Thunderstorm Electric Field Modeling from Electrification to Terrestrial Gamma-ray Flash Production

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Abstract

Knowledge of the electric field structures inside thunderstorms is necessary for understanding of thunderstorm electrification, lightning initiation, and terrestrial gamma-ray flash (TGF) production. However, existing knowledge comes largely from weather balloon measurements that provide a limited view that entangles motion of the balloon (spatial variability) with overall evolution of the storm (temporal variability). More advanced interpretation of such data and connection of it to the broader context requires comprehensive modeling of the full process. We describe such a model, built on simple approximations of electrification processes, the resulting currents, charge structures, and electric fields, including a crude probabilistic lightning model. The result is a reasonably realistic model of thunderstorm field and its evolution that can be used to predict possible balloon measurements of electric field, with results that are in good qualitative agreement with existing balloon data. The resulting electric field is then also used as input to a Geant4 simulation of relativistic electron behavior to understand when and where TGF production is likely to occur in the dynamic thunderstorm electric field. The combination of meteorological drivers of electrification, constrained by comparison to balloon data, and in turn how they may give rise to TGFs, provides a unique tool to aid in our understanding of such processes and how they are linked.

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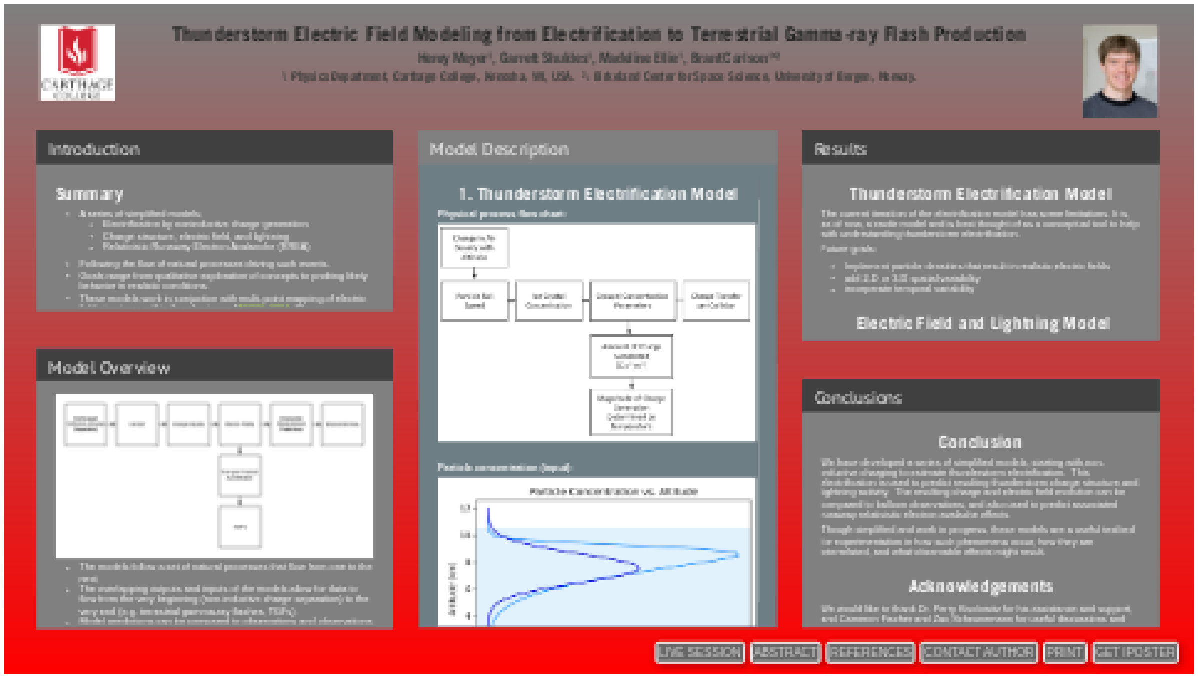

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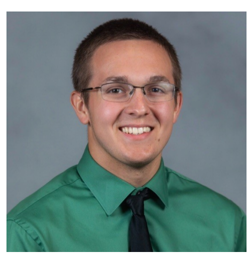


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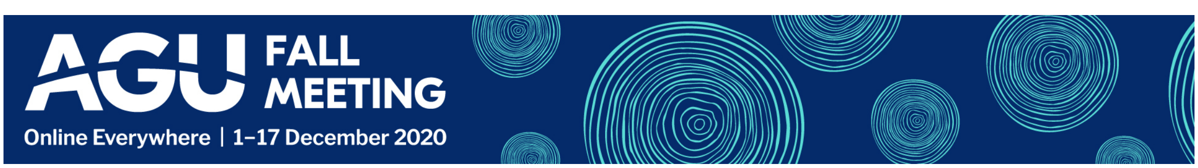


