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Lightning optical emission: Monte Carlo modeling of signal propagation in complex microphysics

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Model Introduction

Signal propagation: how does light from lightning behave once it is emitted

- Monte Carlo methods for propagation

- Phase function approximation: Phase function describes the distribution of scattering angles
  - An approximated phase function performs similarly to <u>the phase function</u>*

- The scattering environment is described using modeled microphysics
  - <u>Heterogeneous microphysics</u>* is the most important component, and controls how and where light exits the cloud

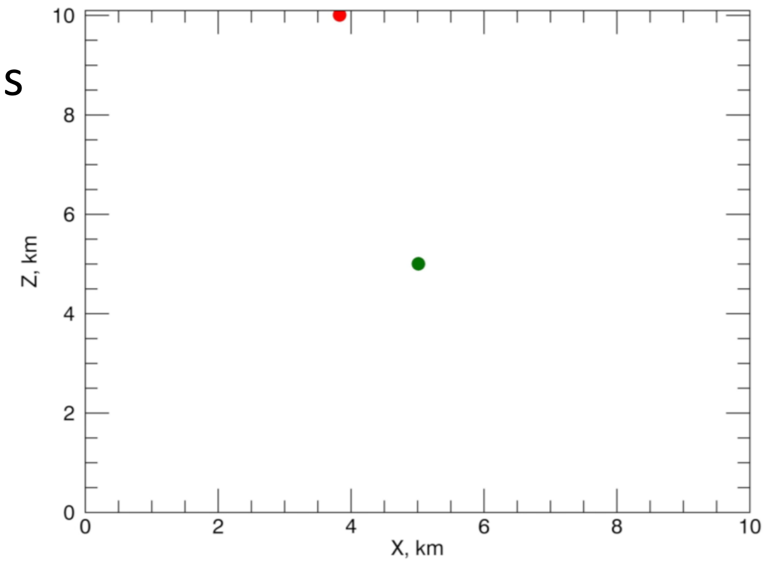
- <u>Where/Amount of light emitted</u>* can be scaled by charge neutralized, optical pulse, user input
  - Charge neutralized and channel orientation is simulated using the branched lightning model (Mansell, et al, 2002)

- Space and Time constraints:
  - No limits within the scattering, but the microphysics are limited to model resolution (1km for WRF, 125m for COMMAS).

Physical Approach: Monte Carlo Methods

- ‘Photons’ are released isotropically, travel a <u>distance</u>, reach a scatterer and interact by:
  - Scattering a into a <u>direction</u>
  - Being <u>absorbed</u>

This process is repeated until ‘photons’ are absorbed or a cloud boundary is reached.



- The ‘distance’ : a randomly determined portion of the Mean Free Path (Λ)
  - MFP is a function of microphysics: diameter and concentration

- The ‘direction’ : randomly selected via the Mie approximating Henyey-Greenstein phase function
  - HG is a function of the asymmetry factor: g, dependent on the size, wavelength, and refractive indices

- When absorbed: randomly determined, the probability is controlled by $1-\omega_0$, a function of the absorption coefficient, wavelength and microphysics

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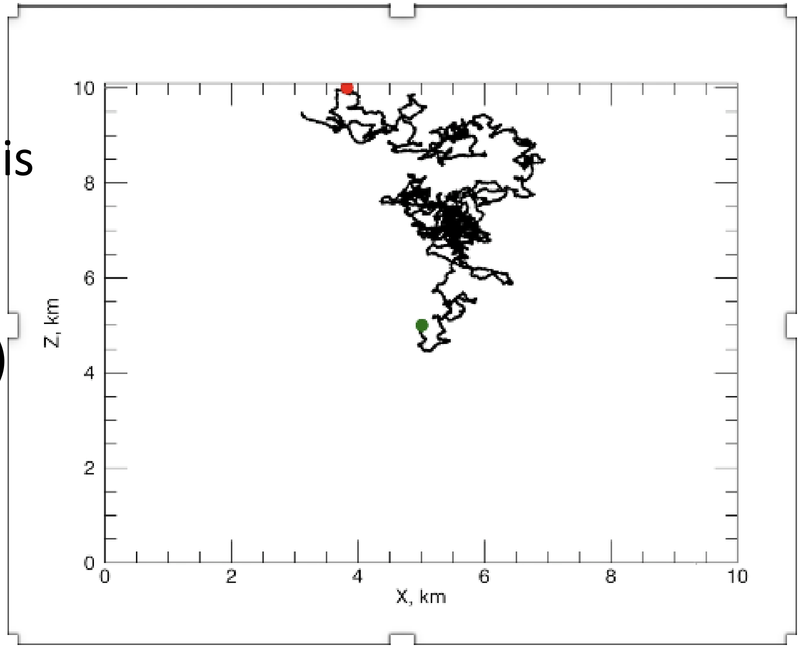

