to compare the predicted extent and geometry of the streamer-leader channel network to the extent and geometry indicated by existing 4D lightning mapping systems.

2.3.5 Summary of recommended next steps

Investment in a consolidated streamer-leader model that produces the required outputs is one of the most urgent needs in the lightning modeling effort, especially because of its coupling to the discharge model. Comparison of the more complex plasma-aware models to the simpler quasi-electrostatic models and their produced geometries will likely be helpful in understanding how to efficiently model this part of the problem. Linking this model to other components, including integrating feedback into the cloud model, is a key practical challenge in building the holistic lightning model.

2.4 Lightning Discharge Model

Following from the development of the leader channel, larger-scale, discharges (scale of kiloamps) happen along the channel. These high-current phenomena include:

- Recoil/K-change processes (Jensen et al. 2023)
    - Modeling of these processes is at a very rudimentary stage, and would benefit from additional research.
- Return strokes
    - The highly-mature transmission line model describes the rate that the hot wavefront propagates along a leader segment connected to ground, but once the wavefront enters the cloud the energy must contend with the full branched leader structure and a more complex background electrostatic environment.

Note that other high-current or energetic phenomena (such as NBEs and TGFs) are discussed in the model sections (such as the Initiation Model) that produce those currents. The currents described by the Discharge Model are unique in that they serve to rebalance charge along some relatively extensive segment of the leader network, instead of being a high-current, relatively localized phenomenon.

Modeling of the connection to ground ("attachment") has been well-studied (Nag et al., 2023a), and uses the transmission line model when a ground connection is deemed necessary by the streamer-leader model. The return stroke current wave is a very fast (of order 10^8 ms^{-1}) process.

IC discharges on leader networks connecting space charge regions of opposite polarity should have some similar behaviors to return strokes, such as speed, though the nature of the channel conductivity is unclear and currents tend to be smaller. Intermediate-scale current models (e.g., for K-changes) are likely a science frontier, and efforts to build connections in the gap between streamer-leader creation and kiloamp-scale currents are needed. Some of the physics is understood, but a concrete predictive model has not been implemented numerically. The speeds of these strokes are slower than return strokes (10^6-10^7 ms^{-1}, Da Silva, Winn et al. 2023), but faster than the speeds of leader development (10^4-10^6 ms^{-1}). However, some negative leaders may also have currents near 1 kA as they step forward.

The streamer-leader model, a model for the production of intermediate currents like K-changes, and the return stroke model all produce currents in a channel of some length and geometry. The aggregate of these models is a current waveform that can drive optical, RF, and chemical models.

Typical models consider a short cylinder of charged air (corona) and a central hot and conductive channel. The kA-scale discharge drains this corona charge, and may need to do so across multiple cylinder segments at once. A physical model with 3D geometry may be needed to model the physical processes at points where leader channels meet (branch points) and the continuum component of the light output increases (Orville and Uman 1965). The discharge model will in general use first-principles physics or phenomenological models on these cylindrical geometries to estimate conditions in each short segment of the lightning channel. A review of the more-mature return stroke models is provided in Appendix 3.

2.4.1 Inputs:

- The leader network.
- The attachment event.

2.4.2 Outputs:

For short sections of the channel:

- Time and space distribution of key variables: temperature, gas species, energy levels, etc.
- Time and space distribution of currents flowing through the channel

For the whole discharge:

- Modified properties of the streamer-leader network

2.4.3 Evaluation methods

Subsequent sections describe forward modeling of optical, RF, and other observable signals. Varying levels of fidelity might be modeled and matched to observations depending on the need. For instance, correct predictions of storm-total optical flux over a time scale of minutes might be sufficient for data assimilation and numerical weather prediction, while a more sophisticated model might try to accurately predict the number, spatial distribution, and current distribution of return strokes and k-changes as a function of distance from the flash origin.

Because streamer-leader networks and the high current discharges themselves develop stochastically, ensemble modeling (many realizations of each discharge tree) will support statistical characterization of the predicted phenomena, providing model error bars that will be useful for comparison to observations.

2.4.4 Uncertainties

As noted above, high current discharges are initiated by conditions within the streamer-leader network, and feed back into the streamer-leader network after each discharge event (e.g., return stroke, k-change). Because the physics is highly dynamic and full of feedbacks, the logic of computational implementation and handoff between the model components remains unclear, and is a design challenge that will need to be resolved alongside the physical modeling choices.

2.4.5 Summary of recommended next steps

Better define the connection between the discharge model and streamer-leader model, including the interface between simpler return stroke models and how they modify the cloud. Refine the understanding of K-change / recoil processes on decayed channels concurrently with an implementation of a practical process model.

3. Functional Description: Lightning Signal and Sensor Models

In this section, we build on the physical model components described in Section 2.

3.1 Preamble: Decoupling of Lightning Physics from Observing System Simulation

The aggregate streamer-leader and discharge models give as output (often time-resolved) the channel geometry and currents/ionization/thermalization states associated with that geometry. Those models also produce a final space charge distribution. Regardless of the internal details of the discharge model itself, these outputs can be used to produce signals that then propagate to sensor models.

The decoupling of signal production from the discharge model enables greater modularity and testability. The community should be able to generate optical and RF signals, and improve these components, with a degree of independence. It opens the participation of a wider range of workers by not requiring them to be familiar with the details of how a discharge develops and moves charge around. It also allows tailoring of signal production for different levels of complexity and fidelity.

For this reason, we have intentionally avoided discussing observable signals in the streamer-leader and discharge models.

3.2 Electromagnetic field change model

A complete theory for all electric and magnetic field changes is given by (Shao 2016), framed in terms of the Uman et al. (1975) electrostatic (integral of current), induction (current), and radiation (rate of change of current) terms. Shao generalizes it to use an arbitrary 3D current source and observing location. A summary of various approaches, parameters, and variables associated with computation of return stroke electromagnetic fields is found in Rakov and Uman (1998) and Rakov and Uman (2003, Ch. 12). A "unified approach" to compute fields and match to observed ones for all major processes in negative cloud-to-ground first strokes in a self-consistent manner is found in Nag and Rakov (2016).

3.2.1 Inputs:

- Channel geometry, current (including waveform and propagation speed), and net storm charge structure as a function of time during the discharge (as available, or assumed constant)
- Observation locations of interest

3.2.2 Outputs:

- Electric and magnetic field at each observation location as a function of time (i.e., field change).

3.2.3 Uncertainties

Uncertainties in return stroke models are associated with channel geometry (including branching, Nag and Rakov, 2015), variability of current propagation speed along the channel, waveshape of the current source, as well as the nature of the strike object (e.g., Baba and Rakov, 2005; Zhu et al. 2018). Uncertainties can be limited by observations. For example, channel-base current measurements can be made for upward (e.g. Watanabe et al., 2019) and downward (Nag et al., 2023b) cloud-to-ground lightning. However, most lightning (an estimated 70%, e.g. Boccippio et al. 2000) occurs in-cloud, for which there is virtually no way to make in-situ measurements of the plasma discharge currents. Instead, observationally constrained EM field change models have historically been used to obtain an estimate of the plasma discharge currents and not the other way around, given an estimate of the plasma discharge geometry and assumed direction of current flow (Krehbiel et al. 1979). Modeling as envisioned here will produce an explicit source geometry and currents, and so it is uncertain how out of line observation-driven estimates of plasma process will be found to be, or if that will just indicate a model shortcoming.

3.2.4 Evaluation methods

The currents (magnitude and direction) of different plasma discharge processes involved in lightning must continue to be measured (when possible) and studied. High-speed video camera observations can be used to constrain channel geometry, at least for channels outside the cloud. Measurements with the long-used electric and magnetic field change instruments, especially when calibrated and deployed as an array, can help constrain charge motions during lightning. For measurements of the radio fields, see the discussion of evaluation methods in the section below. However, use of dual-polarized receivers within an interferometry array (cf., Shao, 2016) and alongside fast field change measurements has been highly beneficial and should continue. The number of receivers could be increased to better spatially resolve the current sources, particularly current flow directions on as yet un-probed (smaller) scales, and among many ongoing plasma discharge processes occurring simultaneously. Statistical characterization of the amplitude of field changes and waveform shapes across a large population of flashes would also be beneficial.