INTRODUCTION

Summary

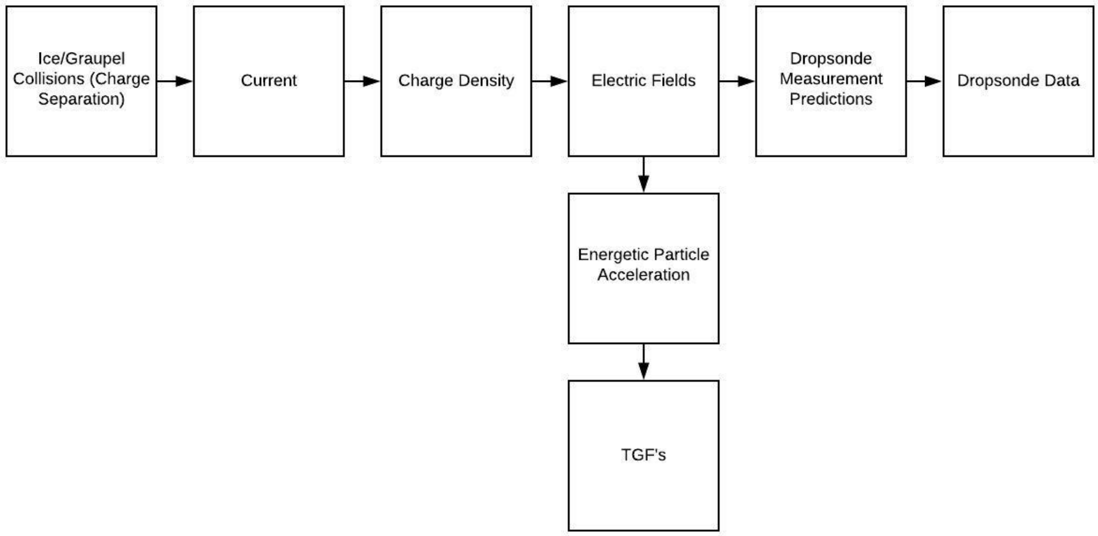
- A series of simplified models:
  - Electrification by noninductive charge generation
  - Charge structure, electric field, and lightning
  - Relativistic Runaway Electron Avalanche (RREA)
- Following the flow of natural processes driving such events.
- Goals range from qualitative exploration of concepts to probing likely behavior in realistic conditions.
- These models work in conjuction with multi-point mapping of electric field structures within thunderstorms [AE008-0004 (/Default.aspx?s=DA-94-D1-B4-BD-E8-86-1A-99-96-D2-68-C0-26-CC-02), 2].

Introduction

The true charge structure and geometry of thunderstorms is still a topic of some debate. Thunderstorms evolve with time, but most current observations inescapably link spatial and temporal variability of the charge structure. This lack of data separating spatial and temporal variability has led to relatively little analysis of the effects of such combined variability.

This project aims to produce a comprehensive model of electrification, lightning, and associated energetic particle effects to help interpret data that separates spatial and temporal variability. A related undergraduate research project [AE008-0004 (/Default.aspx?s=DA-94-D1-B4-BD-E8-86-1A-99-96-D2-68-C0-26-CC-02)] aims to develop instruments to collect such data. Together, these projects hope to help develop a comprehensive understanding of the thunderstorm electrical environment.