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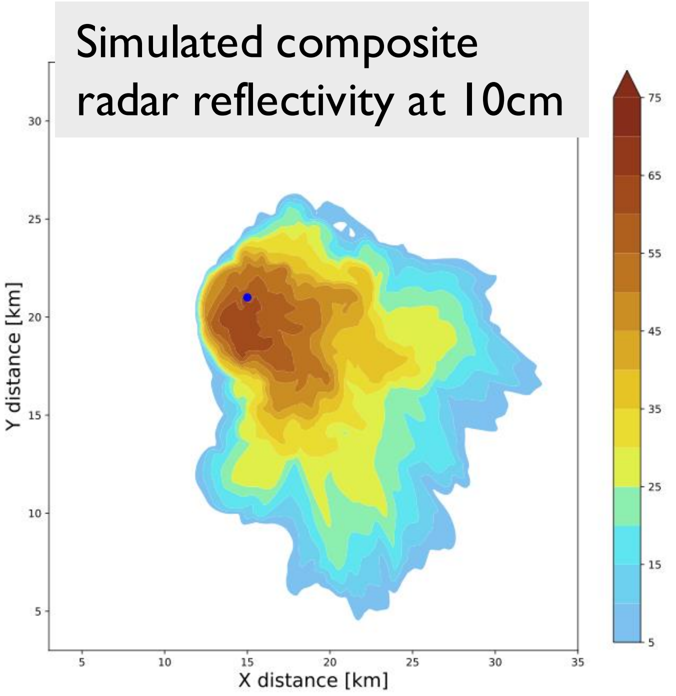
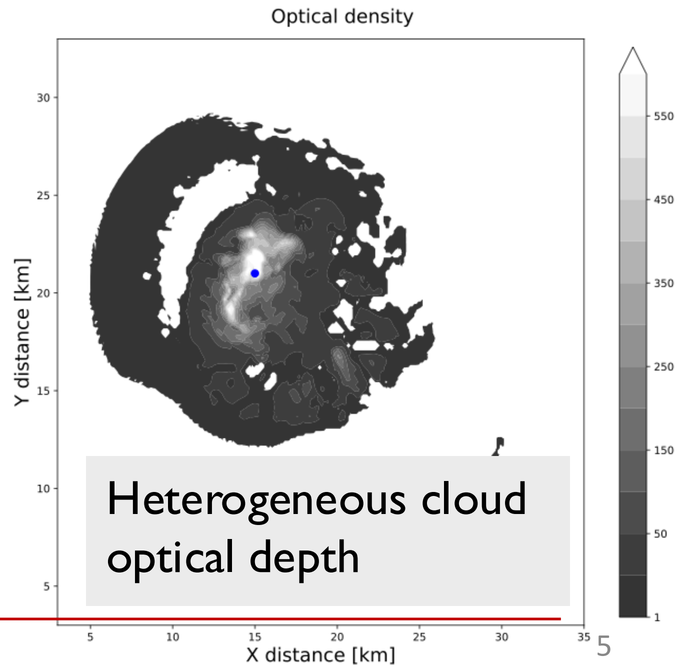
Physical Approach: Microphysics

- The model ingests microphysics by the mean free path: $\Lambda = \dfrac{1}{2\pi a^2 N}$
  - NSSL 2-moment gives 6 species: droplets, rain, ice, hail, graupel, snow
  - For each model gridpoint we find the MFP where:
    - a is the concentration-weighted mean radius
    - N is the number concentration
  - Cloud is defined by all microphysical species: 200m MFP
- Current simulations: COMMAS 125m/30s of 2015 July 10th Case (Brothers et al, 2018)

Atmospheric Scientist: **Radar reflectivity**
Optical/Scattering: **Cloud optical depth**