Moreover, efforts are only nascent in mapping currents to individual channels using simultaneous VHF mapping and LF/VLF measurements, especially for slower processes. Isolated (and usually impulsive) things like dart leaders, stepped leaders, initial breakdown pulses, and NBEs are generally easier, although Stozlenburg et al. (2021) showed the slowly varying initial E-change ("EIC") can be deduced, giving some hope of measuring slowly varying currents, too.

3.2.5 Summary of recommended next steps

Production of signals in a standardized data format, initially driven by idealized waveforms, and eventually with current waveforms produced by the initiation, streamer-leader, and discharge models.

3.3 Radio frequency source model

This output is the radiation term in the Uman et al. (1975) formulation. The full electromagnetic model above may not be necessary in some situations, so a more direct RF production model for a transmitting source is also desirable.

3.3.1 Inputs

- One of the following:
    - Channel geometry and current as a function of time during the discharge
    - Full output from the electromagnetic field change model

3.3.2 Outputs

- RF emission location
- RF spectrum: power as a function of radio frequency and time.

3.3.3 Uncertainties

A major uncertainty is the issue of "ground truth" – what measurement(s) will validate the model? There is presently no consistent version of a "complete" radio spectrum of lightning. One issue is that there are different types of plasma discharge processes occurring in lightning, and each may exhibit a different radio spectrum, and not all lightning contains all of these processes. For instance, a cloud-to-ground lightning will naturally include a return stroke, whereas in-cloud lightning will not; NBEs (which produce the strongest known terrestrial emission of VHF) occur in some lightning events, but not all (Rison et al., 2016). Furthermore, there are new types of processes still being discovered, e.g., "return stroke like" events termed Energetic In-Cloud Pulses (EIPs) that discharge 100s of kA without ever discharging to ground (Lyu et al., 2015, 2016). In addition, it is likely that the changing plasma properties with altitude (e.g., Garnug et al, 2021) will affect the electromagnetic emissions produced, which would mean that lightning in different geographic locations where lightning tends to occur at differing altitudes due to different temperature and water content conditions (e.g., Bruning et al. 2014) would actually radiate different electromagnetic spectra.

One of the main issues in quantifying "the entire" lightning spectrum is that lightning is so incredibly broadband. While, historically, measurements of lightning radio emissions have been over relatively narrow (Le Vine, 1987) and wide (Villanueva et al., 1994) bands, they have been insufficient to provide a complete representation of the various processes. There have been a few attempts to stitch together different bandwidth measurements over time to create a more broadband spectrum of lightning (per the issues raised in the previous paragraph, this method may be problematic across different lightning records). However, the difficulty of this "stitching" is compounded by the fact that lightning researchers have a habit of making uncalibrated radio measurements (operating in "digital units" or "arbitrary units"), particularly when it comes to high frequency (HF) and very high frequency (VHF) emissions used for interferometry or time-difference-of-arrival (TDOA) mapping, because calibrated emissions are not a requisite for mapping.

3.3.4 Evaluation methods

The need for calibrated broadband radio measurements is clear. However, these measurements must be accompanied by process-validation measurements, such as 3-D mapping, to make some sense of how the spectrum might change in the presence of different plasma discharge processes, as well as to include other pertinent information, such as discharge altitude. The ideal scenario would be the 3-D radio imaging of many, many lightning events throughout different geographic regions using a network of extremely broadband calibrated sensors – in post-processing, the RF images could be created using different selections of bandwidth to see which processes radiate with which bandwidth(s), similar to false color radio images produced in astronomy.

Nevertheless, many radio measurements are made operationally and in field campaigns. Statistical comparison of the relative amplitudes of measured radio waveforms with the bands measured, and across a diverse population of flashes, will allow for comparison of the relative prevalence of the correct radio source processes in the model.

3.3.5 Summary of recommended next steps

Production of signals in a standardized data format, driven by outputs of the electromagnetic field change model.

3.4 RF propagation model to space

RF signals undergo dispersion while propagating through the ionosphere. A high fidelity model would simulate the group delay, mode splitting, and refractive effects of a cold (i.e., collision-less) magnetized plasma on the RF wave. A simplified model could ignore signal polarization and refraction and only account for first-order refractive effects.

3.4.1 Inputs

- Time series and polarization of RF signal at source location
- Location of RF emission
- Observation location
- Date and time of emission
- Noise background at observation location
- Ionospheric total electron content and density along propagation paths
    - Simulated from mature models (e.g., NeQuick2), which require as inputs the date and time, starting and ending locations of propagation path, and either the f10.7 solar flux or R.12 sunspot index.
    - electron density as a function of the propagation path provides an estimate of the location of the ionospheric pierce point for high fidelity models
- Magnetic field at one or more locations in the ionosphere
    - Simulated from mature models (e.g., IGRF or WMM), which require a location, date, and time.

3.4.2 Outputs

- 3D RF time series at observation location

3.4.3 Uncertainties

Any tractable model makes simplifying assumptions about the extent and density profile of the ionosphere, leading to error in the output signals (e.g., the amount of group delay, refraction, mode splitting). The amount of error depends on the frequency content of the signal being modeled (high frequencies have less error).

3.4.4 Evaluation methods

Evaluation of measured and simulated transionospheric signals is useful for understanding limitations of the model. The level of fidelity required by the model depends on how the output signals are used in sensor models and scientific applications.

3.4.5 Summary of recommended next steps

Implement an open-source model based on documented techniques (e.g., Light 2021), and test with signals produced by the RF source model, including design of a comparison to observations.

3.5 RF propagation model to ground receivers

3.5.1 Inputs

- Time series of RF signal at source location
- Location of RF emission
- Shape and composition/conductivity of lower Earth boundary
- Atmospheric density (for refraction)
- Observation location
- Noise background at observation location
- Ionospheric total electron content and density (for lower-frequency measurements)

3.5.2 Outputs

- RF time series at observation location

3.5.3 Uncertainties

In most cases, the atmospheric density profile should be a generally small source of error, though ducting conditions for radio waves (tied to atmospheric density inversions, the gradients of which are among the greater challenges in atmosphere models) are a source of propagation uncertainty.

Properties of the ground and how it impacts the ground wave are a source of possible error. It is known that propagation over non-flat terrain benefits from replacing the Uman (1975) solutions with finite-difference time-domain (FDTD) propagation (Baba and Rakov 2007; Li et al. 2014). Atmosphere models are coupled to land models that include information about soil moisture and temperature through the first few meters and may be used to set that portion of the lower boundary condition, alongside static soils, geology, and terrain; land surface soil moisture content is also an acknowledged source of error in atmospheric models.

For uncertainties regarding the ionosphere, see the section on RF propagation to space.

3.5.4 Evaluation methods

After implementation of the model, any uncertainties would show up in predictions of the propagated signals. Model maturity as evaluated in many prior studies suggests RF propagation uncertainties are much lower than those of the source signals themselves, but predictions must be monitored for proper signal strength and frequency-dependent dispersion predictions, among other factors.

3.5.5 Summary of recommended next steps

Implementation of an open, documented version of existing approaches, and testing with outputs of the RF source model, across a variety of frequency bands, targeting the downstream observing systems being modeled.

3.6 Optical Signal Source Model

Optical signals originate in the very hot core, and the behavior of air at very high temperatures provides the fundamental information for the development of an optical signal model. Streamer and leader processes at lower, but still hot, temperatures also produce observable optical signals. A complete model of these signals includes the spectral behavior and its changes over time (temperature and total luminosity). Also note that the lightning source is optically thin, and therefore not blackbody.

(Perez-Invernon et al, 2022) describe the common method for synthesizing the spectral signature of lightning. The energy of hot air in thermodynamic equilibrium, partitioned into all available particle states, yields a set of population densities of the various molecules and atoms and their electronic states. Spectral databases that provide state transition probabilities and wavelengths lead to a set of spectral line intensities. Continuum radiation, originating primarily from Bremsstrahlung and recombination processes, is often ignored in studies of lightning spectra that need to be included in the model.