MODEL OVERVIEW

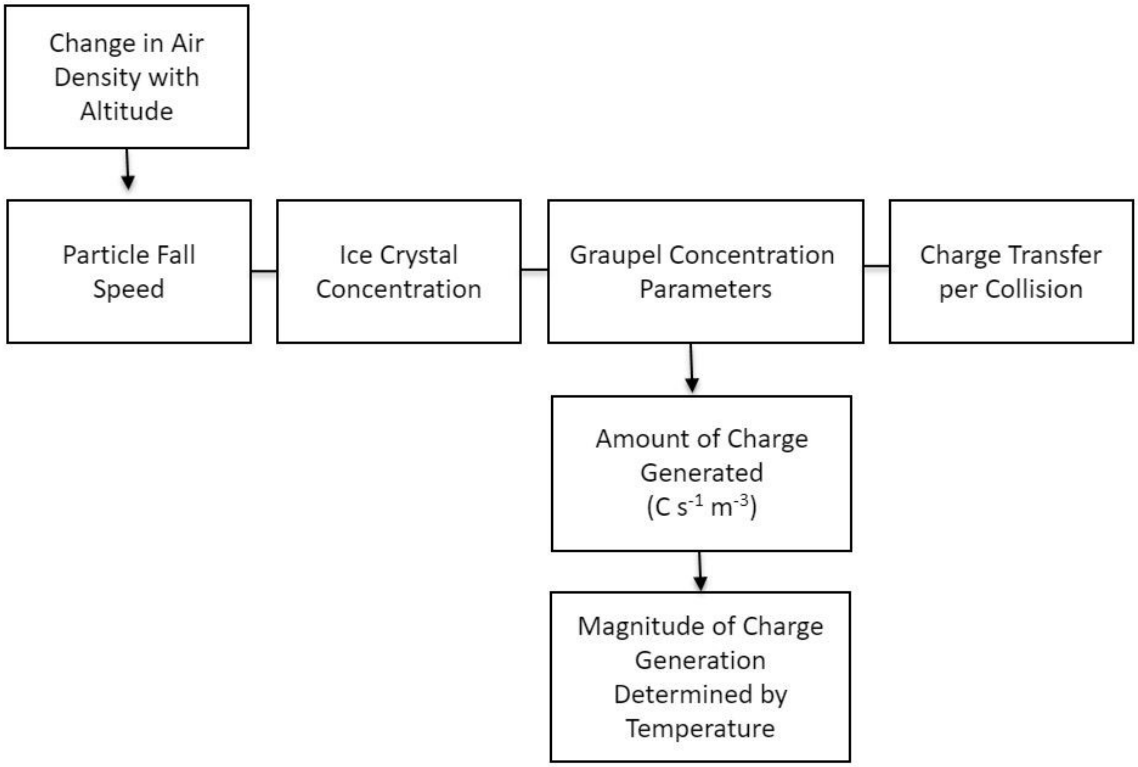


- The models follow a set of natural processes that flow from one to the next
- The overlapping outputs and inputs of the models allow for data to flow from the very beginning (non-inductive charge separation) to the very end (e.g. terrestrial gamma-ray flashes, TGFs).
- Model predictions can be compared to observations and observations can be used to constrain model parameters.
- The electrification, electric field, and lighting models are built using Python.
- The RREA model is built in C++ using Geant4 [1].

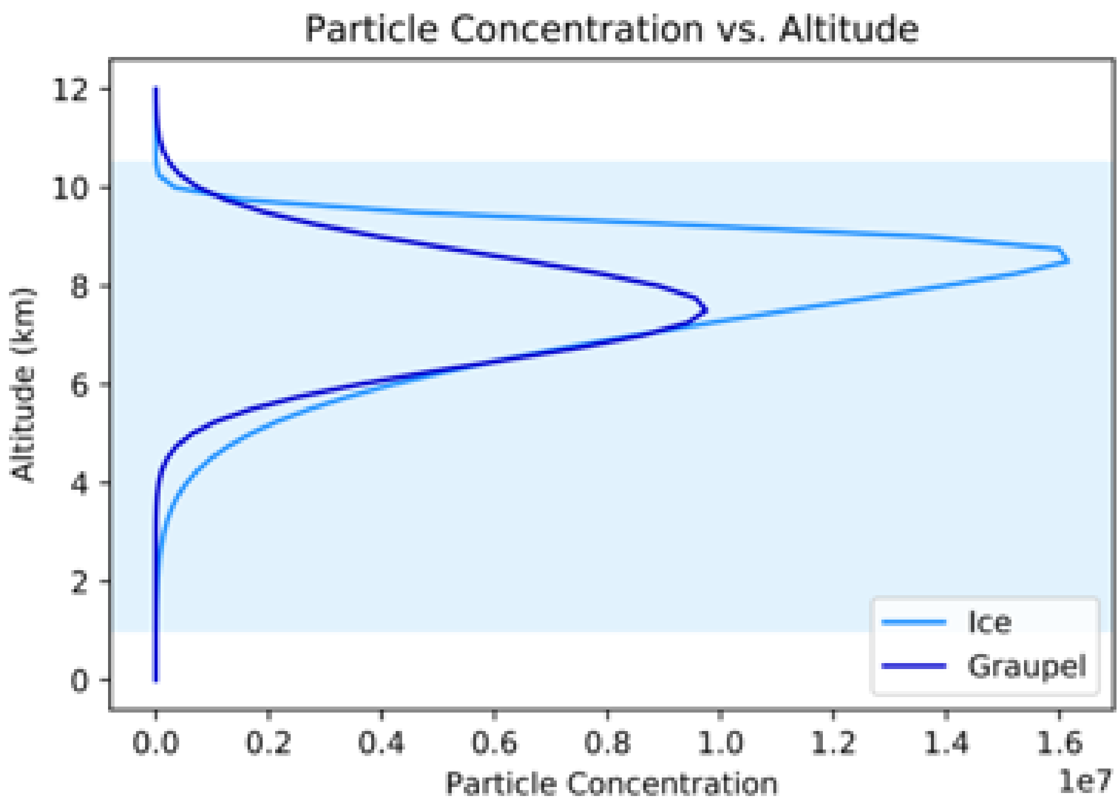
MODEL DESCRIPTION

1. Thunderstorm Electrification Model

Physical process flow chart:

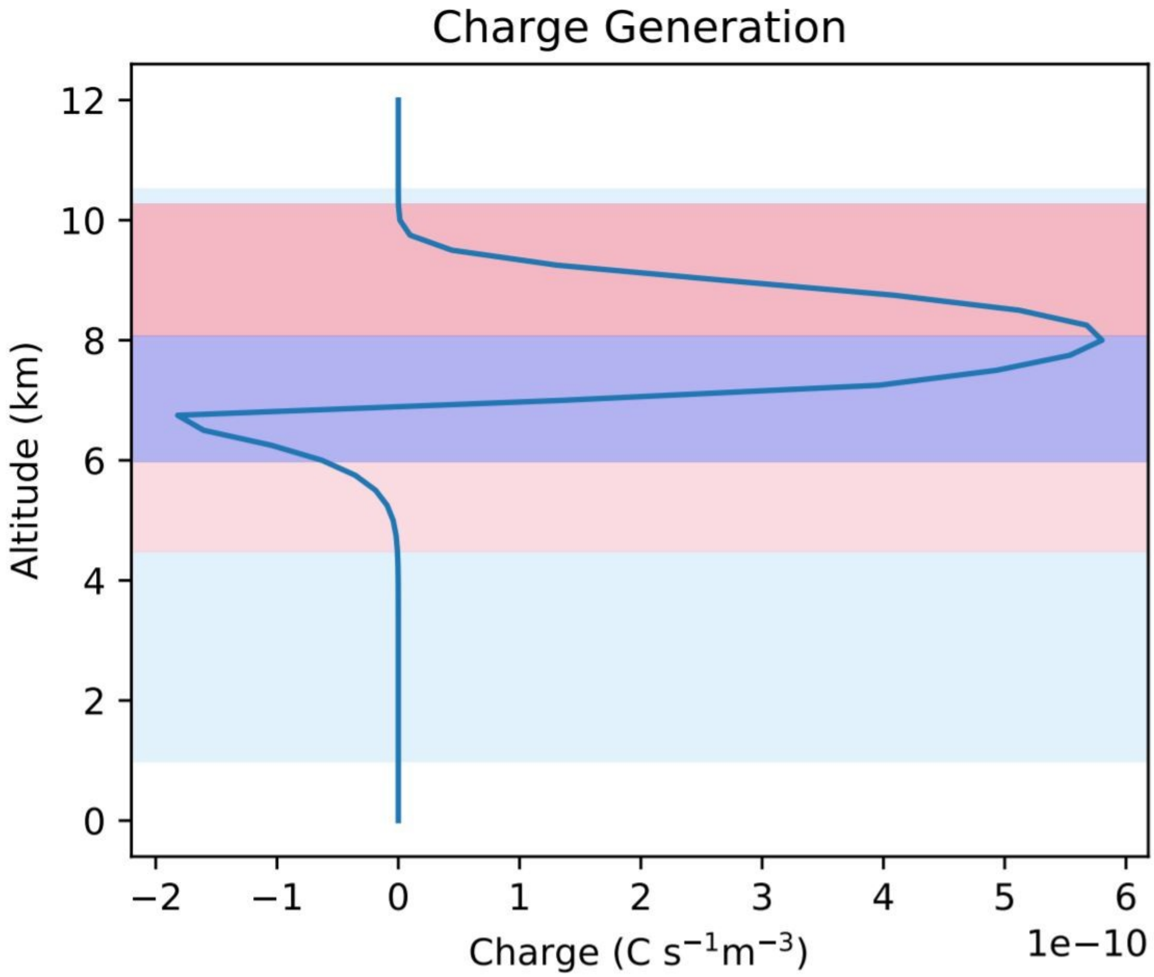


Particle concentration (input):



Charge generation:

- This charge structure is connected to the particle concentration via equations used in Ziegler's 1991 model [5]
- Reversal enforced artificially.