Neither fully describe the environment





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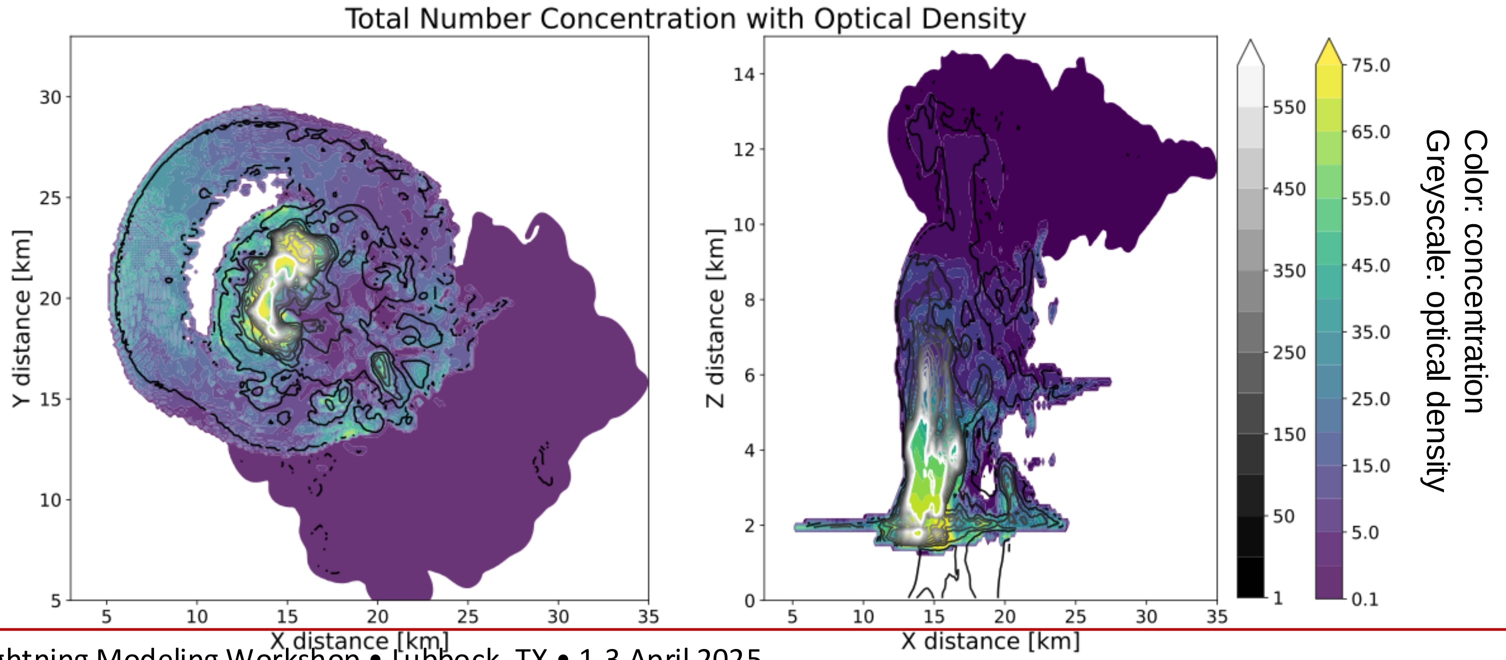
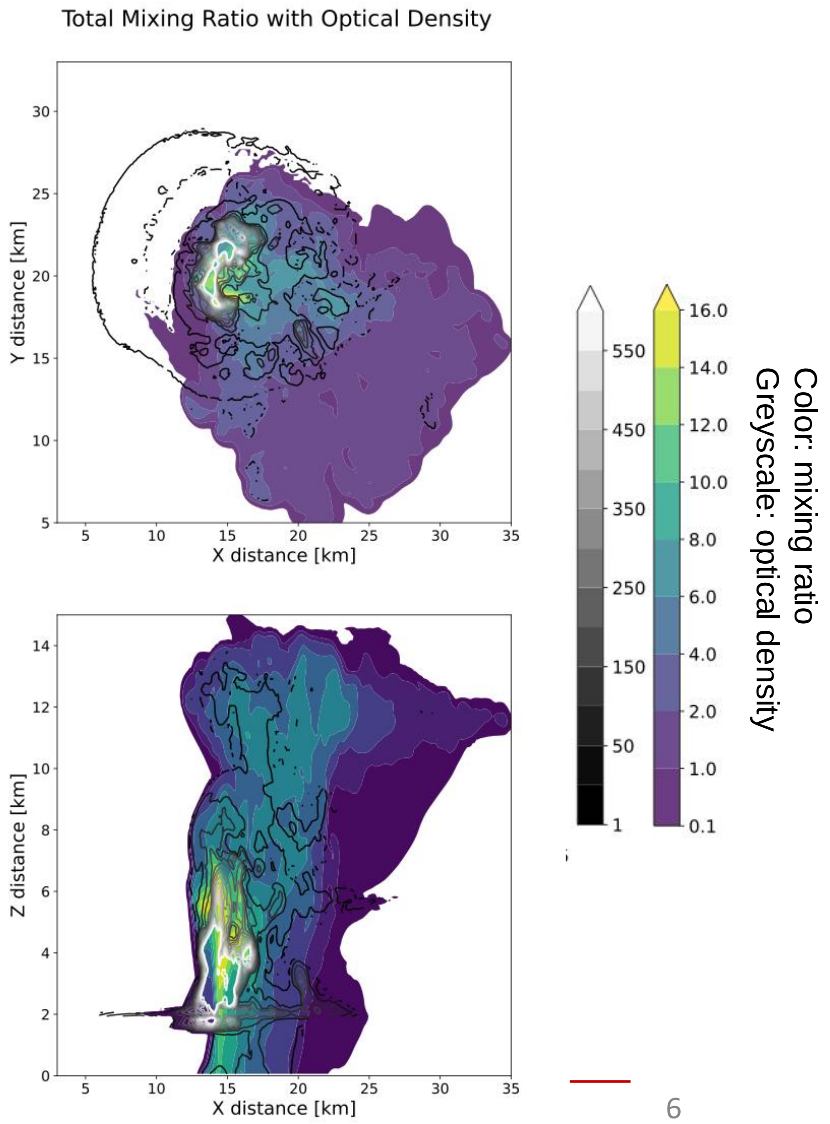