It may be important to consider the effects of the primary radiations on the local, cold air environment. High-energy photons are absorbed by and excite molecules at ambient temperature, which then emit longer wavelength, lower energy photons (Cressault, 2015). These longer wavelength radiations can be observable outside the cloud, and might offer new insights into the in-cloud behavior of lightning.

Rimbaud (Rimbaud *et al*., 2024) models the lightning discharge as a series of point sources, illuminated sequentially as the current wave front moves along the lightning channel.

3.6.1 Inputs

- Channel geometry, current, and ionization/thermalization state as a function of time
- Tables of molecular and atomic line spectra
- Models of continuum radiation

3.6.2 Outputs

- Location and geometry of source
- Photons produced:
    - Total power and wavelength
    - Line and continuum emission

3.6.3 Uncertainties

- Spectral databases often include data quality information

3.6.4 Evaluation methods

Because the cloud environment is assumed to add too much confusion to an analysis, most studies of lightning spectra report only on the light produced by exposed channels. This holistic model might provide the means to understand in-cloud sources even when observed through cloudy paths, as detailed in the next section.

3.6.5 Summary of recommended next steps

- Collect models of the partitioning of air into constituent molecules, atoms, and electronic states as a function of temperature.
- Collect appropriate spectral databases (NIST)
- Collect models of the effects of particle motion and other processes on the width and other features of spectral lines.
- Collect models of continuum processes

3.7 Optical Signal Propagation Model

Cloud droplets scatter photons (UV to IR), greatly increasing path lengths and delays from source to exit events at the cloud's surface. While they have very high single scattering albedo at the wavelengths of interest, very large numbers of scattering events in cumulonimbus clouds can eventually reduce observable outputs. At shorter wavelengths, Rayleigh scattering from ambient air molecules is important. And macroscopic particles (graupel, *etc*.) may be more important for light losses than droplets.

Scattering events should not alter the lightning spectrum, although differences in path length might affect results when observed at high sampling rates. Inelastic scattering (absorption and subsequent remission) can alter the lightning spectrum. (*E.g*., air fluorescence from TGFs.)

Cloud effects are typically modeled using Monte Carlo simulation methods (e.g., Brunner and Bitzer 2020), although ray tracing methods can also be effective. In optically thick conditions, a diffusion model might provide useful results at low cost. Most of the light from a source will exit at the area on the cloud's boundary/surface that is closest to the source.

Some users are interested in the distribution of photon path lengths and corresponding travel time delays.

Rimbaud (Rimbaud *et al*., 2024) uses 3D Monte-Carlo simulation to model the propagation of in-cloud lightning optical signals from a multitude of point sources to their time and space dependent exit from the cloud's surface. Cloud media consist of a variety of particle types (cloud droplets, raindrops, graupel, ice crystals, and snow), and cloud properties vary with position (defined on a mesh of volume elements). Particle albedo and scattering properties are derived from a variety of recent microphysical models.

3.7.1 Inputs

- Location and geometry of sources, including total photon count or power

- Cloud microphysics: concentration, geometry, and particle size distribution in 3D space
- Cloud boundary (especially shape)
- Observation location

3.7.2 Outputs

- Number of photons (or power) as a function of wavelength and time (spectrogram: see, for example, figure 12 in Walker & Christian 2019)
- Account for inelastic scattering in transport media

3.7.3 Uncertainties

A major uncertainty in optical signal propagation models is inadequate understanding of hydrometeor distributions (e.g., ice crystals, graupel, cloud water droplets, etc.). These control the effective optical opacity of the cloud and the amount of optical energy that can escape from, e.g., cloud top. Thus, this uncertainty is coupled to well-known uncertainties in cloud-resolving models themselves. There are additional uncertainties related to dimensionality assumptions. For example, 1D scattering models are less computationally intensive to run but cannot account for the nontrivial amount of optical energy that can escape from the sides of a cloud. This signal can be scattered again from surrounding clouds and be observed from a space-based sensor as well. Finally, uncertainties for scattering of non-spherical ice crystals of varied shapes may in some cases result in additional complexity in the scattering model.

3.7.4 Evaluation methods

Comparison of simulation results to both satellite and suborbital (e.g., ground-based or airborne) observations is warranted. Cloud simulations can be evaluated indirectly through simulated and real weather radar and passive microwave observations, alongside real and emulated optical signals for an ensemble of clouds. The goal is to control for similar cloud properties and isolate the cloud and optical modeling uncertainties using a Bayesian approach (e.g., Matsui et al. 2023). Airborne optical observations (e.g., from the Fly's Eye GLM Simulator, or FEGS; Quick et al. 2020) have been made with airborne/ground-based radar/radiometers in at least two recent field campaigns. These campaigns have also provided in-cloud mapping of lightning channels via VHF observations; hence, the position of the illuminating channel inside the cloud is known. These observations usually see light after it is modified by the cloud environment, and so the iterative refinement of signal and propagation models, and comparison to observations, will yield new insights into lightning behavior inside clouds as well as the effects of the cloud on these signals.

3.7.5 Summary of recommended next steps

The community needs to transition toward more complex, multidimensional (e.g., 2D or 3D) modeling of optical propagation through realistically modeled clouds. Due to the integrated nature of optical scattering and hydrometeor distribution modeling, the community should do coupled investigations that evaluate ongoing improvements in both facets. These studies ought to make use of recent field campaign data for couple model validation .

3.8 Other sensor models

Many of the following models are relatively simple transformations (e.g., integration, bandpass filters; integrated counts) of the generalized physical variables above.

- Electrostatic sensors (DC E field)
- Electric field change sensors (slow, fast antennas for E)
- Optical sensors
    - Radiometer/photometer
    - Pixelated sensors
- Sound (thunder)
- Gamma-rays

3.8.1 Uncertainties

Uncertainties vary by sensor type and the phenomenon being measured. For example, for infrasound measurements knowledge of atmospheric state (e.g., pressure, temperature, humidity, etc.) is extremely important. Meanwhile, electrostatic sensor models suffer from uncertainties related to thunderstorm charge distribution, corona discharge, and local site effects. However, in general improvements in other elements of the end-to-end system (e.g., cloud modeling) would provide downstream benefits to a variety of sensor models.

3.8.2 Evaluation methods

In general, sensor models need to be validated using comparison to real-world observations using the sensor of choice. In addition, sensor models need to consider (and accurately reflect) the results of laboratory calibration of the real sensors themselves.

Calibration of observation systems is only sometimes performed, and will be needed to be done more regularly for a rigorous quantitative comparison.

3.8.3 Summary of recommended next steps

A key need is the development of generalized code hooks so that arbitrary sensor models can be efficiently connected with other components of the end-to-end lightning modeling system. This would allow the use of the end-to-end system as a true Observing System Simulation Experiment (OSSE) framework. OSSEs play a key role in quantifying the predicted utility of new sensors, including ground-based, airborne, and satellite-based instruments. They also provide the key link to understanding what the sensors are actually telling us about the phenomena they are observing.

3.9 Ancillary models

3.9.1 Chemistry model

The time dynamics of leader currents, temperature, and charge also imply chemical dissociation and recombination. New chemical species such as NOx and HOx are produced. Lightning is the largest non-anthropogenic sources of uncertainty in climate models, so an improved physical model prediction of these species, driven by the plasma processes already modeled in the lightning model, will help improve satellite and ground observation campaigns focused on improving climate modeling efforts, as well as enable new forms of parameterization development.

3.9.2 Models of strikes to the built and natural environment

Return strokes striking ground, with current waveforms predicted by the discharge model, can be used to drive models of materials in the built or natural environment, and impacts to those materials. For instance, building structural and electrical damage or wildfire models are examples of such models.

3.10 Observational Measurement Suite and End-to-End Validation Approach

Each of the model components described above has its own section on evaluation methods, and the purpose of this section is to synthesize these ideas, aiming to evaluate the end-to-end capability of the model.

There are numerous examples of observational campaigns where coordinated large teams with expertise in varied measurement systems (e.g., the recent ALOFT campaign; Østgaard et al. 2024) achieve superlative improvements to understanding compared to individual teams investigating in isolation. Such campaigns will be necessary for evaluation of the end-to-end model. The availability of the model will make new, testable predictions and so can inform even more powerful measurement campaign designs.

