THE AFIT OF TODAY IS THE AIR & SPACE FORCE OF TOMORROW

What does an obscured lightning flash look like from orbit?

Modeling Lightning Flashes Within Dissimilar Non-Homogeneous Cloud Structures

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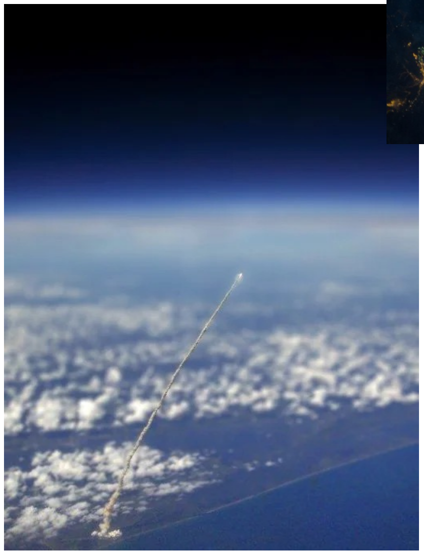
Overview

- Motivation
- Background
- Methodology
- Results
- Conclusion

Motivation

- Vis/IR Satellites can't see under clouds very well[citation needed]
- Lightning detectors and surveillance satellites both rely on anomalously strong emissions
- How can we tell the source of the emissions obscured by clouds?
- **We can help by modeling lightning flashes to train detection algorithms**



Background

- Multiple scattering in the cloud leads to peak delay and time-broadening of 100s of µs from the initial flash
- Four previous studies used simplified geometry and homogenous characteristics for clouds
- One previous study used weather model output to make a non-homogenous cloud – the cloud was a one-dimensionally non-homogeneous rectangular prism
- **Ultimately, these clouds were not realistic**

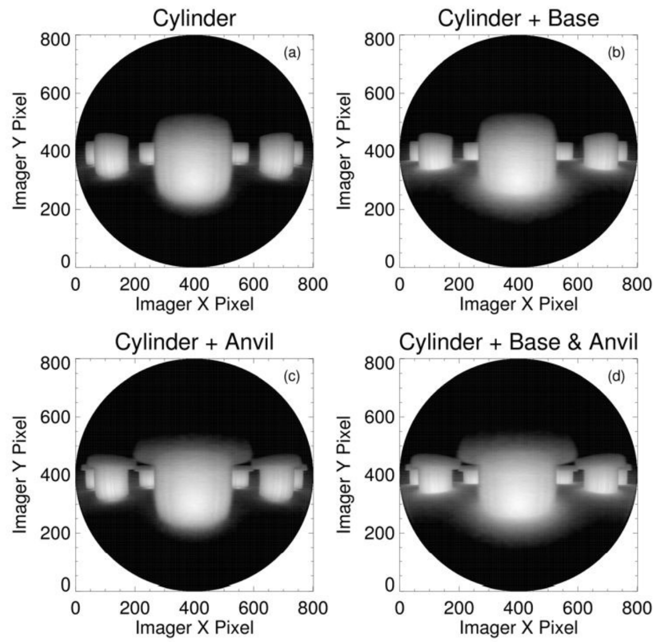


Figure 1. Visualization of the geometries of the finite cylindrical clouds. A wide angle (180°) camera is placed at the midlevel of the 3-D cloud domain and pointed toward the horizon. The radiance from the Cylinder (a), Cylinder + Base (b), Cylinder + Anvil (c) and Cylinder + Base & Anvil illuminated from below are imaged with a logarithmic normalization applied.

Examples of cloud geometry used by Peterson, 2020

Methodology

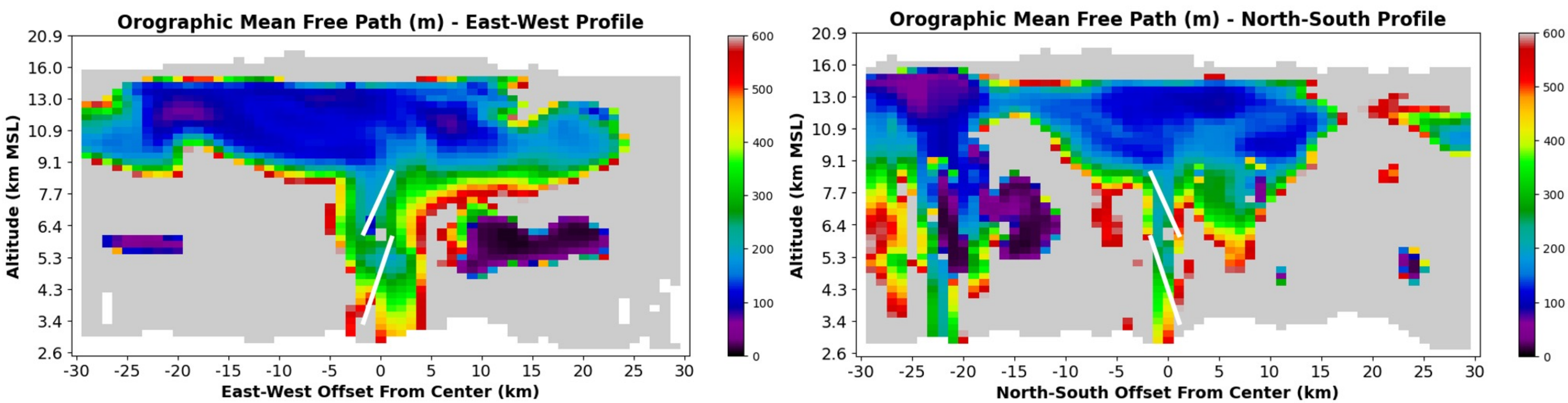
- Four thunderstorm events chosen for diversity of formation mechanism and structure
- WRF output for 6 hydrometeor species used to calculate photon mean free path (NIR 777.4 nm)
  - 1 km horizontal resolution [61 x 61 km]
  - 14 mb (~300 m) vertical resolution [900-76 mb (~20 km)]
  - 223,260 total grid points
- Photons emitted from a diagonal linear source 5 km long between 6-9 (2-5) km MSL with realistic time distribution
- Multiple scattering simulated with Monte Carlo method
  - Photons were allowed to exit and reenter clouds
  - Ground scattering simulated as 0.45 albedo Lambertian
- Exit/absorption points, directions, and times recorded

Results
Cloud Structure & Exit Types

Case	Absorbed by Cloud	Absorbed by Ground	Emitted from Cloud Top	Emitted from Cloud Bottom	Emitted from Cloud Side
Orographic Lift IC	0.3%	53.6%	34.2%	5.5%	6.4%
Orographic Lift CG	0.2%	65.9%	22.9%	4.7%	6.3%
Supercell IC	10.8%	39.0%	34.9%	7.0%	8.3%
Supercell CG	4.1%	70.3%	14.2%	5.8%	5.6%
Sea Breeze IC	1.5%	20.7%	38.7%	3.2%	35.9%
Sea Breeze CG	2.0%	58.5%	21.6%	3.0%	14.9%
Tropical MCS IC	1.5%	27.4%	53.4%	3.6%	14.1%
Tropical MCS CG	1.2%	54.0%	34.7%	1.4%	8.7%

Results

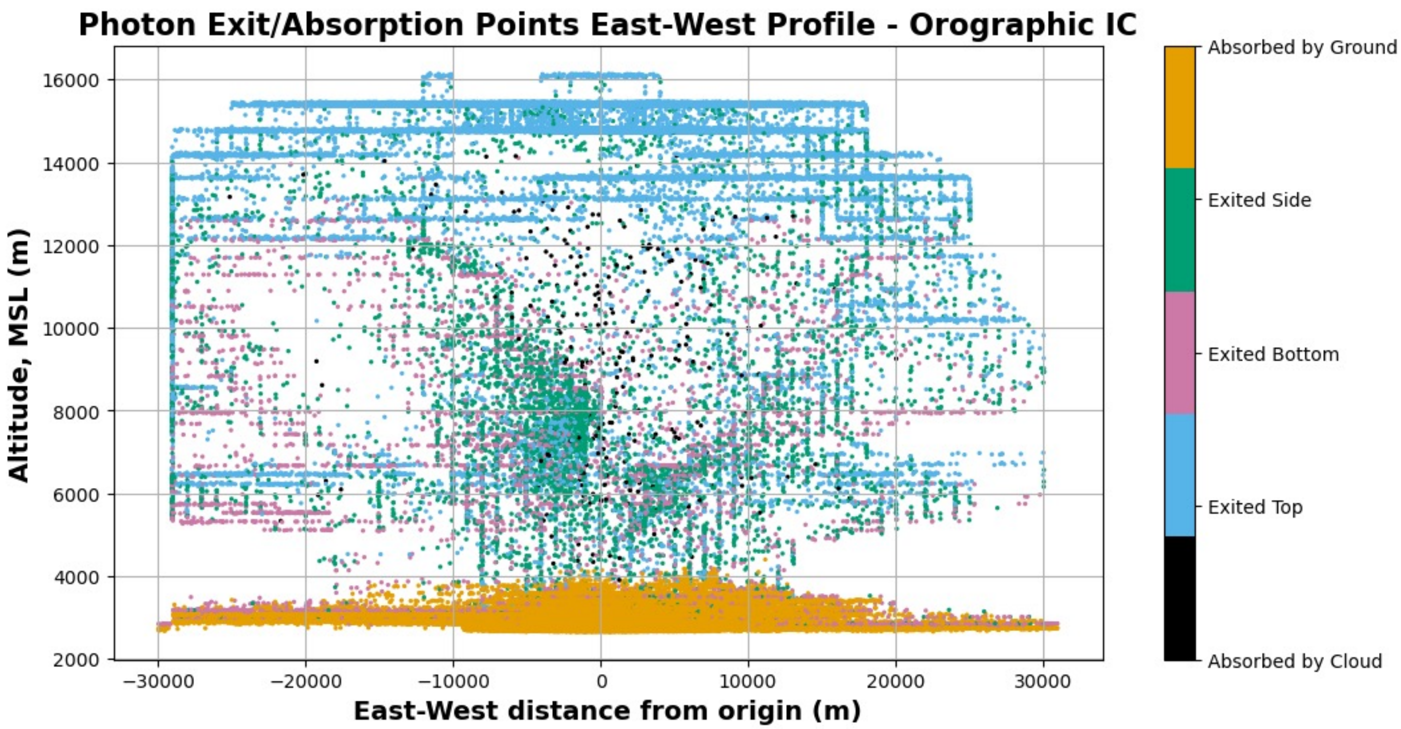
Cloud Structure & Exit Types – Orographic Lift