Model Use: Heterogeneous Microphysics

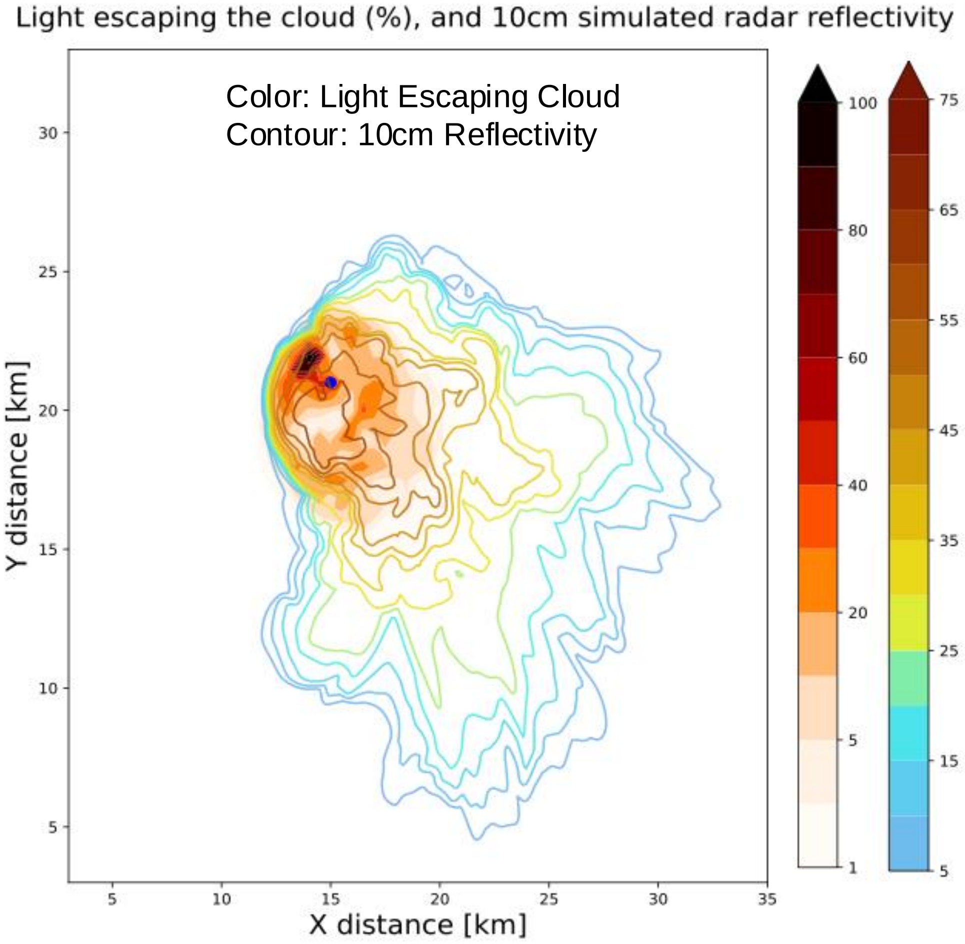
Determining microphysical controls on optical emission in 777nm/337nm