Ideally, each of the model component outputs would be directly testable with an instrument. Limitations in sampling (in space, time, and sensitivity) prevent complete coverage. The purpose of this section is to articulate available and high-priority, low-hanging new measurements suite that can cover as many of the model predictions as possible.

Errors are inherent in modeling and simulation work. These may be due to model physics shortcomings, the chaotic nature of the physical systems (both cloud and discharge processes), and errors in the measurements themselves.

The accurate prediction of thunderstorms within an otherwise favorable environment, the turbulent structure of internal thunderstorm flows, and the stochastic development of a lightning channel are all sources of uncertainty. A statistical approach is necessary to characterize an ensemble of flashes in an ensemble of storms, characterizing their predicted distribution functions.

Tracking of thunderstorms will be needed to characterize the storm population and the accuracy of model prediction of the distribution of storm properties. To these tracks can be attached microphysical properties measured by polarimetric weather radar, and the distribution of lightning flash properties within each storm.

Additional, targeted field campaign measurements can investigate internal storm properties, providing measurements not retrievable from operational measurements. These include rapidly updating, multi-frequency weather radar and in-situ balloon measurements of microphysics and electrostatic fields within storms, electric field change and radio interferometric measurements of lightning flash energetics and channel structure, in-situ penetrations with aircraft to characterize microphysics and chemistry, and overflights with research aircraft and balloons to measure the optical pulses produced by lightning from UV to near infrared. Ground teams can make similar optical, field change, and radio measurements to those from aircraft, characterizing both the upward and downward fluxes.

Any research-grade measurements can be operated in two modes: the first is semi-operational continuous observation from supersites, with a standard product suite targeted at validation of a standard model configuration. This mode enables a statistical validation approach. The second mode is to focus on individual storm case studies, accompanied by the highest-resolution model simulations that can be useful in targeted investigations of process physics and covariances between terms in the governing equations. Observation comparison can then enable attribution of causality for model errors, and model reruns focused on correcting physical deficiencies. Many of these needs are shared with NASA, NSF, NOAA and DOE-sponsored missions and field campaigns to understand uncertainties in fundamental cloud processes, chief among them 10-100% uncertainty in updraft magnitudes and attendant implications for mixed-phase cloud microphysical process rates driven by those updrafts.

Supplementing and aligning lightning modeling and observation efforts with other measurement campaigns studying deep convection is a powerful source of synergy. During field campaigns, special forecasting is often conducted to plan field operations, enabling real-time reflection on lightning forecasts produced by the model in a quasi-operational setting. It should also be an aim to more regularly include lightning modeling in other deep convection research studies as an additional validation parameter alongside radar and satellite measures of convective processes. The upcoming NASA INCUS campaign (Dolan et al. 2023) is one such opportunity.

Regional variability of storm modes and electrification behaviors is well documented in the literature. Therefore, a network of supersites and/or a succession of field campaigns is necessary to cover geographic and temporal variability in storm mode, range of flash rates, and discharge types. It may also be possible, at much lower cost, to retrospectively simulate and analyze older field campaign data; there are plausible targets of opportunity dating back to the STEPS-2000 campaign, which is the first with a good archive of 3D VHF lightning mapping arrays (LMAs) and research radar coverage. There are on the order of ten field campaigns in the last quarter century with similar measurements. Establishment of semi-operational LMAs since that time has also resulted in several 10-20 year long regional datasets with mapped channel structures that are suitable for re-forecasting with the holistic lightning model.

4. Concluding Remarks

This document has described a five-year effort to synthesize the current state of understanding of thunderstorm electrification and lightning into an integrated modeling system suitable for explicit physical forward modeling of electrostatic, radio, optical, and other observable signals produced by lightning.

Existing model components are sufficiently mature, and observational and computational capability sufficiently advanced, that the time is right to try to integrate these components and organize systematic comparisons to observations. The main body of this document outlines the inputs and outputs that must be generated at the interfaces between the major model components. Each component requires investment in routine use and development of data formats to support practical linkage, and to help resolve remaining uncertainties.

While uncertainties exist in all model components, the electrified weather modeling and sensor forward modeling pieces are relatively mature. The most significant need for investment is in the components related to lightning physics. Especially crucial are the streamer-leader and intra-cloud discharge modeling components, and their integration with a cloud modeling system, since they feed back into it. Outputs from the lightning physics model components are essential to driving the other sensor modeling efforts with realistic signals that are consistent with cloud structure during the lifecycle of a thunderstorm.

With this roadmap, it is now possible to envision investment in an open-source model of lightning sustained by a community of practice that can coordinate efforts to achieve the grand challenge of an end-to-end prediction of lightning, and its comparison to the plentiful lightning observations now available.

Appendices

Appendix 1: Energy conservation and outside-in process refinement as a modeling philosophy

As introduced in the Overview of Major Model Components, we favor an outside-in modeling approach, based on high-level energy conservation, and iterative process refinement driven by mismatches between higher-level models.

For lightning, many process models at finer scales have been developed, often spurred by measurements of a radio or optical signal at some characteristic time and space scale within the lightning discharge, so we know we will need to account for them within the higher-level constraints and observable phenomenology. In this way, we preserve the surest bet in physics (energy conservation), and a modeling capability that can handle whole-thunderstorm lifecycles, while nesting downward into greater process refinement to identify conflicting predictions, shortcomings, and opportunities to advance the high-level models.

Lightning develops within a quasi-electrostatic background field, where a large electric field is produced by a reservoir of electric potential created by space charge attached to hydrometeors inside and outside a cloud. Lightning rearranges this charge and reduces the electric field. Therefore, the highest-level viable, physical model of lightning would take the electrostatic background and reduce it accordance with its spatial distribution and energy content, with the lightning channel filling that volume of space in a relatively general way – and indeed this is what has been proposed by MacGorman et al. (2001), Fierroet al. (2013), and Fierroet al. (2015).

The next level of refinement are models like those of (Mansell et al. 2002). that produce a branched discharge without simulating how the channel ionizes or how current varies along it in detail. These models add the geometry of the channel, but no electrodynamic complexity. This lightning model is fully coupled to models of meteorological processes and hydrometeor electrification, with new discharges developing throughout the life of a storm, and can make predictions of the count of lightning flashes, their spatial extent, and their charge and energy consumption.

At the next stage of process refinement comes consideration of lightning plasma physics and electrodynamic processes (as well as relativistic processes), to predict the dynamics of current flows along lightning channel networks. While these finer-scale process models exist (Plooster 1971, Ripoll et al. 2014a, 2014b, , Da Silva et al. 2019), they have rarely been integrated into realistic storm lifecycles or charge distributions, and that integration is perhaps the greatest need so that comparison with the full suite of lightning observations can begin. The nature of lightning signals expected at (especially optical) sensors from meteorologically complex clouds and extensive discharges (and their more fundamental current flows) is among the largest motivators for an integrated lightning model.

Finally, a word about feedbacks between cloud dynamics and electricity: Electrical energy is thought to be extracted from the energy of convection, in some small enough fraction that feedbacks on cloud processes are not thought to be important (MacGorman and Rust 1998). In reality there may be some nuances related to (for example) removal of charge and electrical forces that impact the force balance on hydrometeors, which through drag affect the fluid flow.