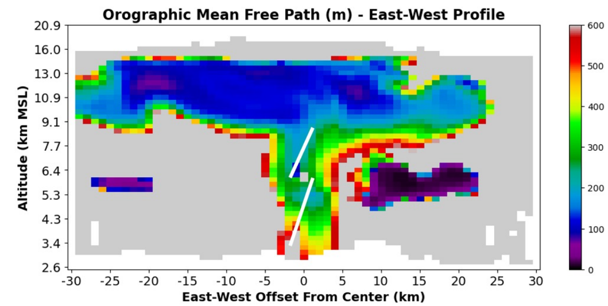


27.12% “cloud” grid boxes 229 m avg “cloud” MFP

Results

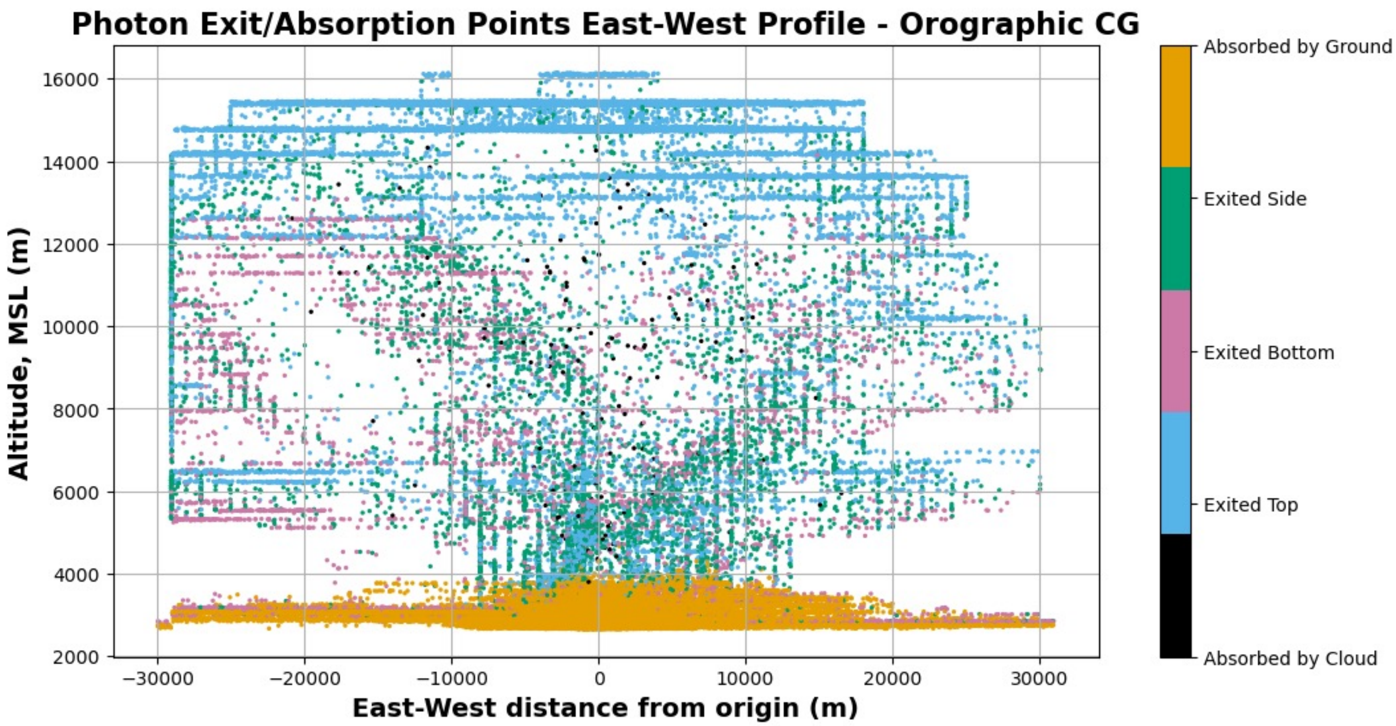
Cloud Structure & Exit Types – Orographic Lift IC

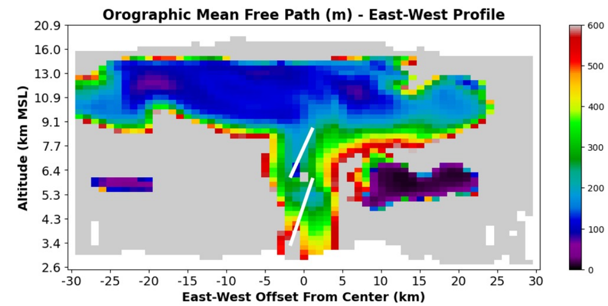




Results

Cloud Structure & Exit Types – Orographic Lift CG





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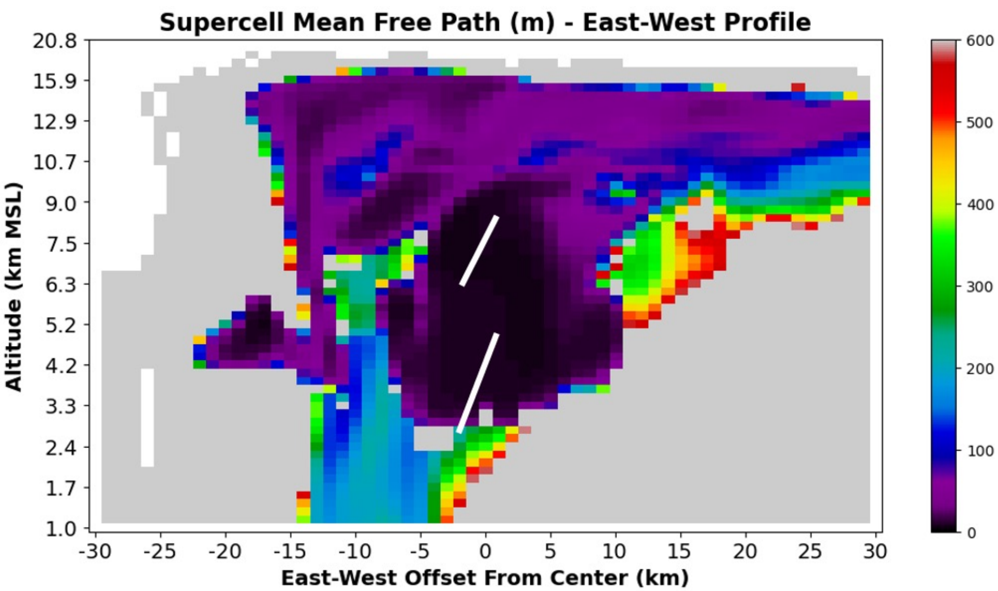
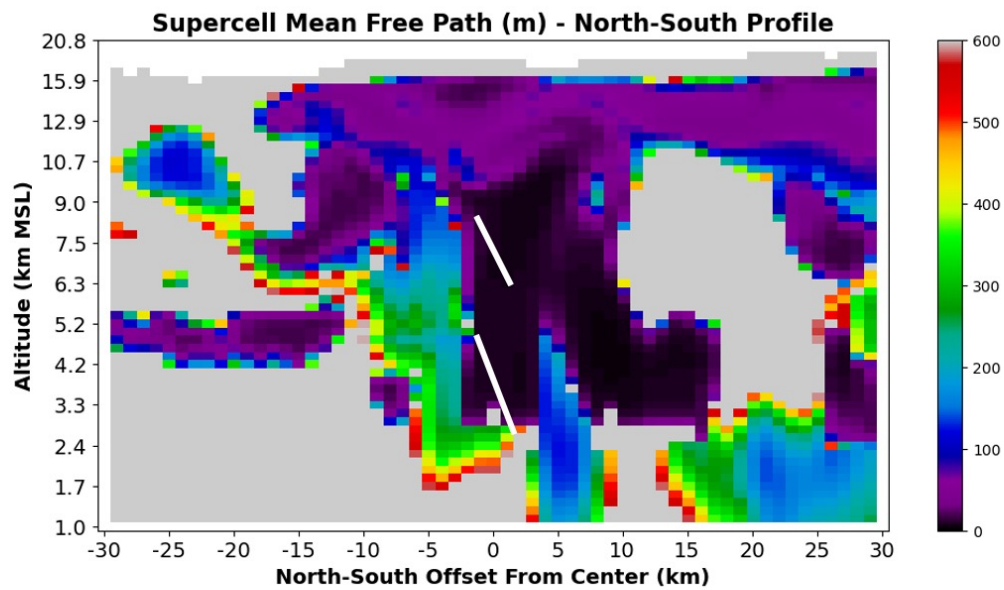
Results