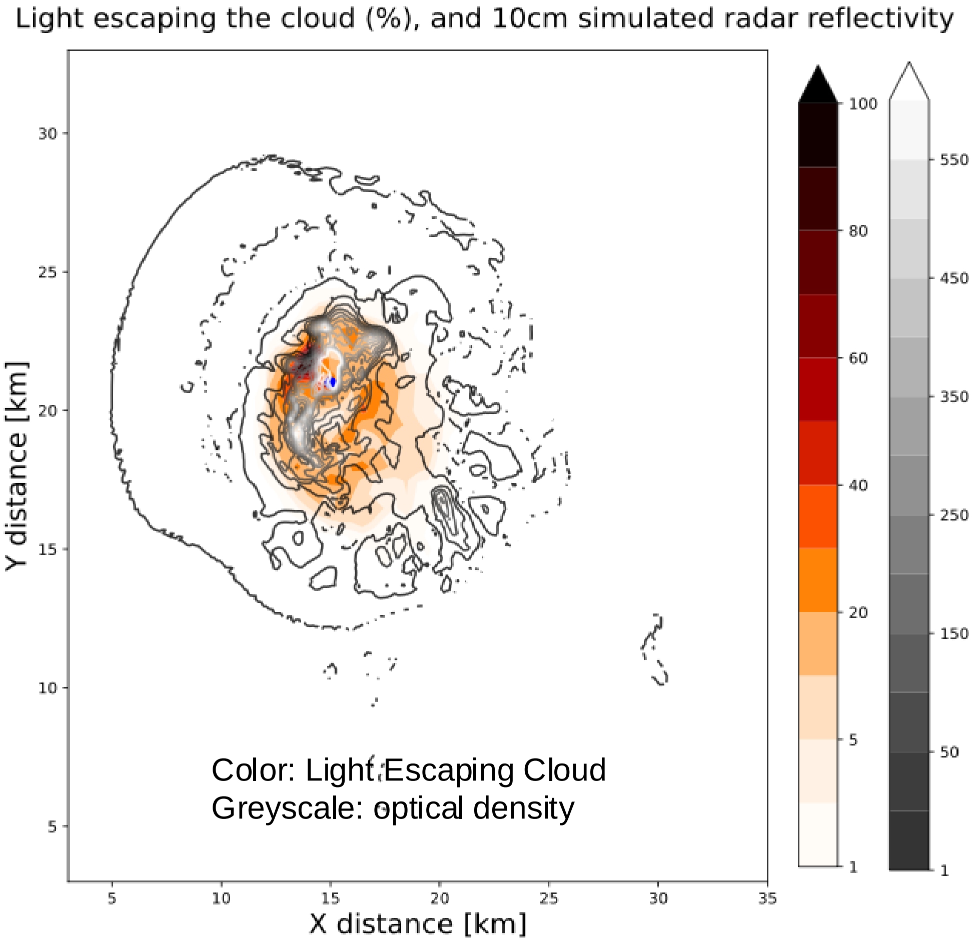
Why are heterogeneous microphysics important?

Characterizing the time of flight

Is there a spatial offset between emission and cloud exit?

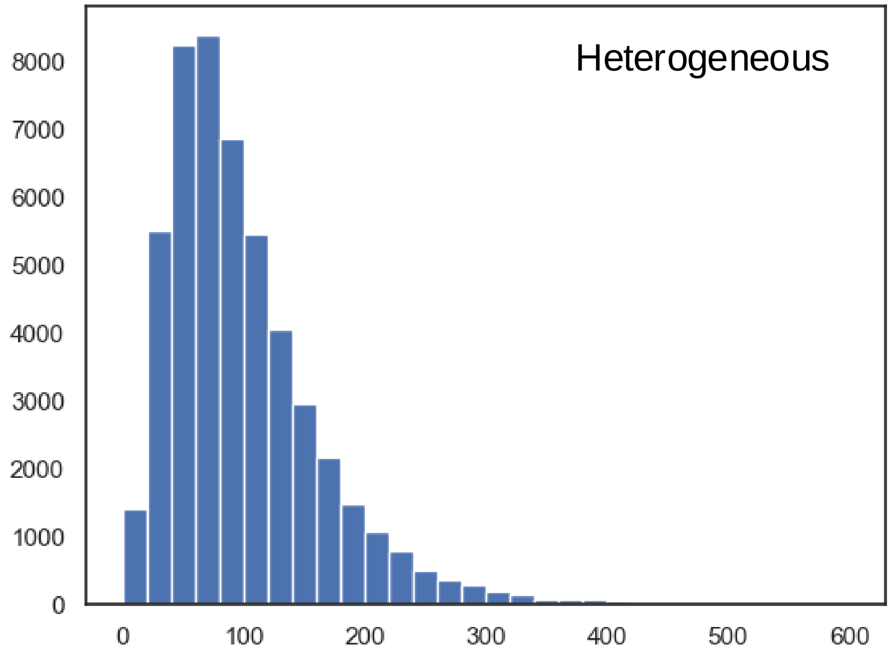
How can we validate the model?