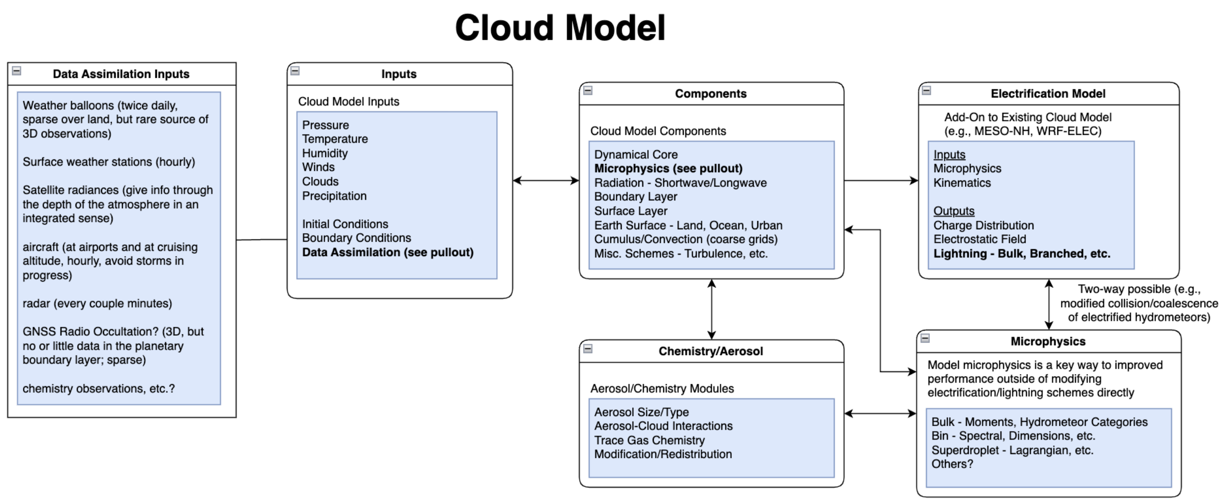
Also impacted are future latent heating fluxes to those hydrometeors as they take slightly different trajectories, as well as effects on collision/coalescence. We do not concern ourselves with them initially in this version of the roadmap, as this is expedient to produce a working, integrated model. However, some feedbacks between electrostatic and electrodynamic processes across model components may be necessary to model the lightning discharge itself.

Appendix 2: Configuration, functionality and operation of cloud models

The purpose of this Appendix is to provide background on the typical configuration choices made in operating cloud models. Because numerical weather prediction and idealized cloud models are themselves complex modeling systems, there is substantial art in operating these models that is known by a large community of practice. This is not a comprehensive review, but rather a practical guide to the choices stakeholders of the lightning model should be aware of when interacting with the cloud modeling component.

1. Configuration of the model
    a. Grid spacing in horizontal, vertical
        i. Require 3-4 km for convection-allowing, and ideally 125-250 m for LES
        ii. model skill ("resolution") is about 7x coarser than grid spacing. If we have a 200-m grid spacing simulation of the storm, resolved structures are >1.5 km, i.e., just within the inertial range (Bryan et al. 2003)
        iii. Higher-resolution "nested" models are recommended to maintain a 4:1 ratio or less in grid refinement
            1. e.g, 200 m horizontal nest inside 750 m nest inside 3 km HRRR
    b. Selection of options and parameters for model components (list in flowchart)
        i. Other choices known to have impacts:
            1. Topography and land use type (including flat / none)
            2. Cloud and precipitation microphysics parameterizations
            3. Sub-grid process models
            4. For idealized model initialization, choice of initial forcing for storm
2. Spinup
    a. As part of initialization from inputs each nest needs some hours of spinup to develop high-resolution features.
        i. Can include data assimilation during spinup, or allow to free run
        ii. Require maybe 4-6 hours model forecast time to spin up 750 m nest from 3 km, then another 4-6 hours for 200 km nest. Situation-dependent. Sensitivity tests are warranted.
    b. Cascade of energy to finer scales depends on terrain resolution, instability, and fine-scale data to assimilate. Without any of these, coarser features will persist on the higher-resolution grid
    c. For ongoing convection, frequent radar assimilation can speed up spin up; however, assimilating radar data more frequently than other observations biases the model toward them, improving radar-observed features but degrading others. We may prefer to spin up preconvective (pre-electrified) environment.
3. Forecast

   a. Update model boundary conditions consistent with initialization during forecast
   b. Output is configured at regular intervals that balance computational expense versus output frequency best needed to communicate with other models.
      i. Writing 3D data is much more expensive than performing in-line computations, so we need to be efficient and focus on only specific variables needed to communicate with other electrification-related models (e.g., streamer/leader simulations, etc.)
4. Data assimilation (DA)
   a. During a forecast, model state can be adjusted using information from new observations – a sort of continuing initialization (variational, Kalman approaches).
      i. See note in spinup section about biasing toward one dataset at expense of others by way of nonuniformity in spatiotemporal coverage.
   b. Right now, DA requires stopping the model, writing output, running a data assimilation scheme, restarting the model and reading. This is computationally expensive. In the future these will run seamlessly.
   c. DA datasets that are currently used and available
      i. Radiosondes (Operational sondes are twice daily and sparse over land and absent over water, but they are a rare source of vertically resolved observations. Field campaigns can provide improved spatiotemporal resolution over a limited domain.)
      ii. Surface weather stations (typically hourly)
      iii. Satellite radiances (give info through the depth of the atmosphere in an integrated sense)
      iv. aircraft (at airports and at cruising altitude, hourly, avoid storms in progress)
      v. radar (every few minutes)
      vi. GNSS Radio Occultation? (3D, but currently little to no data in the planetary boundary layer; sparse)
      vii. Lightning
      viii. Chemistry and aerosol observations (typically satellite or ground-based)
      ix. etc.



Appendix 3: Details of ground strike physics

The behavior of leader networks when they connect to ground, i.e., ground strikes, is a well studied area, and models of the associated return strokes are quite mature. This section summarizes these well-studied physics. Though physical processes may be different for other kinds of discharges, ultimately we would seek similar inputs and outputs from a more complete discharge model that incorporates intermediate current discharges.

In the case of a cloud-to-ground stroke a leader-like channel develops, rising from the ground to meet the leader network at an attachment point (or event). This creates a low resistance channel between the leader network (and any connected space charge in the cloud) and the ground that provides a path for the rapid rise in current flow in the channel. This current initially depletes the charge in the coronal sheath, and subsequently draws on the connected space charge at the opposite end of the channel.

The return stroke has these properties:

- A wavefront forms at the attachment point and travels up (and down) the channel at approximately 1/3 of the speed of light. The actual speed and propagation distance will depend on the physical properties of the leader channel.
- At the wavefront, charge is removed from the coronal sheath and passed down the conductive channel.
- Current in the conductive channel produces a rapid rise in the core temperature (to 30000 °K), and subsequent conversion of molecules to energized atoms.
- Internal energy is distributed over the component molecular and atomic species and their energy levels. Transition probabilities drive spectral outputs and line intensities.
- Photons generated in the hot core may be affected by the lower temperature ambient air, and conditions in the ambient air are affected by the core conditions.

- Special conditions are expected at points where the return stroke reaches a branch point in the leader network. Continuum light might be especially sensitive to these sources.

Appendix 4: Specific project ideas

In the course of developing this document, a few specific project ideas were raised by the authors. While not an exhaustive list, these ideas are captured here, and may include a mix of both practical first steps, as well as efforts that might be possible at end of a long development process.

Statistical parameterization of initiation, streamer-leader, and return stroke models:

- Use detailed initiation, streamer-leader and return stroke models to build a simplified statistical model that can be used with a cloud electrification model.

Testing cloud model details that might impact electrification

- Do km-scale (3 km) vs. LES scale (<1/3 km) simulations have significant impacts on predicted electrical structure and (after integration with other model components) predicted flash rates?
- How much do fluid-perturbed charge distributions in a full cloud model change the behavior of lightning from simple slab-charge models? The electric field relationship to turbulent thunderstorm flows and precipitation habits remains unclear.
- How well do cloud models reproduce extensive stratiform clouds and their precipitation rates, and do the available electrification schemes reproduce the electrical structures observed by in-situ balloon and airplane penetrations?
- The speeds of the vertical motions in clouds that drive precipitation formation are also a primary uncertainty in cloud models and observations. How do lessons learned from ongoing observational and modeling studies impact electrical predictions?

Appendix 5: 2024 Workshop Summary

A 60-person workshop held on 1-3 April 2024 in Albuquerque, NM reviewed existing approaches to modeling each of these physical sub-components, and discussed known capabilities, uncertainties and opportunities for improvement. The initial version of the roadmap was drafted following input from this workshop.

The workshop website, including like to invited speakers and breakout session reports, is available at http://lightning.ttu.edu/workshop/

The workshop panel, who also authored this document, is grateful for the talks given by these invited speakers at the April 2024 workshop, and for the contributions of all attendees during several hours of topical breakout sessions and plenary discussions.