Cloud Structure & Exit Types – Supercell

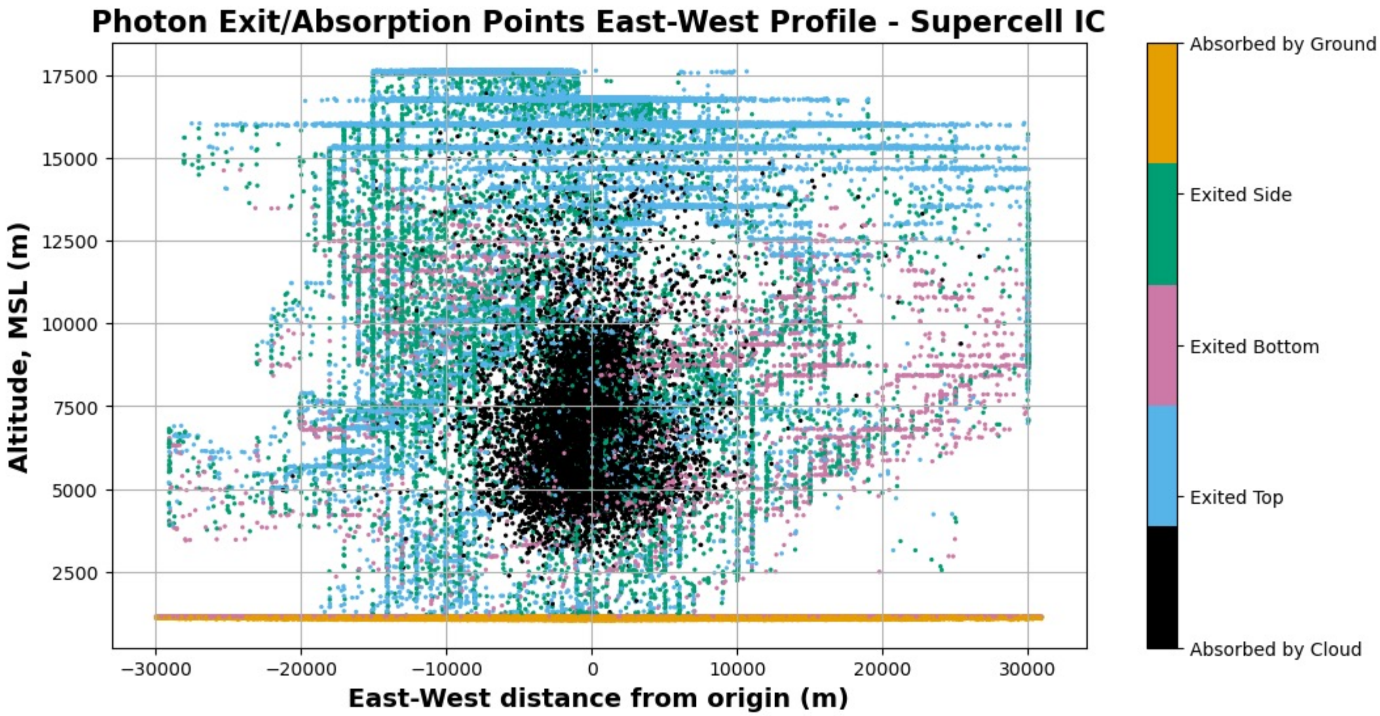


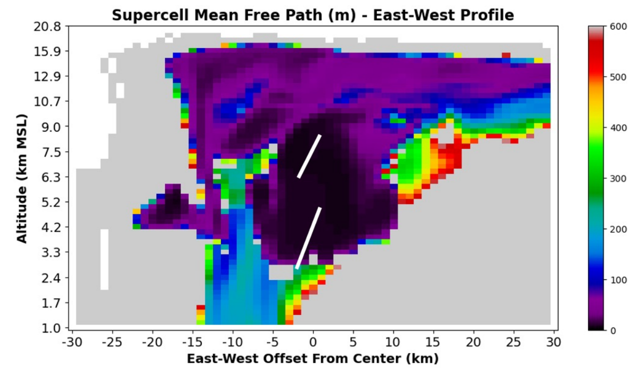


31.16% “cloud” grid boxes   136 m avg “cloud” MFP

Results

Cloud Structure & Exit Types – Supercell IC





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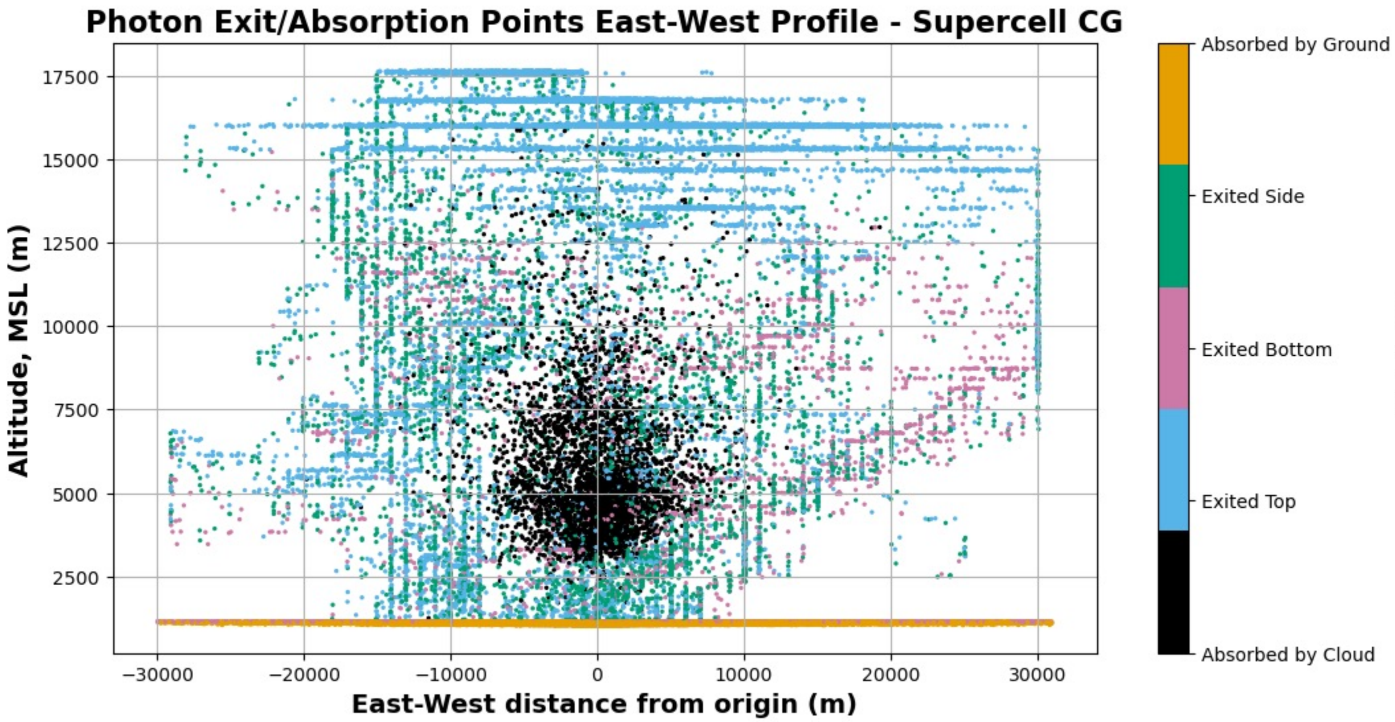
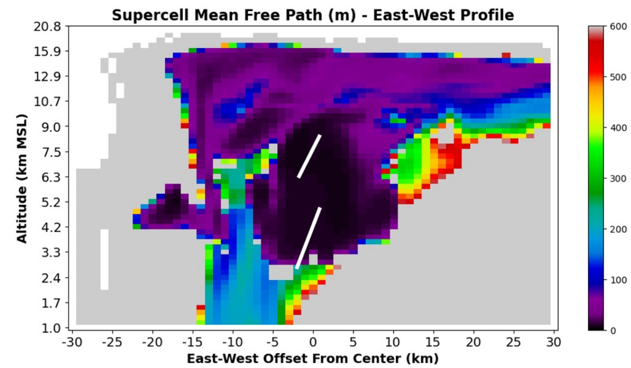
Results

Cloud Structure & Exit Types – Supercell CG





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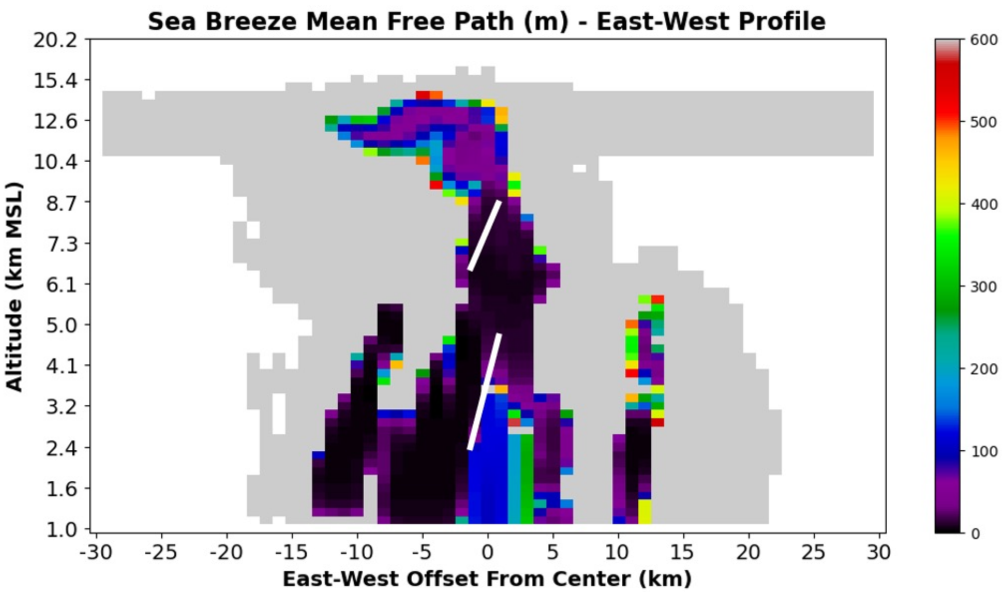
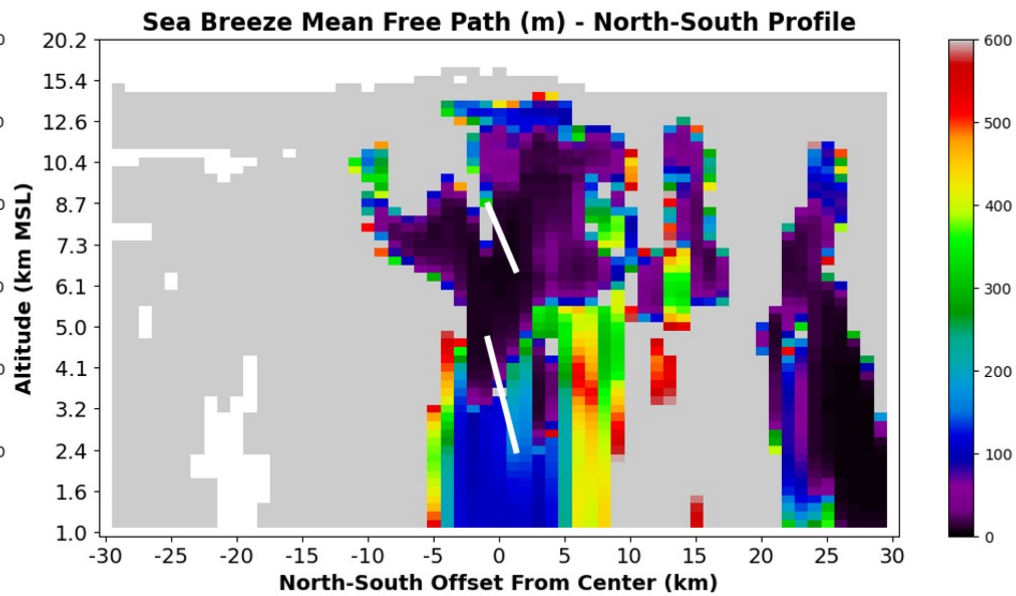
Results