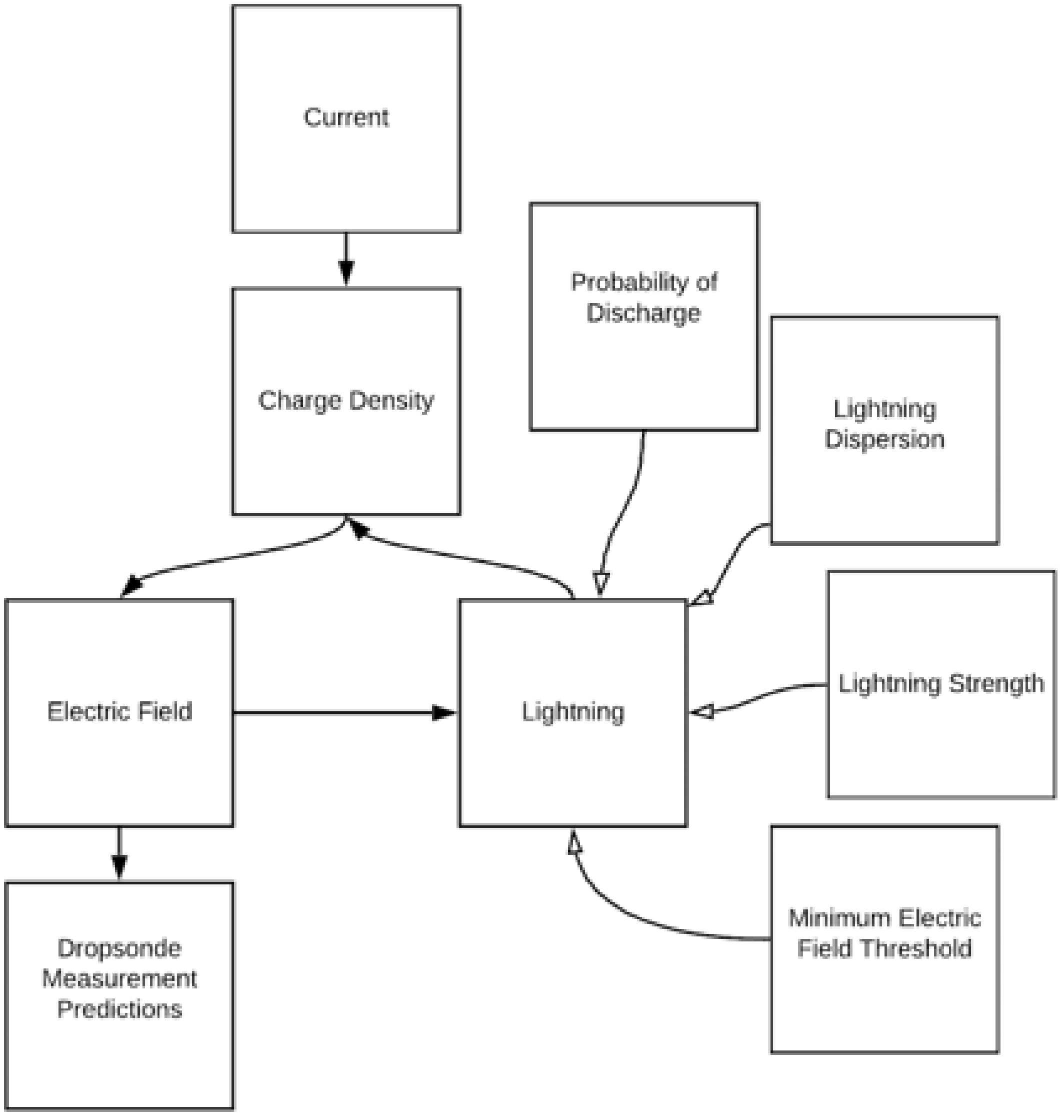


- Built using Python (JuPyter notebook) for easy experimentation.
- Resulting charge generation reproduces the classical tripole structure known to exist in thunderstorms.
- Charge generation provided as input to electric field and lightning model.

2. Electric Field and Lightning Model

- Accepts charge generation as input from the preceding model.
- Simulates the resulting evolution a thunderstorm

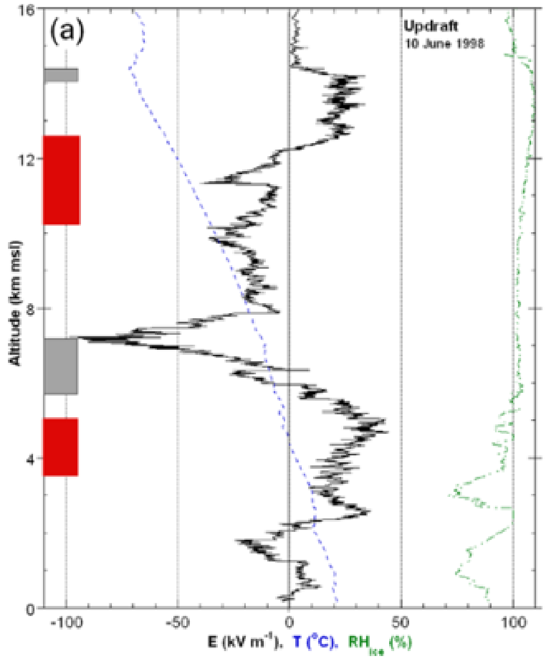
Simulation flow chart:



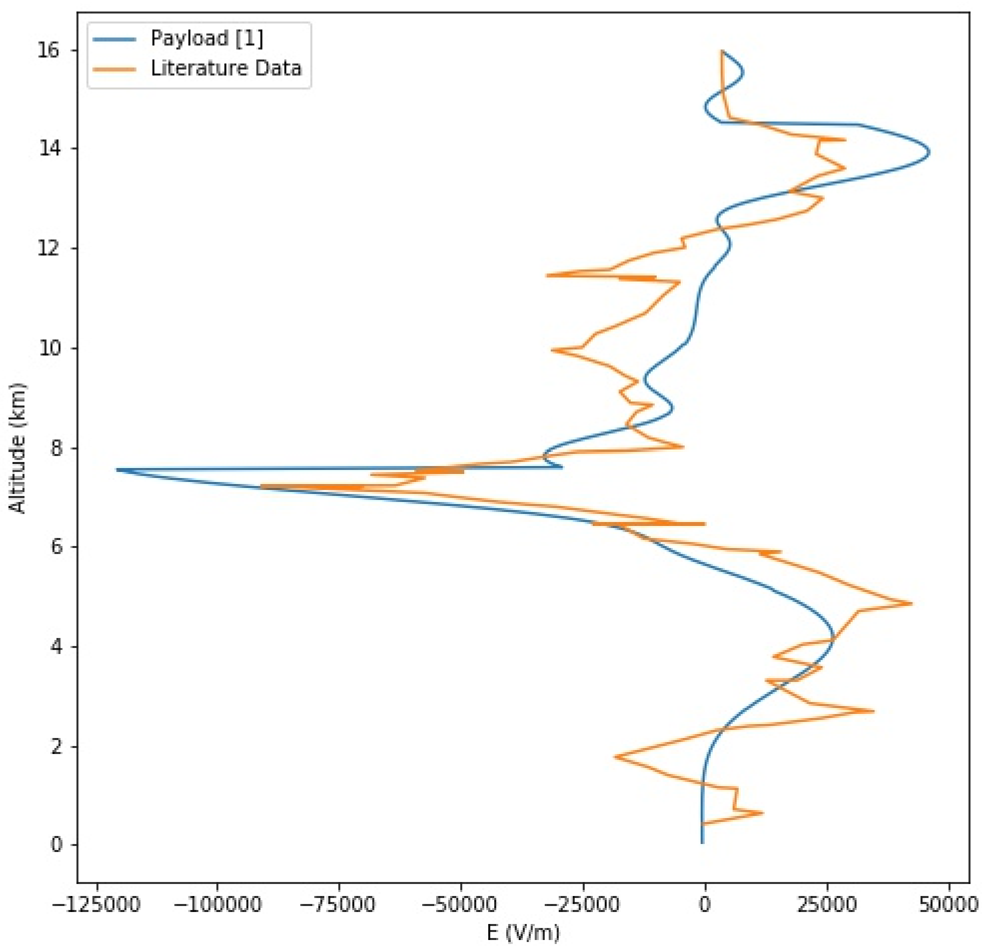
- Many parameters, tuning is possible and expected.
- Crude Lightning Model
  - Two Types of Discharge:
    - Primary: Occurs when the Electric Field exceeds 284kV/m.
    - Secondary: Occurs only after a primary discharge, and if the Electric FIeld still exceeds 100 kV/m.
    - Field thresholds scaled to relevant altitudes.
- Continue cycle for desired duration of simulation.
- Can simulate expected balloon observations.

Sample observations and (fine-tuned) simulation compared

Observations from Stolzenburg and Marshall [4]:



Predicted balloon observations compared to observations:



- Electric field profile and time evolution provided as input to Runaway Relativistic Electron Avalanche (RREA) model