- Joe Dwyer, University of New Hampshire

- Ted Mansell, NOAA National Severe Storms Laboratory
- Amitabh Nag, Los Alamos National Laboratory
- Caitano da Silva, New Mexico Tech
- Patrick Gatlin, NASA Marshall Space Flight Center
- Matthew Hopkins, Sandia National Laboratory
- Patrick McFarland, Penn State University
- Kristen Rasmussen, Colorado State University
- Xuan-Min Shao, Los Alamos National Laboratory
- Scott Wolff, United States Air Force

The panel is also grateful for substantive contributions from many of these individuals to a final review of this document, which uncovered additional references, stakeholders, and other improvements.

Workshop attendees had strong consensus that: (1) the constituent modeling capabilities are mature enough to pursue integrative activities, (2) computational capabilities are at a suitable scale to support the necessary model resolution, and (3) observations are in a golden age with high readiness to test each of the expected model outputs. Nevertheless, where it has been studied as an integrated whole there is a lack of temporal and spatial consistency between modeled systems and physical observations.

The workshop's four primary invited speakers together represent a concrete example of possible first steps toward integration. The Mansell cloud microphysics and electrification scheme is already integrated in widely used weather and cloud-scale forecast systems, and produces realistic, time evolving electric fields. These fields can be used to drive the relativistic field enhancement and flash initiation model of Dwyer. Development of leaders and current flows after flash initiation on a macro scale can be simulated by da Silva's model. The expected observable lightning signals resulting from these current flows are characterized by mature forward models, as described by Nag.

Potential feedbacks at the interface between different model components were discussed, as were initial experiments to couple meteorological, conventional breakdown (streamer), relativistic, and large-scale plasma leader models. Such experiments are also likely to lead to improved physical understanding: models are concrete, quantitative predictions of our best physical theories, so careful experiments at the interface identify inconsistencies alongside discrepancies from observations compared to each physical modeling component. The need for statistical approaches applied to ensembles of model predictions was emphasized. Coordination of practical, collaborative efforts across investigators who are used to making progress through smaller independent projects will also require investment of time and resources.

An observation suite to support validation was discussed. Cloud structures are known to vary significantly by climatological region, with charge structures and lightning varying accordingly, requiring observing at many sites. Instrument network designs for mapping leader activity across many radio bands are mature, as are those for measuring electric fields at the ground. A noted gap was in the observation of the internal four-dimensional variability within storms, including charge on individual hydrometeors and lightning emission spectra close to in-cloud sources, and how they evolve with time. New in situ instruments (perhaps swarms of small sondes) are desired. Spectrally resolved optical measurements are also under-developed, but are a growing area of interest due to their ability to discriminate streamer and leader temperatures and chemistry, and because of the growing prevalence of space-based optical lightning detection imagery. Coordination and execution of ongoing field and laboratory experiments targeted at modeling uncertainties will be a priority.

The multiple physical disciplines involved also intersect with modeling needs for other problem domains, such as laser scattering through realistic clouds, and modeling of realistic signals from explosions. The multi-scale nature of the problem will require careful scoping of the time and space scales of lightning under study.

In summary, model components exist that collectively can simulate many aspects of the lightning problem. The main work needed is to stitch them together, rather than reinventing the existing core modeling capabilities, and to compare integrated, multi-spectral radio and optical predictions from the model to well-designed field observations, both past and future.

References

Aich, V., Holzworth, R., Goodman, S., Kuleshov, Y., Price, C., and Williams, E. (2018). Lightning: A new essential climate variable. Eos, 99.

Attanasio, A., P. R. Krehbiel and C. L. da Silva (2019). "Griffiths and Phelps lightning initiation model, revisited." Journal of Geophysical Research: Atmospheres **124**(14): 8076-8094.

Baba, Y. and Rakov, V. A. (2007). Electromagnetic fields at the top of a tall build- ing associated with nearby lightning return strokes. IEEE Transactions on Electromagnetic Compatibility, 49(3):632–643.

Baba, Y., & Rakov, V. A. (2005). On the use of lumped sources in lightning return stroke models. Journal of Geophysical Research, 110, D03101. https://doi.org/10.1029/2004JD005202

Boccippio, Dennis J., Cummins, Kenneth L., Christian, Hugh J., & Goodman, Steven J. 2000. Combined Satellite- and Surface-Based Estimation of the Intracloud-Cloud-to-Ground Lightning Ratio over the Continental United States. Monthly Weather Review, 129, 108–122.

Bruning, E. C., Weiss, S. A., & Calhoun, K. M., 2014. Continuous variability in thunderstorm primary electrification and an evaluation of inverted-polarity terminology. Atmospheric Research, 135-136, 274–284.

Bruning, E. C. and MacGorman, D. R. (2013). Theory and observations of controls on lightning flash size spectra. J. Atmos. Sci., 70(12):4012–4029.

Brunner, K. N. and Bitzer, P. M. (2020). A first look at cloud inhomogeneity and its effect on lightning optical emission. Geophysical Research Letters, 47(10).

Buechler, D. E. and Goodman, S. J. (1990). Echo size and asymmetry: Impact on nexrad storm identification. Journal of Applied Meteorology, 29(9):962–969.

Cohen, M., et al., 2023: The Impacts of Lightning Beyond the Troposphere. Bulletin of the American Astronomical Society, 55, https://dx.doi.org/10.3847/25c2cfeb.1cd28060

Cressault, Y. (2015). "Basic knowledge on radiative and transport properties to begin in thermal plasmas modelling." AIP advances **5**(5).

Da Silva, C., R. Sonnenfeld, H. Edens, P. Krehbiel, M. Quick and W. Koshak (2019). "The plasma nature of lightning channels and the resulting nonlinear resistance." Journal of Geophysical Research: Atmospheres **124**(16): 9442-9463.

Da Silva, C., W. Winn, M. Taylor, G. Aulich, S. Hunyady, K. Eack, H. Edens, R. Sonnenfeld, P. Krehbiel and E. Eastvedt (2023). "Polarity asymmetries in rocket-triggered lightning." Geophysical Research Letters **50**(17): e2023GL105041.

Da Silva, C. L. and V. P. Pasko (2013). "Dynamics of streamer-to-leader transition at reduced air densities and its implications for propagation of lightning leaders and gigantic jets." Journal of Geophysical Research: Atmospheres **118**(24): 13,561-513,590.Emersic, C., 2006. Investigations into Thunderstorm Electrification Processes. PhD dissertation, University of Manchester (UK).

Dolan, B., Kollias, P., van den Heever, S. C., Rasmussen, K. L., Oue, M., Luke, E., Lamer, K., Treserras, B. P., Haddad, Z., Stephens, G., and Chandrasekar, V. (2023). Time resolved reflectivity measurements of convective clouds. Geophysical Research Letters, 50(22).

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." Monthly Weather Review **141**(7): 2390-2415.

Fierro, A. O., E. R. Mansell, C. L. Ziegler and D. R. MacGorman (2015). "Explicitly simulated electrification and lightning within a tropical cyclone based on the environment of Hurricane Isaac (2012)." Journal of the Atmospheric Sciences **72**(11): 4167-4193.

Garnung, M. B., Celestin, S., & Farges, T. (2021). HF-VHF electromagnetic emissions from collisions of sprite streamers. Journal of Geophysical Research: Space Physics, 126, e2020JA028824. https://doi.org/10.1029/2020JA028824

Griffiths, R. and C. Phelps (1976). "A model for lightning initiation arising from positive corona streamer development." Journal of Geophysical Research **81**(21): 3671-3676.

Helsdon Jr., J. H., G. Wu, and R. D. Farley (1992), An intracloud lightning parameterization scheme for a storm electrification model, J. Geophys. Res., 97(D5), 5865–5884, doi:10.1029/92JD00077.

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." Journal of Geophysical Research: Atmospheres **128**(23): e2023JD039104.

Khain, A. P., & Pinsky, M. (2018, July 5). Physical Processes in Clouds and Cloud Modeling. Cambridge University Press. https://doi.org/10.1017/9781139049481

Kostinskiy, A. Y., Marshall, T. C., and Stolzenburg, M. (2020). The mechanism of the origin and development of lightning from initiating event to initial breakdown pulses (v.2). Journal of Geophysical Research: Atmospheres, 125(22).