Cloud Structure & Exit Types – Sea Breeze

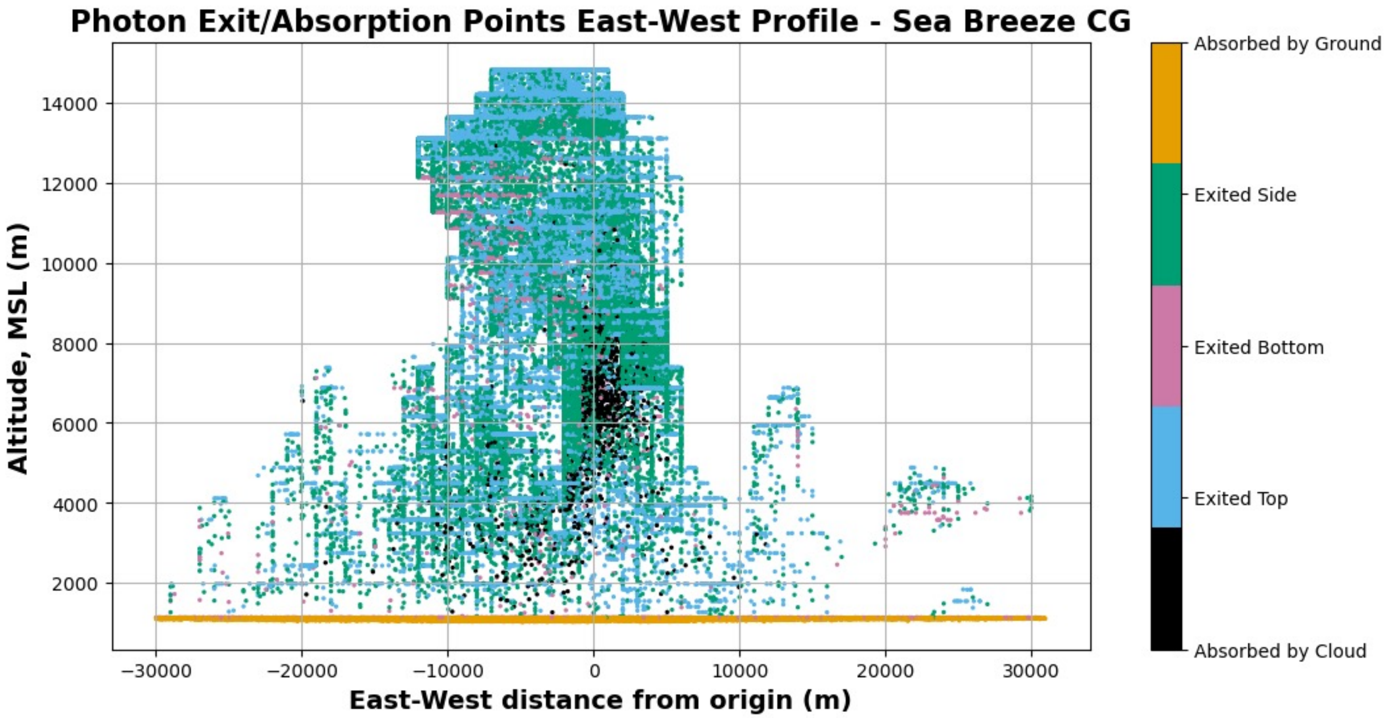


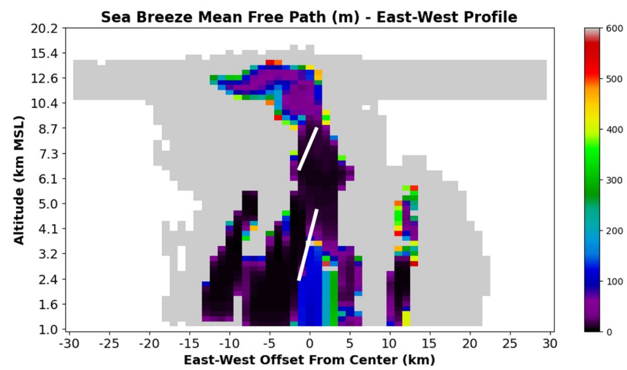


7.25% “cloud” grid boxes   127 m avg “cloud” MFP

Results

Cloud Structure & Exit Types – Sea Breeze IC





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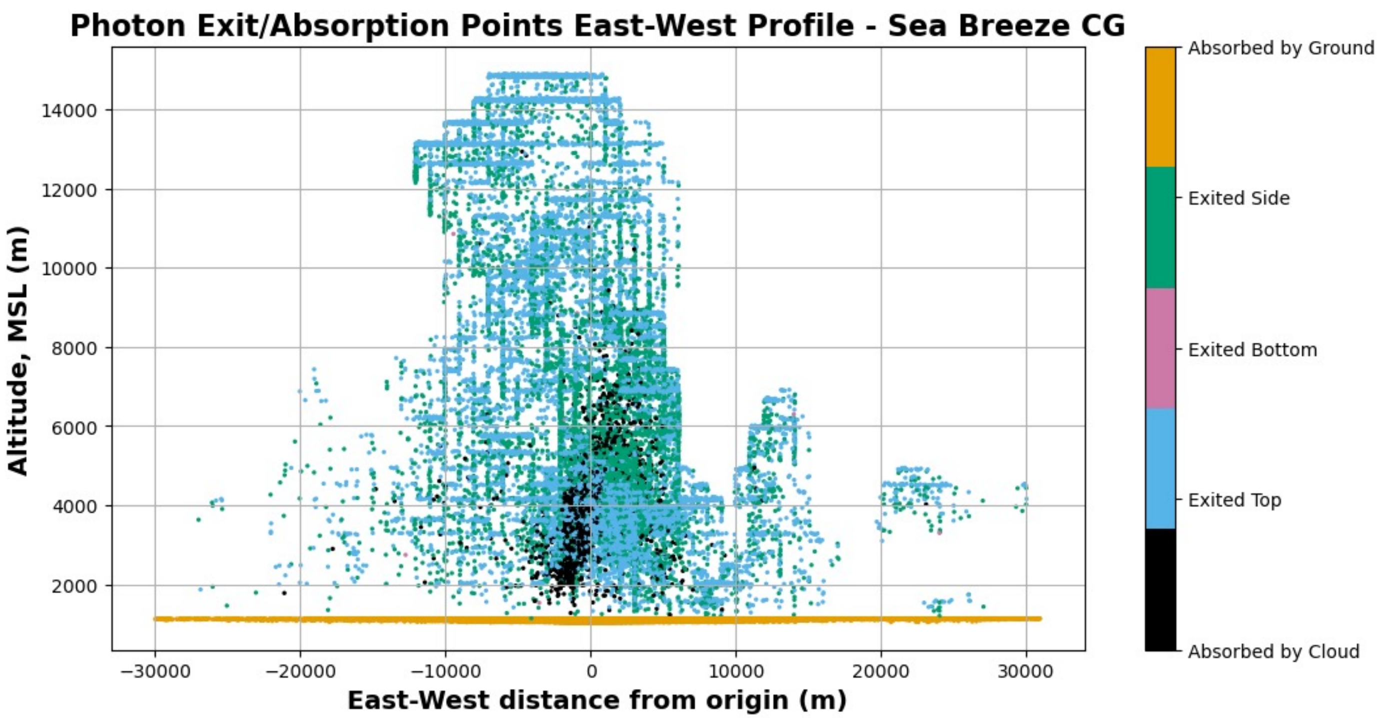
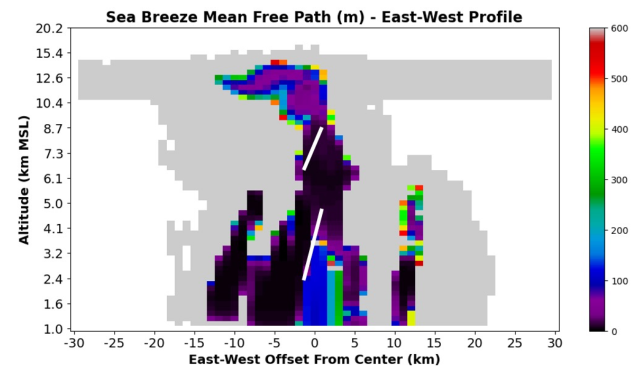
Results

Cloud Structure & Exit Types – Sea Breeze CG





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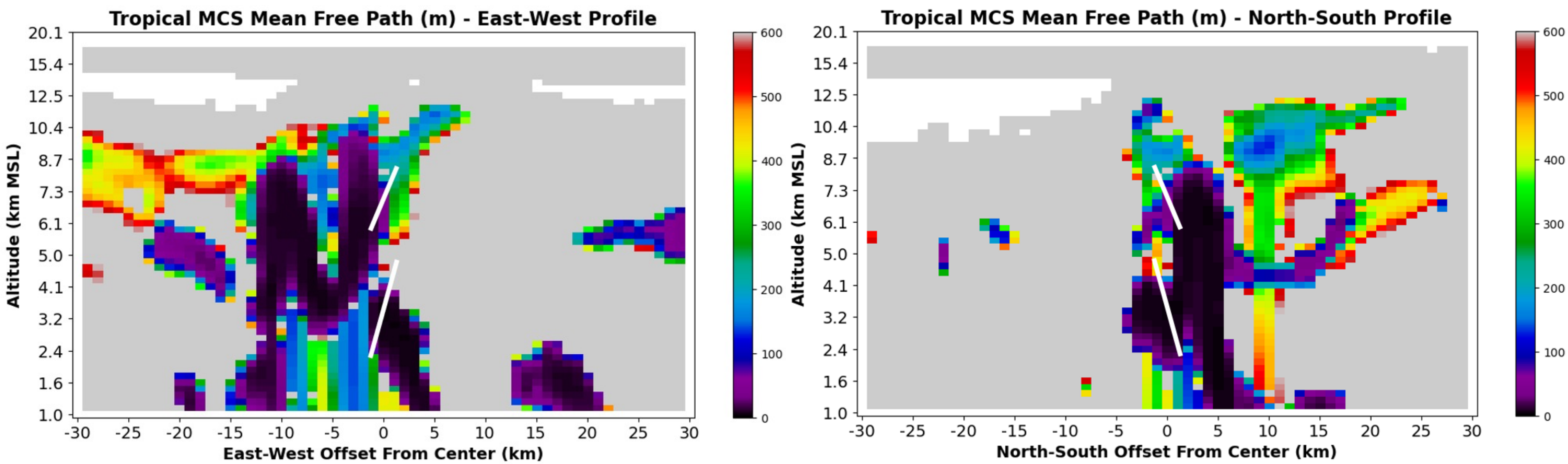
Results

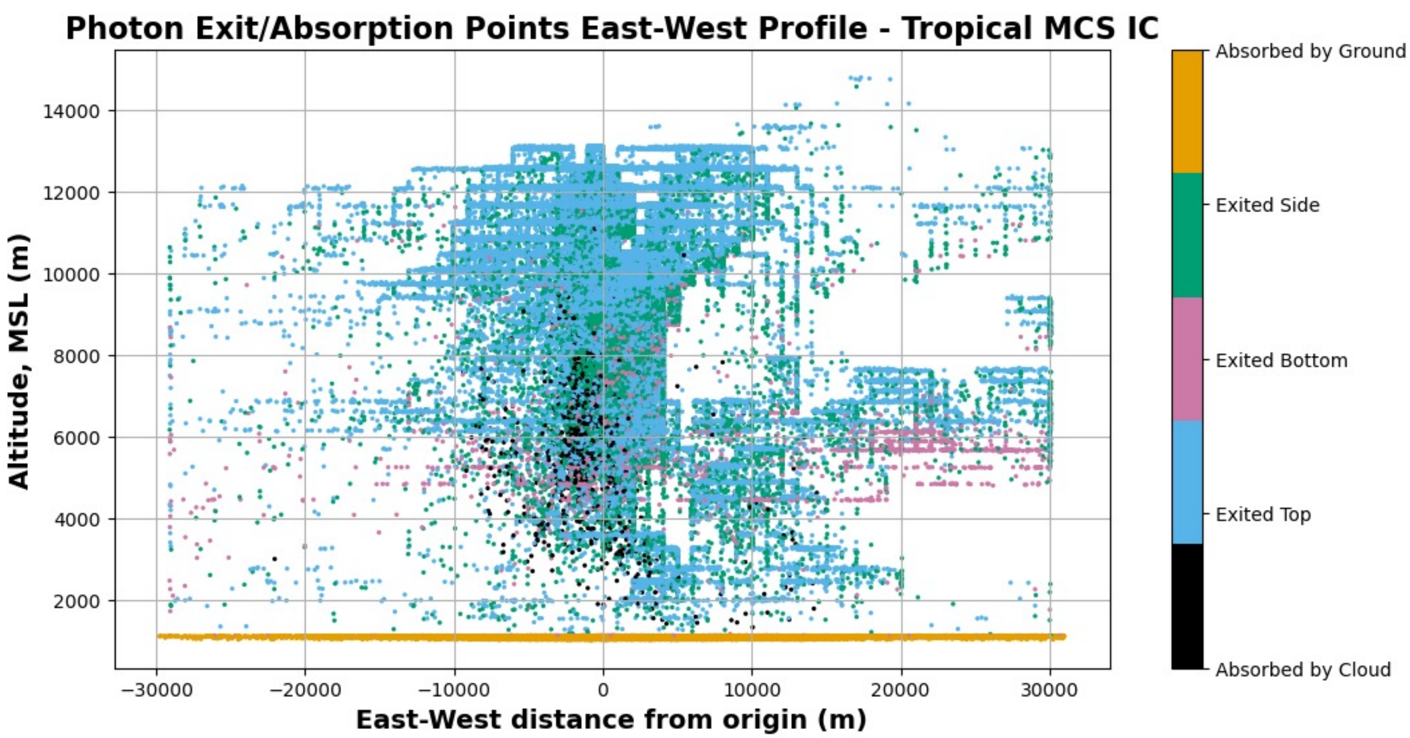
Cloud Structure & Exit Types – Tropical MCS