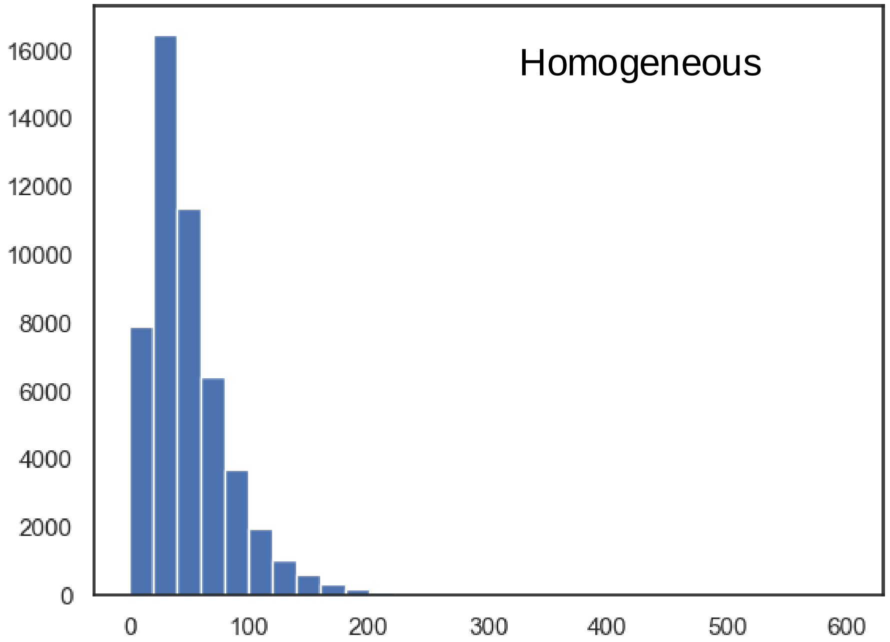




Model Use: Heterogeneous Microphysics

- Uniform simulations at a single level
- The time of flight follows the optical density gradient
- Quantify mean time of flight based on the optical density