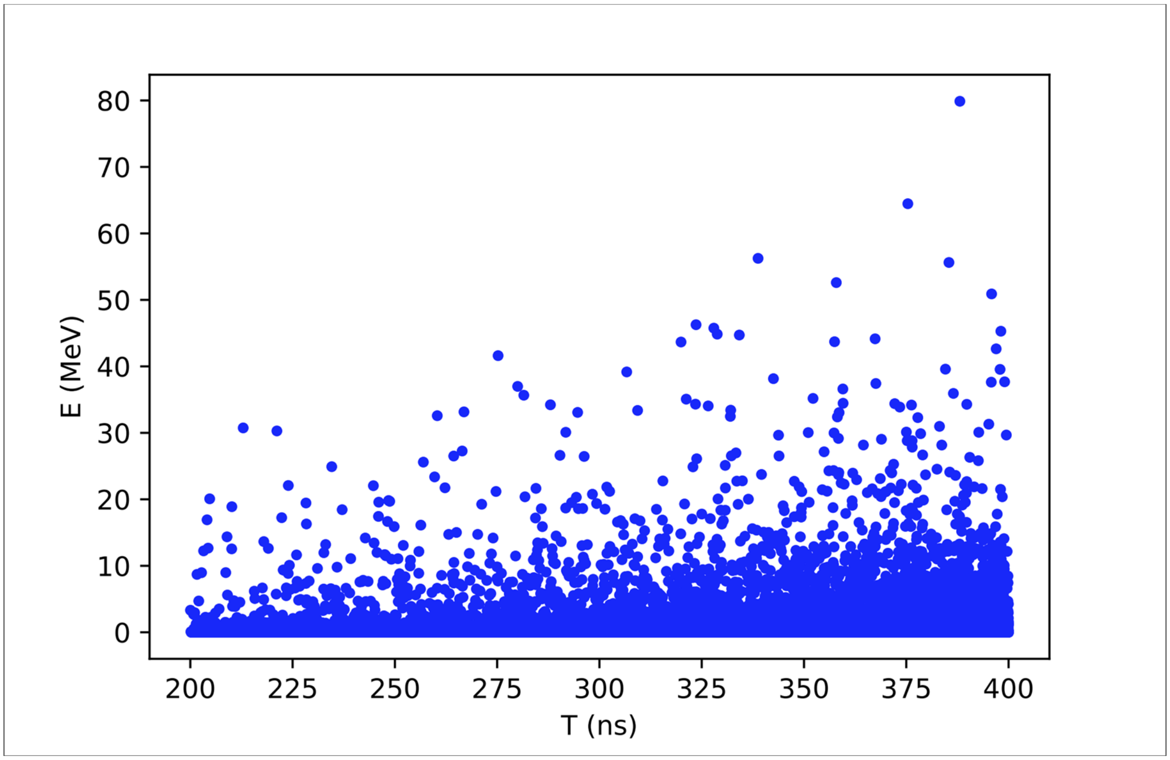
3. RREA model

- Plan to accept electric field from electric field and lightning model.
- Built in C++ using Geant 4. [1]
- Currently the model simulates a volume of air with uniform electric field and 100 electrons.

Sample Simulation

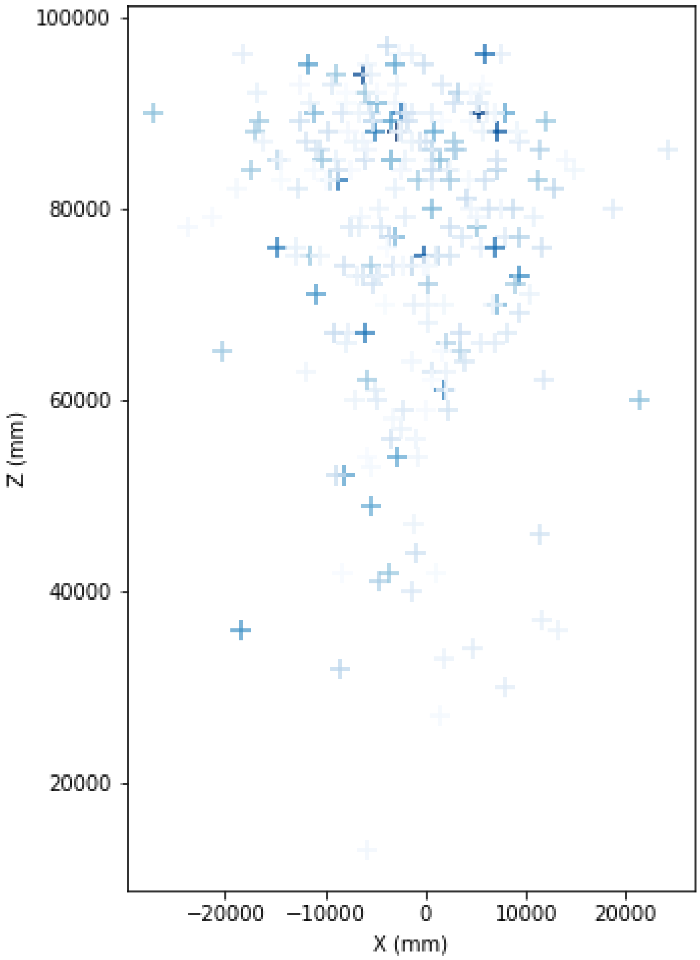
- Uniform Electric Field of 284 kV/m
- time limit of 10 microseconds

Photon production, energy vs time:



- Demonstrates clear population and energy growth

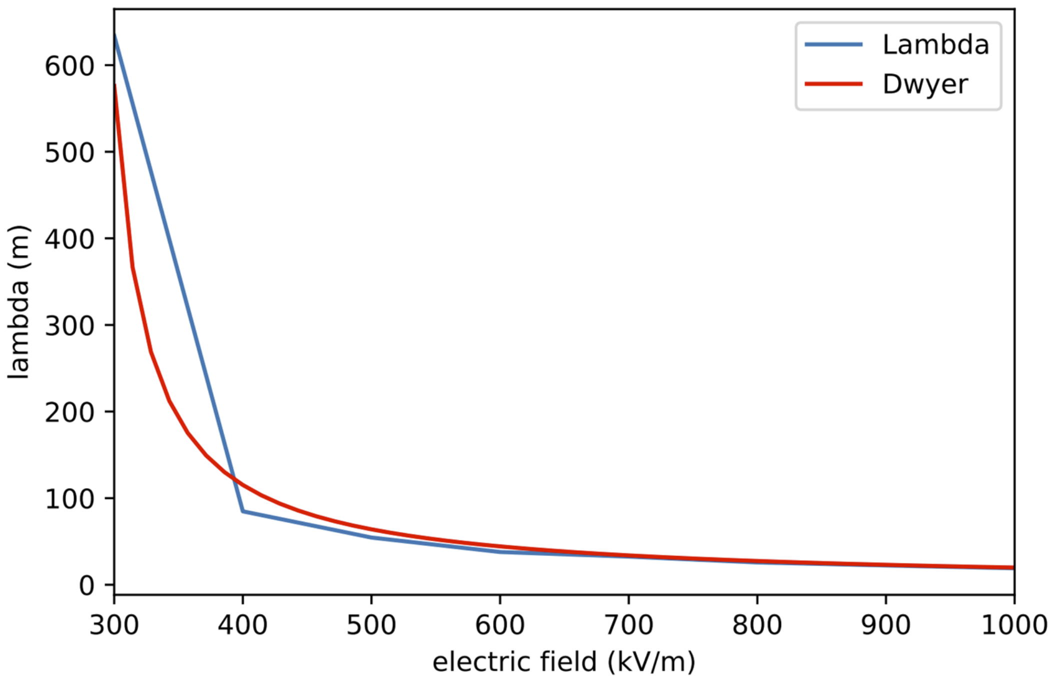
Photon production positions (colored by energy):



- This figure provides a visual representation of the two-dimensional spatial distribution of energetic photons produced in the TGF event
- The saturation of the color corresponds with the initial energy of the photon
- Again shows clear avalanche growth.

Model Validation

Comparison of model growth to Dwyer [3] empirical formula



- This figure shows the avalanche growth scale vs. electric field strength.
- Empirical formula for comparison from Dwyer [3]: $\lambda = \frac{7200\ \mathrm{kV}}{E-(275\ \mathrm{kV/m})}$
- The data collected to compute the growth scale was collected across 10 runs, each time incrementing the strength of the electric field by a factor of 100 kV/m.
- For stronger electric fields shorter time limits were necessary to prevent memory overflow. Fortunately, the data necessary for compute the growth scale can be collected in a shorter time period for stronger electric fields.
- Results Follow the empirical growth scale given in Dwyer's 2003 publication [3], but a correction factor of 1/2 is necessary for unknown reasons.

RESULTS

Thunderstorm Electrification Model

The current iteration of the electrification model has some limitations. It is, as of now, a crude model and is best thought of as a conceptual tool to help with understanding thunderstorm electrification.

Future goals:

- Implement particle densities that result in realistic electric fields
- add 2-D or 3-D spatial variability
- incorperate temporal variability

Electric Field and Lightning Model

The electric field and lightning model is currently one-dimensional, only capturing vertical structure. While this allows for comparison to existing data, but lateral structure may also prove to be important. This model was created for analysis and interpretation of existing data and to study limitations of the interpretations of such data. The model can also be used be used to test the accuracy of the Dropsonde experiment described in [AE008-0004 (/Default.aspx?s=DA-94-D1-B4-BD-E8-86-1A-99-96-D2-68-C0-26-CC-02), 2]

Future goals:

- Incorporate the added complexity of two-dimensional or three-dimensional spatial variability in electric fields.
- Introduce a more sophisticated lightning model to better represent the reality of a thunderstorm.

RREA Model

The model is currently limited to short durations for single runs as needed to run on a personal computer with a reasonable amount of memory. It does not currently incorporate the temporally or spatial variability of the electric that is present in a real thunderstorm.

Future goals:

- Implementation of a vertically and temporally variable electric field from electric field model.
- Measurement of relativistic feedback effects.
- Prediction of radiation production, dose, and observable effects.
- Optimizations to allow for larger simulations with limited computational resources.

CONCLUSIONS

Conclusion

We have developed a series of simplified models, starting with non-inductive charging to estimate thunderstorm electrification. This electrification is used to predict resulting thunderstorm charge structure and lightning activity. The resulting charge and electric field evolution can be compared to balloon observations, and also used to predict associated runaway relativistic electron avalache effects.

Though simplified and work in progress, these models are a useful testbed for experimentation in how such phenomena occur, how they are interrelated, and what observable effects might result.

Acknowledgements

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