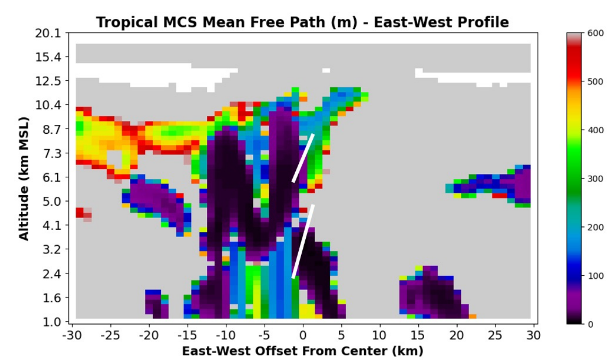


19.69% "cloud" grid boxes   189 m avg "cloud" MFP

Results

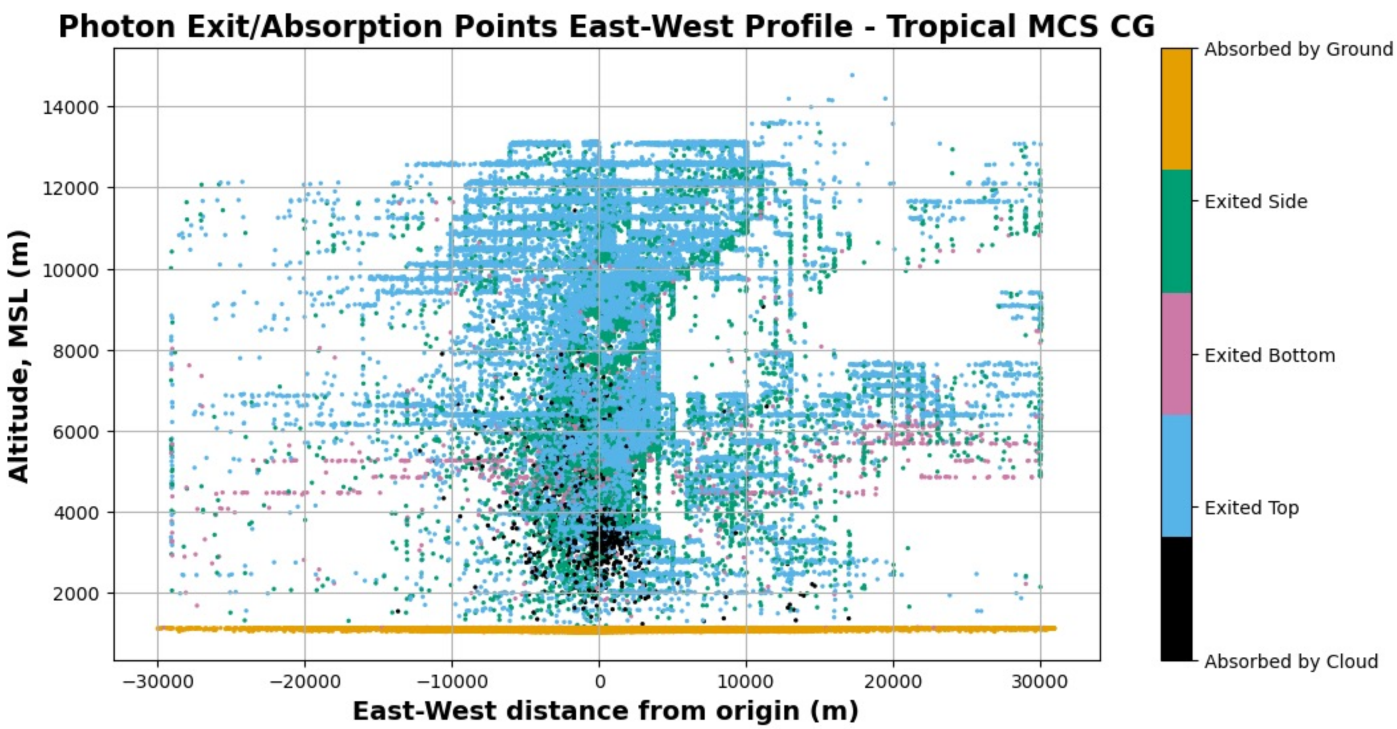
Cloud Structure & Exit Types – Tropical MCS IC

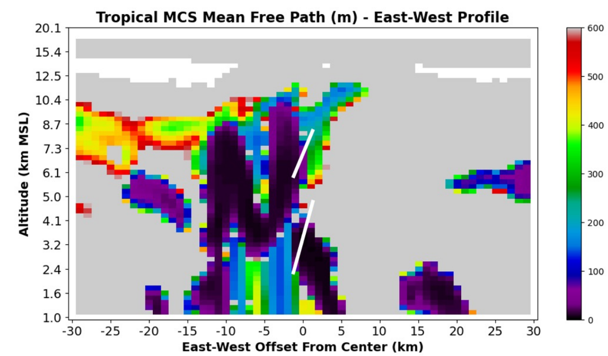




Results

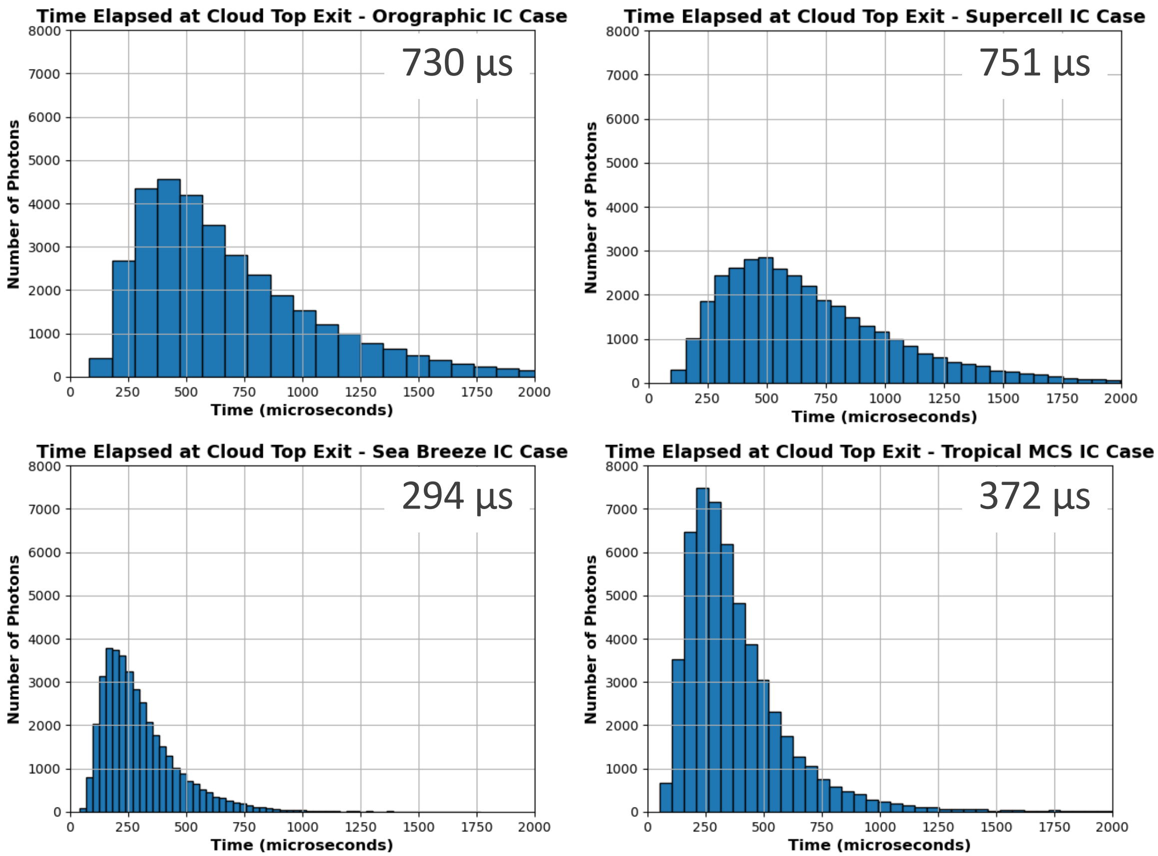
Cloud Structure & Exit Types – Tropical MCS CG