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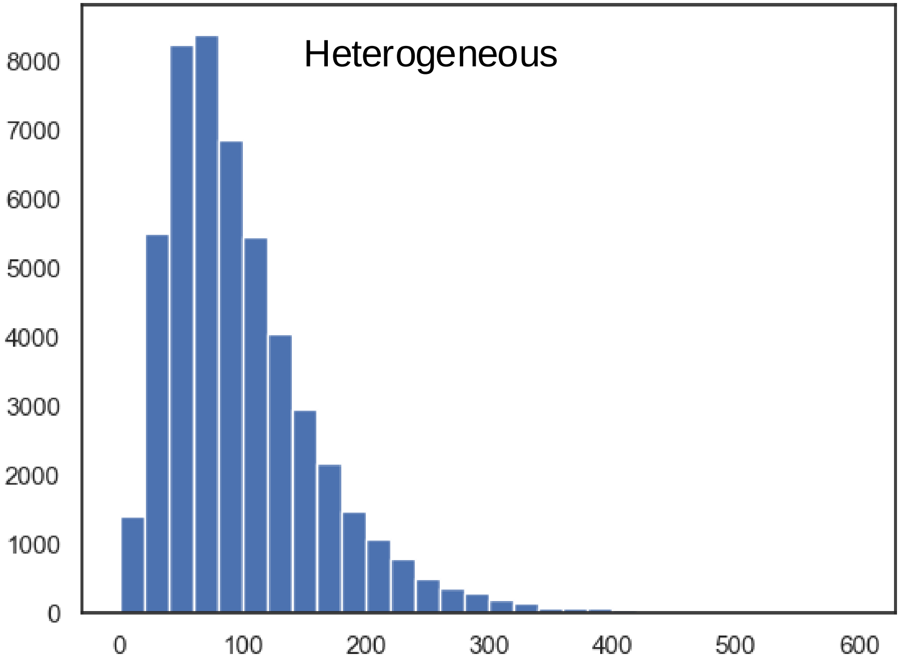
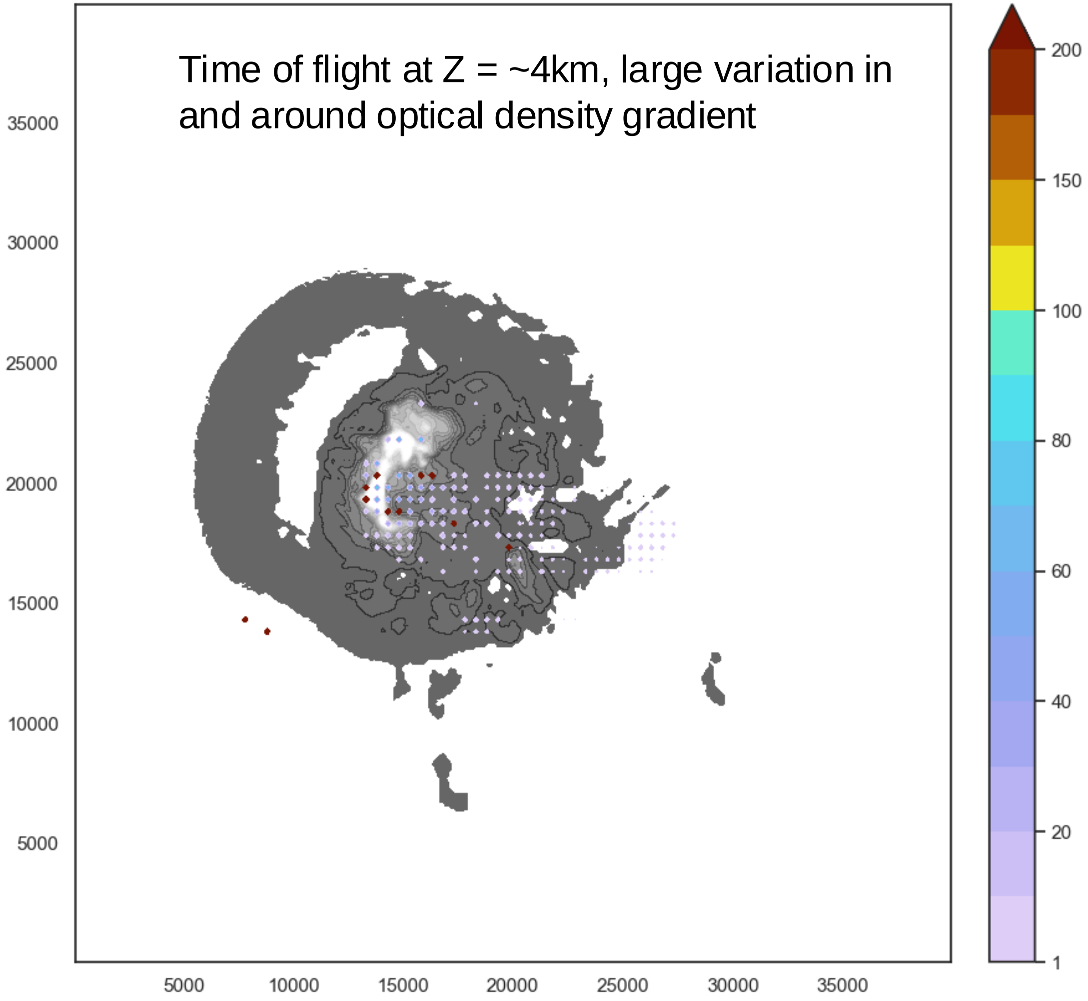