Krehbiel, P. R., J. A. Riousset, V. P. Pasko, R. J. Thomas, W. Rison, M. A. Stanley and H. E. Edens (2008). "Upward electrical discharges from thunderstorms." Nature Geoscience **1**(4): 233-237.

Krehbiel, P. R., M. Brook, And R. A. Mccrory (1979). An Analysis of the Charge Structure of Lightning Discharges to Ground. J. Geophys. Res., 84(C5).

Lac, C., Chaboureau, J. P., Masson, V., Pinty, J. P., Tulet, P., Escobar, J., ... & Wautelet, P. (2018). Overview of the Meso-NH model version 5.4 and its applications. Geoscientific Model Development, 11(5), 1929-1969.

Le Vine, D. M. (1987). Review of Measurements of the RF Spectrum of Radiation from Lightning. Meteorol. Atmos. Phys. 37, 195-204 (1987)

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

Li, D., Zhang, Q., Wang, Z., and Liu, T. (2014). Computation of lightning horizontal field over the two-dimensional rough ground by using the three-dimensional FDTD. IEEE Transactions on Electromagnetic Compatibility, 56(1):143–148.

Liu, Ningyu, Kosar, Burcu, Sadighi, Samaneh, Dwyer, Joseph R., & Rassoul, Hamid K. 2012. Formation of Streamer Discharges from an Isolated Ionization Column at Subbreakdown Conditions. Phys. Rev. Lett., 109(2).

Lyu, F., Cummer, Steven A., Briggs, Michael, Marisaldi, Martino, Blakeslee, Richard J., Bruning, Eric, Wilson, Jennifer G., Rison, William, Krehbiel, Paul, Lu, Gaopeng, Cramer, Eric, Fitzpatrick, Gerard, Mailyan, Bagrat, McBreen, Sheila, Roberts, Oliver J., & Stanbro, Matthew. 2016. Ground detection of terrestrial gamma ray flashes from distant radio signals. Geophys. Res. Lett., 43(16), 8728–8734. 2016GL070154.

Lyu, F., Cummer, S. A., & McTague, L. 2015. Insights into high peak current in-cloud lightning events during thunderstorms. Geophys. Res. Lett., 42(Aug.), 6836–6843.

MacGorman, D. R. and W. D. Rust (1998). The electrical nature of storms, Oxford University Press, USA.

MacGorman, D. R., J. M. Straka and C. L. Ziegler (2001). "A lightning parameterization for numerical cloud models." Journal of Applied Meteorology and Climatology **40**(3): 459-478.

Mansell, E. R., Ziegler, C. L., and Bruning, E. C. (2010). Simulated electrification of a small thunderstorm with two-moment bulk microphysics. J. Atmos. Sci., 67(1):171–194.

Mansell, E. R., MacGorman, D. R., Ziegler, C. L., and Straka, J. M. (2005). Charge structure and lightning sensitivity in a simulated multicell thunderstorm. J. Geophys. Res., 110(D12).

Mansell, E. R., D. R. MacGorman, C. L. Ziegler and J. M. Straka (2002). "Simulated three-dimensional branched lightning in a numerical thunderstorm model." Journal of Geophysical Research: Atmospheres **107**(D9): ACL 2-1-ACL 2-12.

Marisaldi, M., et al., 2024: Highly dynamic gamma-ray emissions are common in tropical thunderclouds. *Nature*, DOI: 10.1038/s41586-024-07936-6.

Marshall, Thomas C., McCarthy, Michael P., & Rust, W. David. 1995b. Electric Field Magnitudes and Lightning Initiation in Thunderstorms. J. Geophys. Res., 100(D4), 7097–7103.

Marshall, Thomas C., & Rust, W. David. 1991. Electric Field Soundings Through Thunderstorms. J. Geophys. Res., 96(D12), 22297–22306.

Matsui, T., Wolff, D. B., Lang, S., Mohr, K., Zhang, M., Xie, S., Tang, S., Saleeby, S. M., Posselt, D. J., Braun, S. A., Chern, J., Dolan, B., Pippitt, J. L., and Loftus, A. M. (2023). Systematic validation of ensemble cloud process simulations using polarimetric radar observations and simulator over the nasa wallops flight facility. Journal of Geophysical Research: Atmospheres, 128(16).

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., ... & Shi, W. (2006). North American regional reanalysis. Bulletin of the American Meteorological Society, 87(3), 343-360.

Morrison, H., Morales, A., and Villanueva-Birriel, C. (2015). Concurrent sensitivities of an idealized deep convective storm to parameterization of microphysics, horizontal grid resolution, and environmental static stability. Monthly Weather Review, 143(6):2082–2104.

Nag, A., Cummins, K. L., Plaisir, M. N., Brown, R. G., Wilson, J. G., Crawford, D. E., Noggle, R. C., Rassoul, H. K. (2023b), Characteristics of upward-connecting-leader current leading to attachment in downward negative cloud-to-ground lightning strokes, Atmospheric Research, Volume 294, https://doi.org/10.1016/j.atmosres.2023.106943.

Nag, A., Khounate, H., Cummins, K. L., Goldberg, D. J., Imam, A. Y., Plaisir, M. N., & Rassoul, H. K. (2023a). Parameters of the lightning attachment processes in a negative cloud-to-ground stroke observed on a microsecond timescale. Geophysical Research Letters, 50, e2023GL104196. https://doi.org/10.1029/2023GL104196

Nag, A., and Rakov, V. A. (2016), A unified engineering model of the first stroke in downward negative lightning, J. Geophys. Res. Atmos., 121, doi:10.1002/2015JD023777.

Nag, A., and Rakov, V. A. (2010a), Compact intracloud lightning discharges: 1. Mechanism of electromagnetic radiation and modeling, J. Geophys. Res., 115, D20102, doi:10.1029/2010JD014235.

Nag, A., and Rakov, V. A. (2010b), Compact intracloud lightning discharges: 2. Estimation of electrical parameters, J. Geophys. Res., 115, D20103, doi:10.1029/2010JD014237.

National Academies, 2017: Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space, The National Academies Press, Washington, DC, 700 pp., DOI 10.17226/24938.

Orbe, C., Oman, L. D., Strahan, S. E., Waugh, D. W., Pawson, S., Takacs, L. L., & Molod, A. M. (2017). Large-scale atmospheric transport in GEOS replay simulations. *Journal of Advances in Modeling Earth Systems*, *9*(7), 2545-2560.

Orville, R. E. and M. A. Uman (1965). "The optical continuum of lightning." Journal of Geophysical Research **70**(2): 279-282.

Østgaard, N., et al., 2024: Flickering Gamma Flashes – the Missing Link between Gamma Glows and Terrestrial Gamma-Ray Flashes. *Nature*, DOI: 10.1038/s41586-024-07893-0.

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): 2057.

Petersen, D., Bailey, M., Hallett, J., and Beasley, W. (2014). Laboratory investigation of corona initiation by ice crystals and its importance to lightning. Quarterly Journal of the Royal Meteorological Society, 141(689):1283–1293.

Petersen, D., Bailey, M., Hallett, J., and Beasley, W. H. (2006). Laboratory investi- gation of positive streamer discharges from simulated ice hydrometeors. Quarterly Journal of the Royal Meteorological Society, 132(615):263–273.

Peterson, M., Deierling, W., Liu, C., Mach, D., and Kalb, C. (2017). The properties of optical lightning flashes and the clouds they illuminate. Journal of Geophysical Research: Atmospheres, 122(1):423–442.

Plooster, M. N. (1971). "Numerical model of the return stroke of the lightning discharge." The Physics of Fluids **14**(10): 2124-2133.

Quick, M. G., Christian, H. J., Virts, K. S., & Blakeslee, R. J. (2020). Airborne radiometric validation of the geostationary lightning mapper using the Fly's Eye GLM Simulator. *Journal of Applied Remote Sensing*, *14*(4), 044518-044518.

Rasmussen, R. M., Chen, F., Liu, C. H., Ikeda, K., Prein, A., Kim, J., ... & Miguez-Macho, G. (2023). CONUS404: The NCAR–USGS 4-km long-term regional hydroclimate reanalysis over the CONUS. Bulletin of the American Meteorological Society, 104(8), E1382-E1408.