Results

Cloud-Top Radiance & Validation – IC



Results

Cloud-Top Radiance & Validation – IC

Orographic Lift – 0-1000 µs

Eff Pulse Width: 730 µs

Supercell – 0-1000 µs

Eff Pulse Width: 751 µs

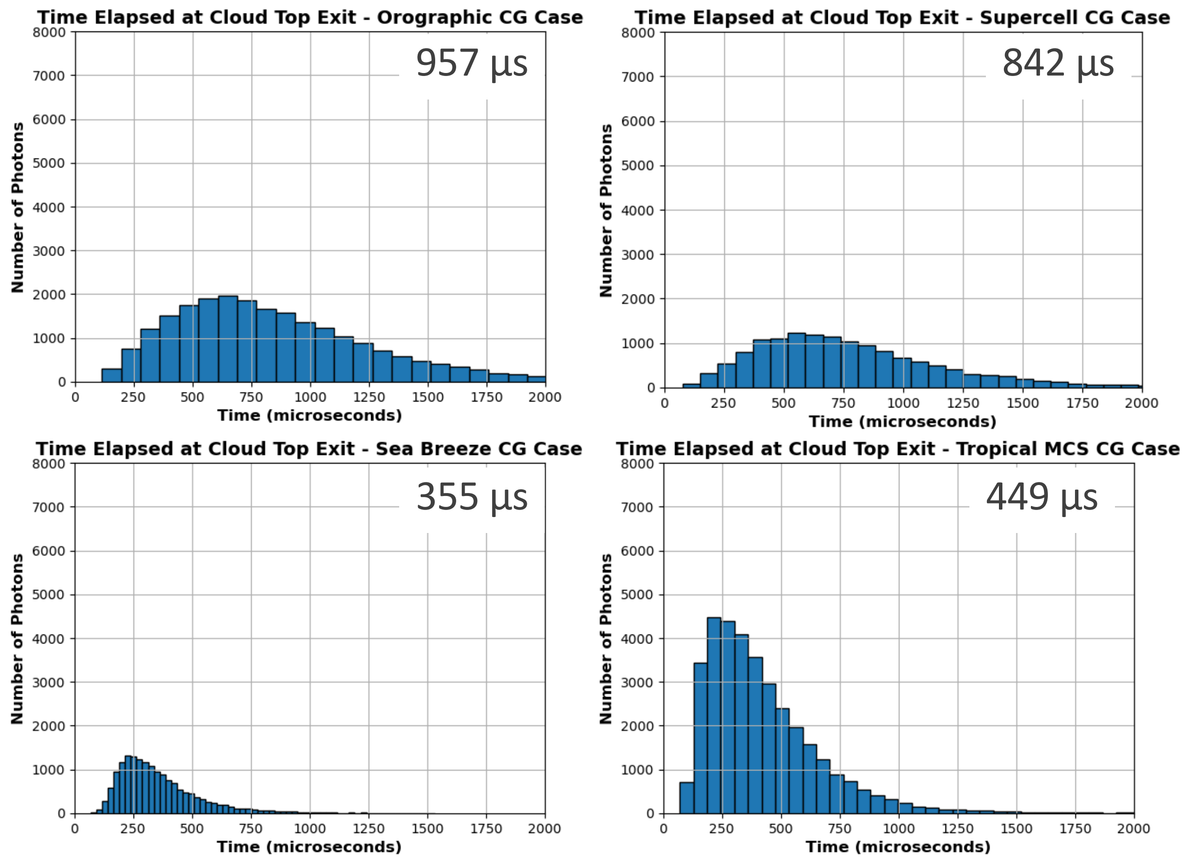
Sea Breeze – 0-1000 µs

Eff Pulse Width: 294 µs

Tropical MCS – 0-1000 µs

Eff Pulse Width: 372 µs

Results
Cloud-Top Radiance & Validation – CG



Results

Cloud-Top Radiance & Validation – CG

Orographic Lift – 0-1000 µs

Eff Pulse Width: 957 µs

Supercell – 0-1000 µs

Eff Pulse Width: 842 µs

Sea Breeze – 0-1000 µs

Eff Pulse Width: 355 µs

Tropical MCS – 0-1000 µs

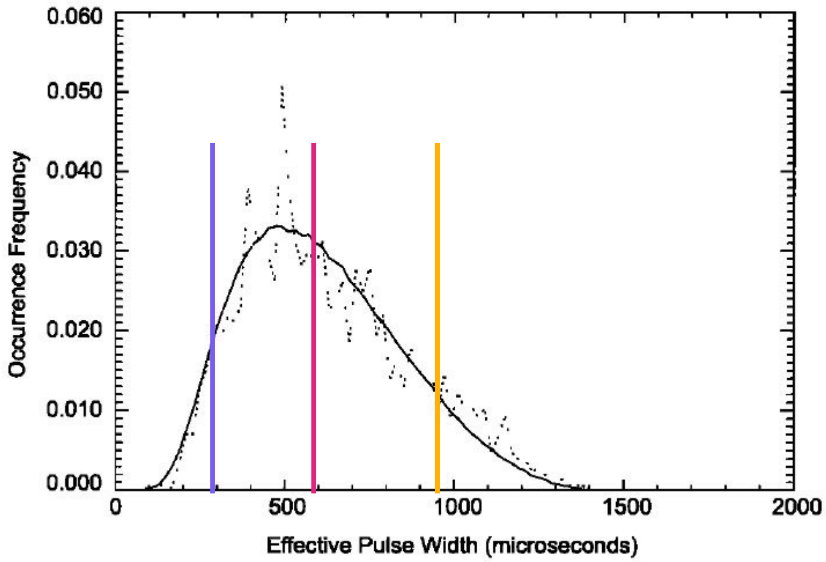
Eff Pulse Width: 449 µs

Results

Validating Cloud-Top Flashes

- **Estimated cloud-top effective pulse widths from simulation fell within distribution of observed flashes, straddling median value**

Event	IC Eff Pulse Width	CG Eff Pulse Width
Orographic Lift	730 μs	957 μs
Supercell	751 μs	842 μs
Sea Breeze	294 μs	355 μs
Tropical MCS	372 μs	449 μs
FORTE Observed Median		592 μs



Distribution of effective pulse widths observed by FORTE satellite as reported by Kirkland et al., 2001

Discussion
Timing of Photon Exit

Optical density or cloud volume, which has more impact?

- Orographic lift and supercell cases had the most pulse-broadening
  - Supercell avg 136 m MFP, Orographic lift avg 229 m MFP
  - Both had extensive cirrus shields, unlike sea breeze and tropical MCS
- Optical density impacted cloud absorption
  - Sea breeze had 1.5/2.0% absorbed vs orographic lift 0.3/0.2% absorbed

Discussion
Location of Photon Exit

- Photons tend to exit the nearest edge of the cloud
- Photons tend to follow mean free path gradients

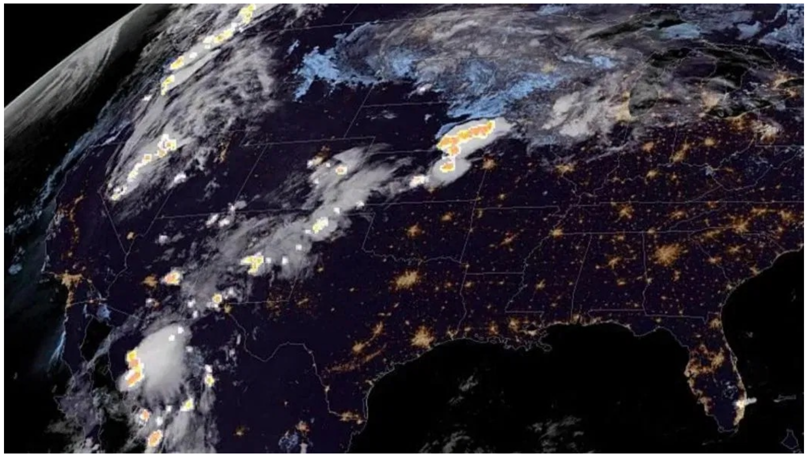
With multiple scattering, radiative transfer looks like diffusion

- Centralized flashes expand outward with time
- Photons from IC flashes were 2x as likely to exit the cloud top
- Photons from CG flashes were 2x as likely to be absorbed by the ground

CG is brighter on the ground, IC is brighter above the cloud

Conclusion

- Generated more realistic clouds for radiative transfer with a weather model
- Modified Monte Carlo multiple-scattering model to handle three-dimensionally non-homogeneous clouds
- Rudimentary validation shows results are in line with observations



Questions?

Sources

- L.W. Thomason and E.P. Krider. The effects of clouds on the light produced by lightning. Journal of The Atmospheric Sciences, pages 2051-2065, September 1982.
- William Koshak, Richard Solakiewicz, Dieudonne Phanord, and Richard Blakeslee. Diffusion model for lightning radiative transfer. Journal of Geophysical Research: Atmospheres, pages 14361-14371, July 1994.
- T.E. Light, D.M. Suszcynsky, M.W. Kirgland, and A.R. Jacobson. Simulations of lightning optical waveforms as seen through clouds by satellites. Journal of Geophysical Research, pages 17103-17114, August 2001.
- M.W. Kirkland, D.M. Suszcynsky, J.L.L. Guillen, and J.L. Green. Optical observations of terrestrial lightning by the forte satellite photodiode detector. Journal of Geophysical Research, pages 33499-33509, December 2001.
- Kelcy Brunner and Phillip Bitzer. A first look at cloud inhomogeneity and its effect on lightning optical emission. Geophysical Research Letters, pages 1-9, May 2020.
- Michael Peterson. Modeling the transmission of optical lightning signals through complex 3-d cloud scenes. Journal of Geophysical Research: Atmospheres, November 2020.

Methodology

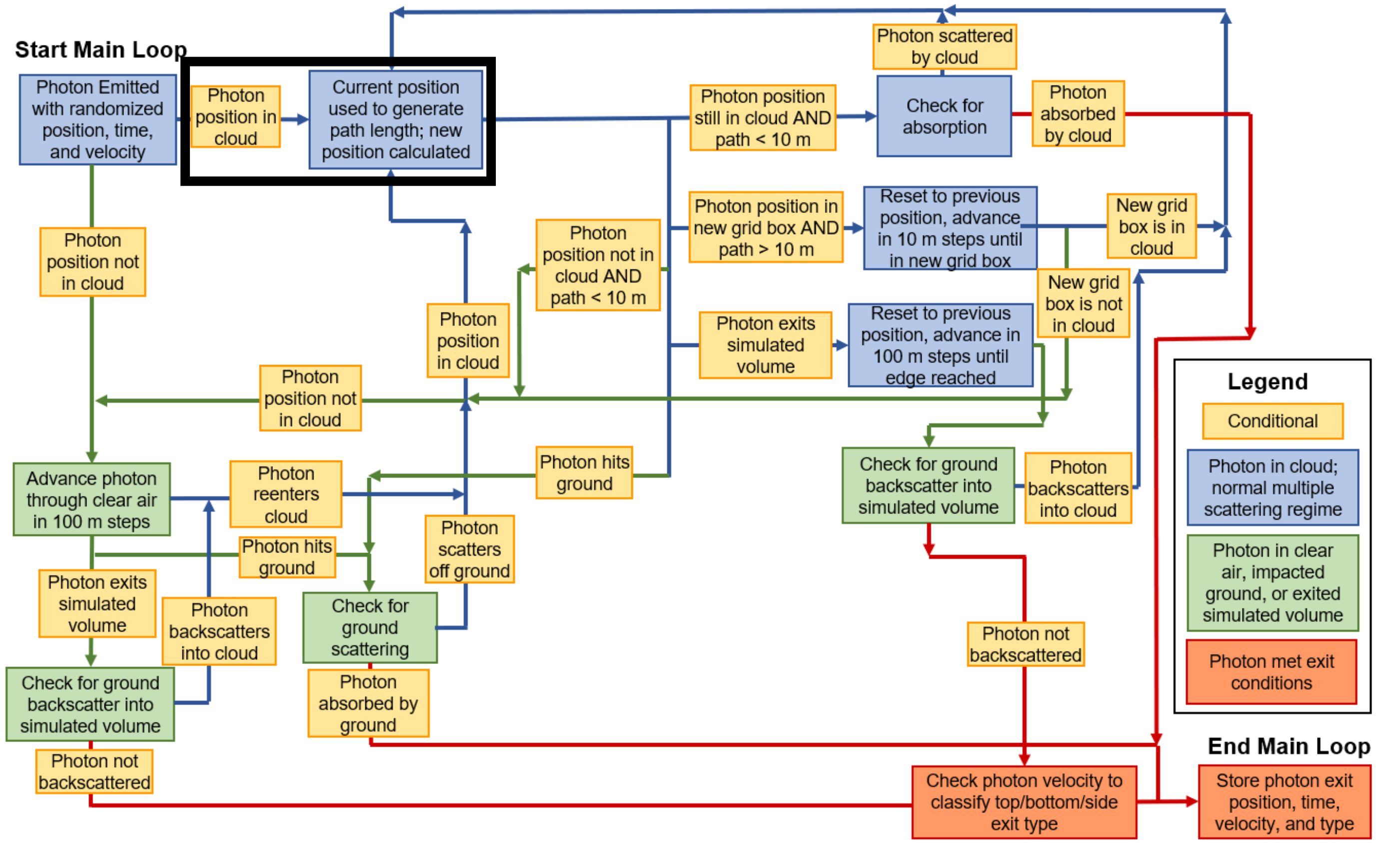
Photon Transit Simulation – Multiple Scattering