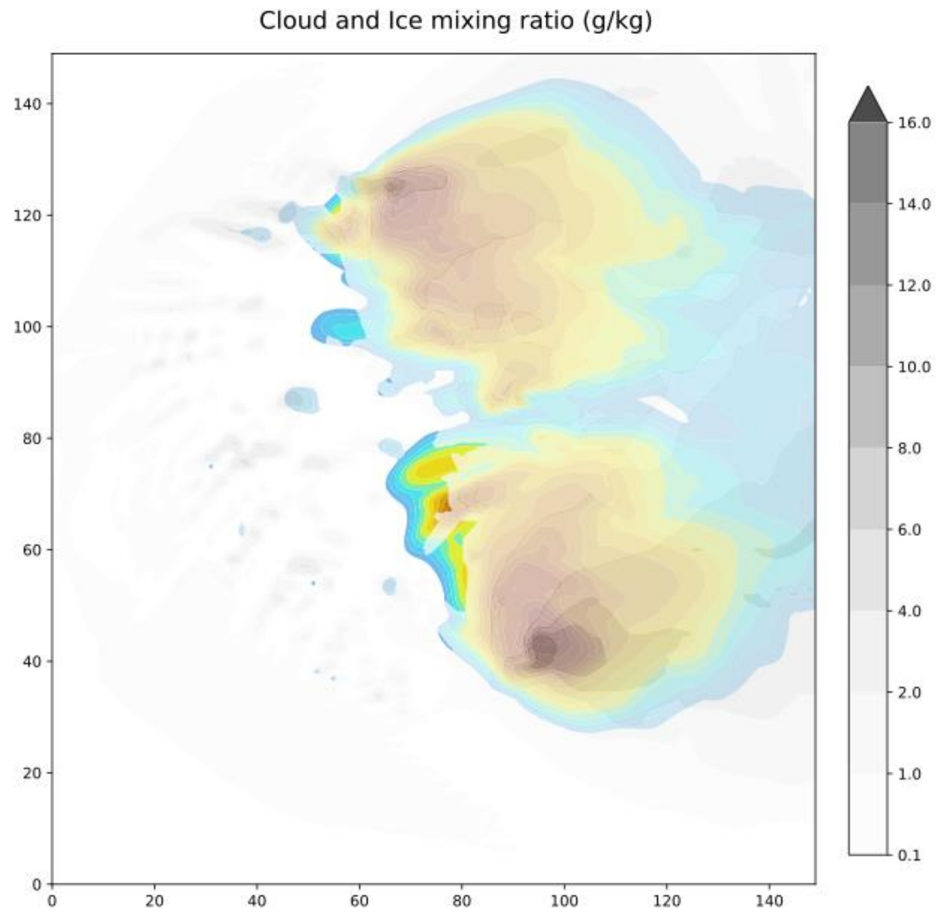


Model Development and Discussion

- Heterogeneous microphysics
  - The largest unknown to us is the cloud.
  - Models get close with high resolution, need more validation and in-cloud observations
  - What degree of resolution is absolutely necessary?
- When, where, and how much light
  - Branched lightning model (Mansell, et al, 2002)
  - Light scaled using charge and integrated optical emission (Quick et al., 2017),
  - 777nm ~ 13% of total optical emission (T. Daniel Walker, Christian, 2017, 2019, personal communication)
- Phase function, scattering physics
  - Non-spherical scatterers
  - Using full phase functions
  - Capturing ice microphysics

Monte Carlo Modeling in 3 Dimensions

- What do we gain in going from 2D to 3D, and why is it impactful?
- What model updates are important and get us closer to proper validation?
  - Instrument modeling – (Rimboud, et al, 2024, Luque et al, 2020)
  - Nonspherical scatterers/different optics (Rimboud, et al, 2024)
  - More wavelengths
  - Broader microphysics
  - More realistic cloud representation



Spare

Physical Approach

- What physics are implemented in this model component?
    - How has this modeling activity been motivated by a larger scientific problem?
    - Describe the current capability
        - What are the key assumptions and simplifications, advantages, and limitations?
        - What are space and time scales are represented?
    - Indicate how the model fits or might fit within the draft framework.
    - How does the wider scientific community use this model component and similar tools?

- What are the current gaps?
    - Within the modeling component you describe above?
    - Within related pieces?
    - What seems within reach in the next 3-5 years? What is decades away?

Model Interoperability, Development

- What are the model inputs?
  - What is the minimum information that is needed to start this model component?
    - Datasets
    - Supporting tools
  - List specific, structured data types or outputs of other modeling systems.

- What are the model outputs?
  - What are the primary outputs of this model component?
  - Describe any valuable internal diagnostics.
  - These could be observational or modeled, historical or operational.
  - What are primary roadblocks and/or opportunities that could arise with current or future outputs?

- How will the model components be shared?
  - What are primary roadblocks that arise when ingesting and sharing inputs/outputs?
  - What opportunities could be facilitated by sharing the model and its inputs/outputs?
  - Describe hindrances to your ability to locate, access, and use data/models that benefit or could benefit your research.
  - If possible, provide suggestions that could make it easier for researchers to obtain and use the data/models.
- Model sticking points, or points to develop:
  - Microphysical inputs – right now we only handle single wavelength, assume spherical shapes,

Model Use and Validation

- How is this model component validated?
  - Describe how, in practice, you judge whether the model is representative of nature
- How will model errors be quantified?
  - How might that error model integrate with other pieces in the modeling framework?
- What observations are necessary for validation
  - What is currently available?
  - What needs to be developed?
  - Scope: 3-5 year development efforts, and longer-term (decadal advancement)