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, doi:10.1029/2006JD007621.

Rison, W., Krehbiel, P. R., Stock, M. G., Edens, H. E., Shao, X.-M., Thomas, R. J., Stanley, M. A., and Zhang, Y. (2016). Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms. Nat Commun, 7.

Ryzhkov, A. V., J. Snyder, J. T. Carlin, A. Khain, and M. Pinsky. 2020. What polarimetric weather radars offer to cloud modelers: Forward radar operators and microphysical/thermodynamic retrievals. Atmosphere 11(4):362. https://doi.org/10.3390/atmos11040362.

Sadighi, S., Liu, N., Dwyer, J. R., and Rassoul, H. K. (2015). Streamer formation and branching from model hydrometeors in subbreakdown conditions inside thunderclouds. Journal of Geophysical Research: Atmospheres, 120(9):3660–3678.

Shakirova, A., Nichman, L., Belacel, N., Nguyen, C., Bliankinshtein, N., Wolde, M., ... & Huang, Y. (2022). Multivariable Characterization of Atmospheric Environment with Data Collected in Flight. *Atmosphere*, *13*(10), 1715.

Stolzenburg, M., Rust, W. D., and Marshall, T. C. (1998). Electrical structure in thunderstorm convective regions 3. Synthesis. J. Geophys. Res., 103(D12):14097–14108.

Rakov, V. A., & Uman, M. A. (2003). Lightning physics and effects. Cambridge University Press.

Rakov, V. A., & Uman, M. A. (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

Rimboud, A., T. Farges, L. C-Labonnote, P. Dubuisson, C. Barthe and F. Thieuleux (2024). "3D Monte-Carlo simulations of lightning optical waveforms and images observable by on-board operational instruments." Journal of Quantitative Spectroscopy and Radiative Transfer **319**: 108950.

Ripoll, J.-F., J. Zinn, P. L. Colestock and C. A. Jeffery (2014b). "On the dynamics of hot air plasmas related to lightning discharges: 2. Electrodynamics." Journal of Geophysical Research: Atmospheres **119**(15): 9218-9235.

Ripoll, J.-F., J. Zinn, C. A. Jeffery and P. L. Colestock (2014a). "On the dynamics of hot air plasmas related to lightning discharges: 1. Gas dynamics." Journal of Geophysical Research: Atmospheres **119**(15): 9196-9217.

Sadighi, S. (2015). Initiation of Streamers from Thundercloud Hydrometeors and Implications to lightning initiation, Florida Institute of Technology.

Salinas, V., Bruning, E. C., and Mansell, E. R. (2022). Examining the kinematic structures within which lightning flashes are initiated using a cloud-resolving model. J. Atmos. Sci., 79(2):513–530.

Saunders, C. (2008). Charge generation and separation charge separation mechanisms in clouds. Space Sci. Rev., 137(1–4).

Shao, X. M. (2016). "Generalization of the lightning electromagnetic equations of Uman, McLain, and Krider based on Jefimenko equations." Journal of Geophysical Research: Atmospheres **121**(7): 3363-3371.

Shao, X.-M., Ho, C., Bowers, G., Blaine, W., & Dingus, B. (2020). Lightning interferometry uncertainty, beam steering interferometry, and evidence of lightning being ignited by a cosmic ray shower. Journal of Geophysical Research: Atmospheres, 125, e2019JD032273. https://doi.org/10.1029/2019JD032273

Shi, Feng, Liu, Ningyu, & Rassoul, Hamid K. 2016. Properties of relatively long streamers initiated from an isolated hydrometeor. J. Geophys. Res., 121, 7284–7295.

Simpson, G. and Scrase, F. J. (1937). The distribution of electricity in thunderclouds. Proc. Roy. Soc. London, Ser. A, 161:309–352.

Smith, T. M., and Coauthors, 2016: Multi-Radar Multi-Sensor (MRMS) Severe weather and aviation products: Initial operating capabilities. *Bull. Amer. Meteor. Soc.*, doi:10.1175/BAMS-D-14-00173.1.

Souza, J. C. S. and Bruning, E. C. (2021). Assessment of turbulence intensity in different spots of lightning flash propagation. Geophys. Res. Lett., 48(21):e2021GL095923.

Stensrud, D. J., M. Xue, L. J. Wicker, K. E. Kelleher, M. P. Foster, J. T. Schaefer, R. S. Schneider, S. G. Benjamin, S. S. Weygandt and J. T. Ferree (2009). "Convective-scale warn-on-forecast system: A vision for 2020." Bulletin of the American Meteorological Society **90**(10): 1487-1500.

Stolzenburg, M., Thomas C. Marshall, Sampath Bandara, Brian Hurley, Raymond Siedlecki, 2021. Ultra-high speed video observations of intracloud lightning flash initiation, Meteorology and Atmospheric Physics (2021) 133:1177–1202, https://doi.org/10.1007/s00703-021-00803-3

Stolzenburg, Maribeth, Marshall, Thomas C., Rust, W. David, Bruning, Eric, MacGorman, Donald R., & Hamlin, Timothy. 2007. Electric field values observed near lightning flash initiations. Geophys. Res. Lett., 34.

Takahashi, T. 1978. Riming electrification as a charge generation mechanism in thunderstorms. J. Atmos. Sci., 35, 1536–1548.

Tao, W.-K. and Moncrieff, M. W. (2009). Multiscale cloud system modeling. Reviews of Geophysics, 47(4).

Thomason, L. W. and Krider, E. P. (1982). The effects of clouds on the light produced by lightning. J. Atmos. Sci., 29:2051–2065.

Uman, M. A., D. K. McLain and E. P. Krider (1975). "The electromagnetic radiation from a finite antenna." Am. J. Phys **43**(1): 33-38.

Walker, T. D., & Christian, H. J. (2019). Triggered lightning spectroscopy: 2. A quantitative analysis. *Journal of Geophysical Research: Atmospheres*, 124, 3930–3942. https://doi.org/10.1029/2018JD029901

Villanueva, Y., Rakov, V., Uman, M., & Brook, M. (1994). Microsecond-scale electric field pulses in cloud lightning discharges. Journal of Geophysical Research, 99, 14353–14360. https://doi.org/10.1029/94JD01121

Watanabe, N., Nag, A., Diendorfer, G., Pichler, H., Schulz, W., Rakov, V. A., Rassoul, H. K. (2019), Characteristics of currents in upward lightning flashes initiated from the Gaisberg Tower, IEEE Transactions on EMC, Vol. 61, No. 3, https://doi.org/10.1109/TEMC.2019.2916047.

Watson, S. S., and T. C. Marshall (2007), Current propagation model for a narrow bipolar pulse, Geophys. Res. Lett., 34, L04816, doi:10.1029/2006GL027426.

Williams, E. R. (2006). Problems in lightning physics—the role of polarity asymmetry. Plasma Sources Sci. Technol., 15.

Winn, William P., Schwede, G. W., & Moore, C. B. 1974. Measurements of Electric Fields in Thunderclouds. J. Geophys. Res., 79(12)

Zhang, J., Howard, K., Langston, C., Kaney, B., Qi, Y., Tang, L., ... & Kitzmiller, D. (2016). Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimation: Initial operating capabilities. *Bulletin of the American Meteorological Society*, *97*(4), 621-638.

Zhang, X., J. H. Helsdon Jr., and R. D. Farley (2003), Numerical modeling of lightning-produced NOx using an explicit lightning scheme: 2. Three-dimensional simulation and expanded chemistry, J. Geophys. Res., 108, 4580, doi:10.1029/2002JD003225, D18.

Zhu, Y., Rakov, V. A., Tran, M. D., Lyu, W., & Micu, D. D. (2018). A modeling study of narrow electric field signatures produced by lightning strikes to tall towers. Journal of Geophysical Research: Atmospheres, 123, 10,260–10,277. https://doi.org/10.1029/2018JD028916

Zipser, E. J., and C. Liu. 2021. Extreme convection vs. extreme rainfall: A global view. Current Climate Change Reports 7(4):121-130. https://doi.org/10.1007/s40641-021-00176-0.