- Mean free path used to generate a random path length

$$d = -\Lambda \log(a)$$

- Photon advances path length in previously-selected direction

- Check condition at new position

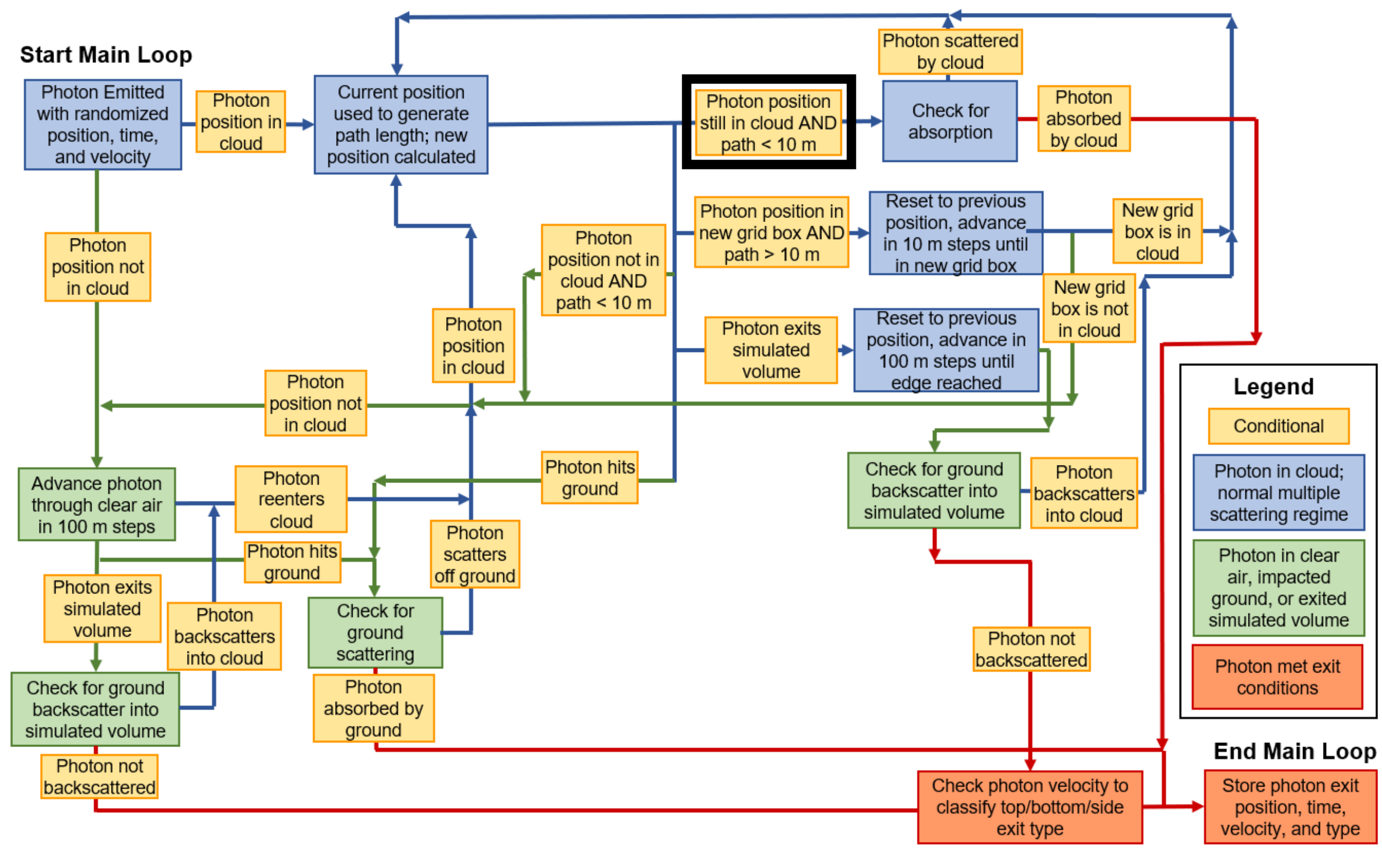


Methodology

Photon Transit Simulation – Multiple Scattering

New position is still “in cloud” AND the path was < 10 m

- Considered to be a realistic move whether photon is in new grid box or not
- Check for absorption by hydrometeor
  - Single-scatter albedo 0.99998
  - Absorption treated as exit
- If no absorption, scattering direction randomized with Henyey-Greenstien phase function using 0.87 asymmetry factor

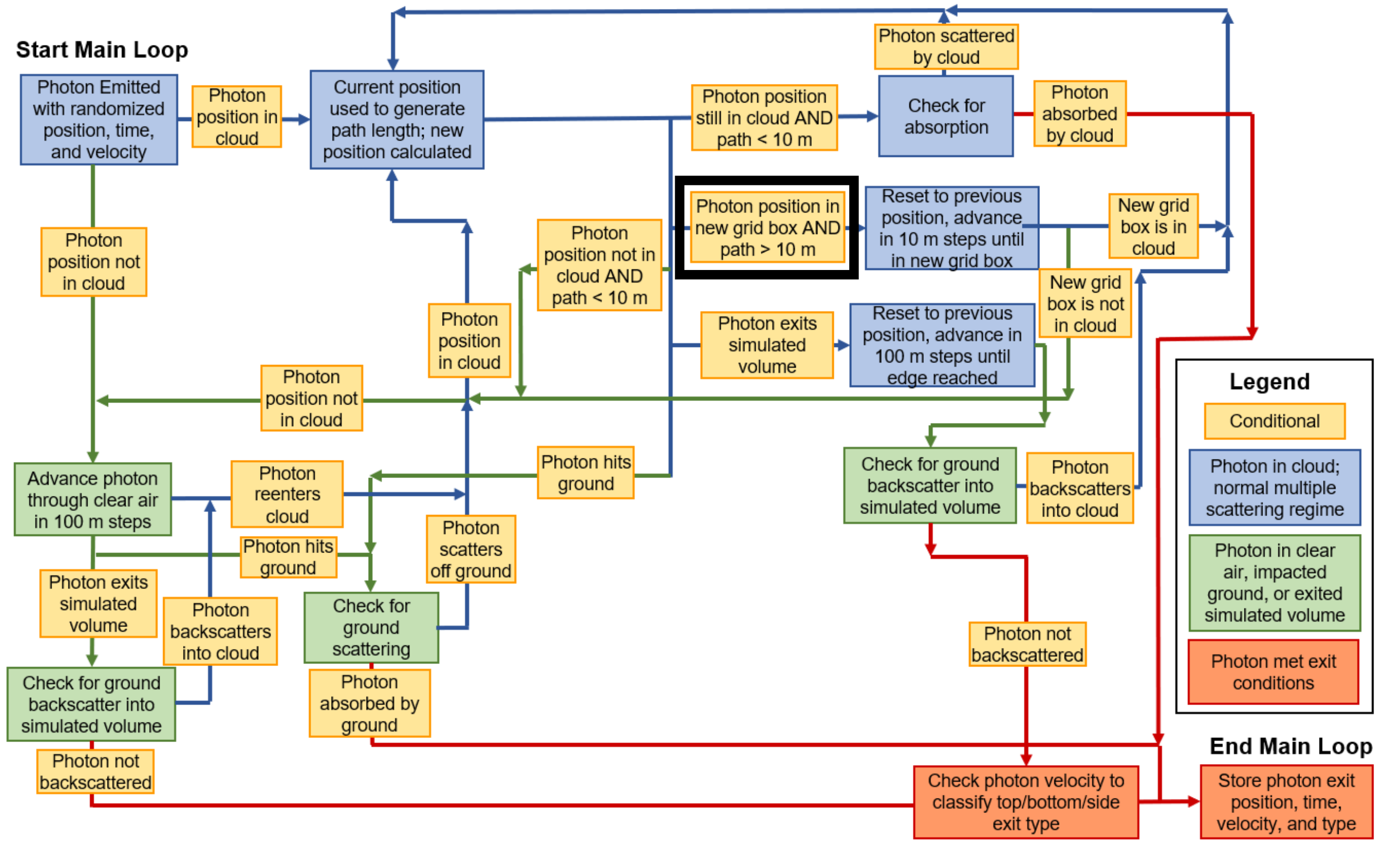


Methodology

Photon Transit Simulation – Multiple Scattering

New position is still "in cloud," but it's in a new grid box AND the path was > 10 m

- Possibly an unrealistic move if the new grid box has a different mean free path
- Reset photon to previous position, advance until it enters new grid box
- Calculate new path length from new position (or follow "clear air" process)



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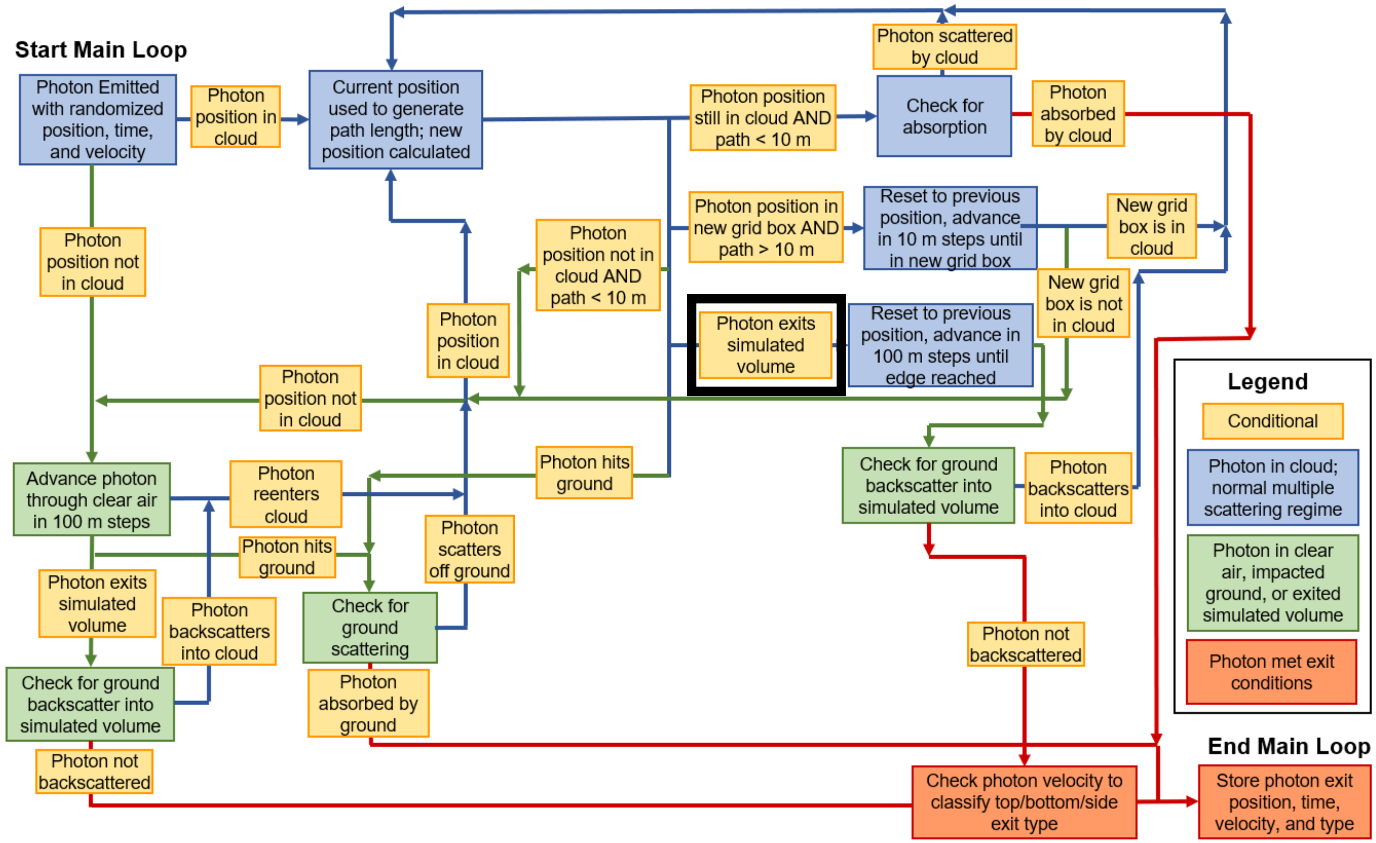
Methodology
Photon Transit Simulation – Multiple Scattering

New position is not in the simulated volume

- Results in either backscatter off ground or exit
- Check for backscatter using surface albedo and solid angle of simulated volume
  - Very rough approximation
- Successful backscatter results in reentry at the same point with opposite direction and time elapsed for traveled distance



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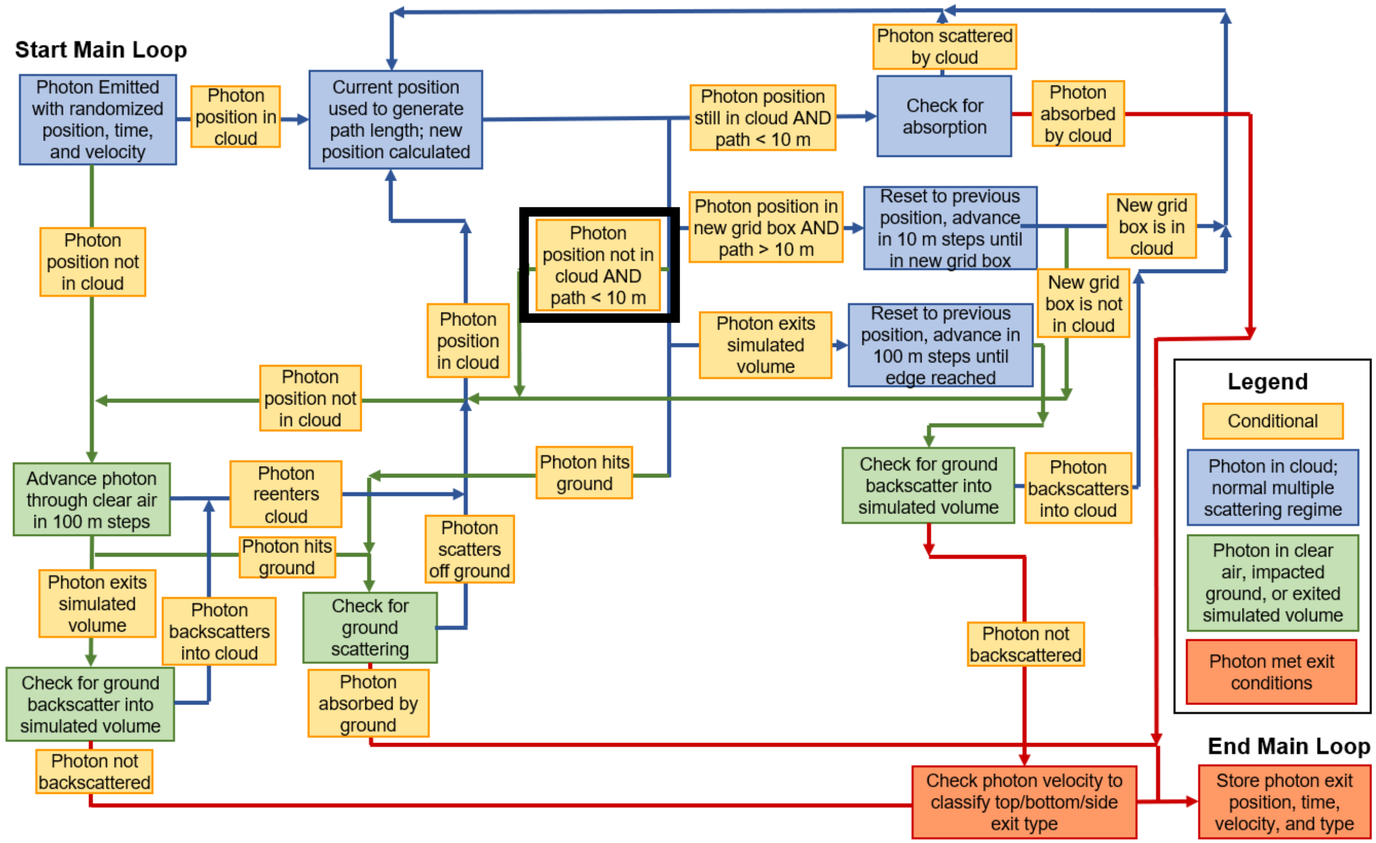
Methodology

Photon Transit Simulation – Multiple Scattering

New position is in "clear air" AND path length < 10 m

- Considered a realistic move
- Photon advanced through "clear air" until state changes
  - Exits simulated volume: see slide 9
  - Hits ground: see slide 11
  - Reenters cloud: new path length calculated, slide 6



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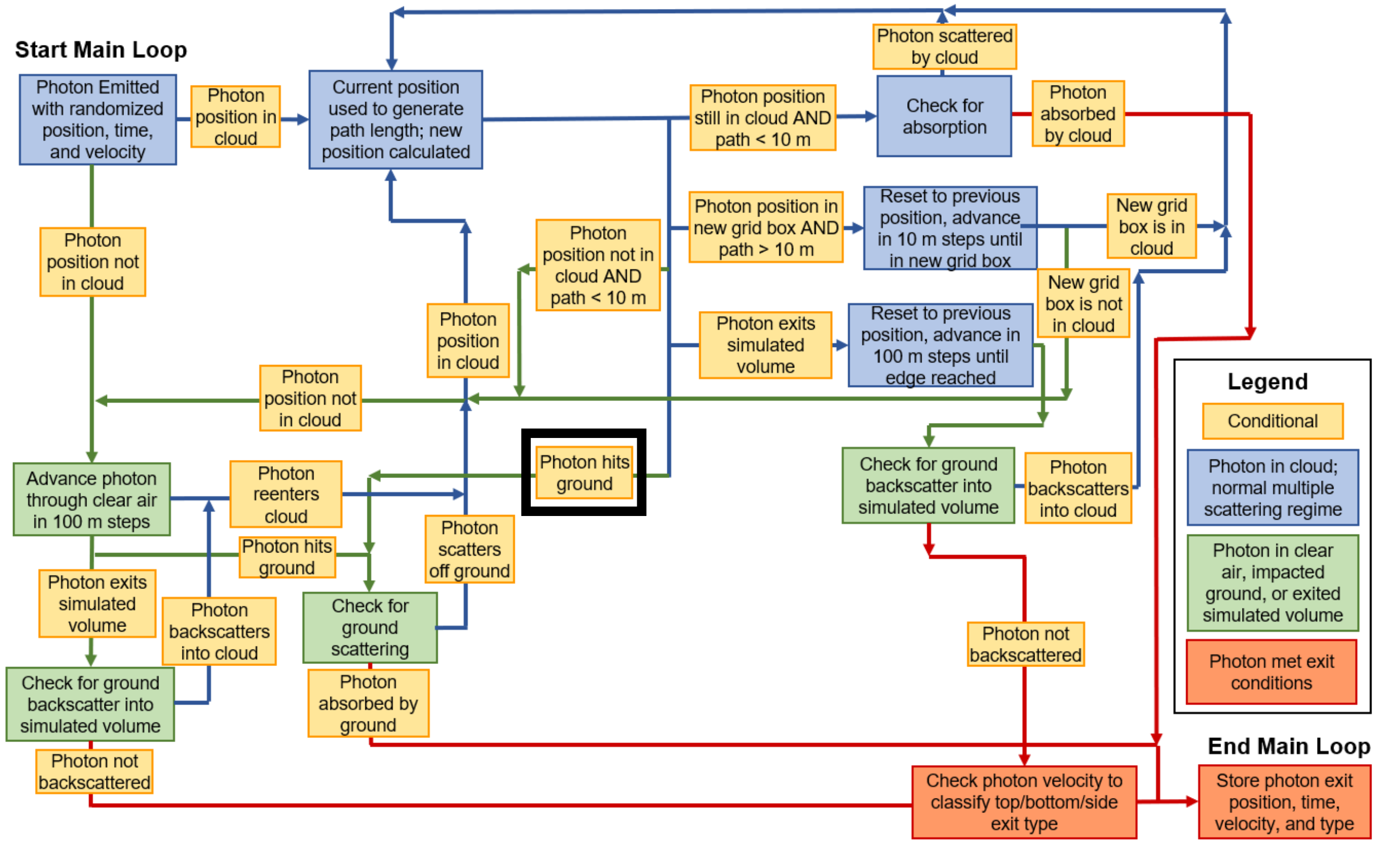
Methodology

Photon Transit Simulation – Multiple Scattering

New position is in the ground

- Results in either scattering or absorption (exit)
- Ground considered to be a Lambertian scatterer with albedo 0.45
- Scatter results in random upward direction
- Absorption results in exit



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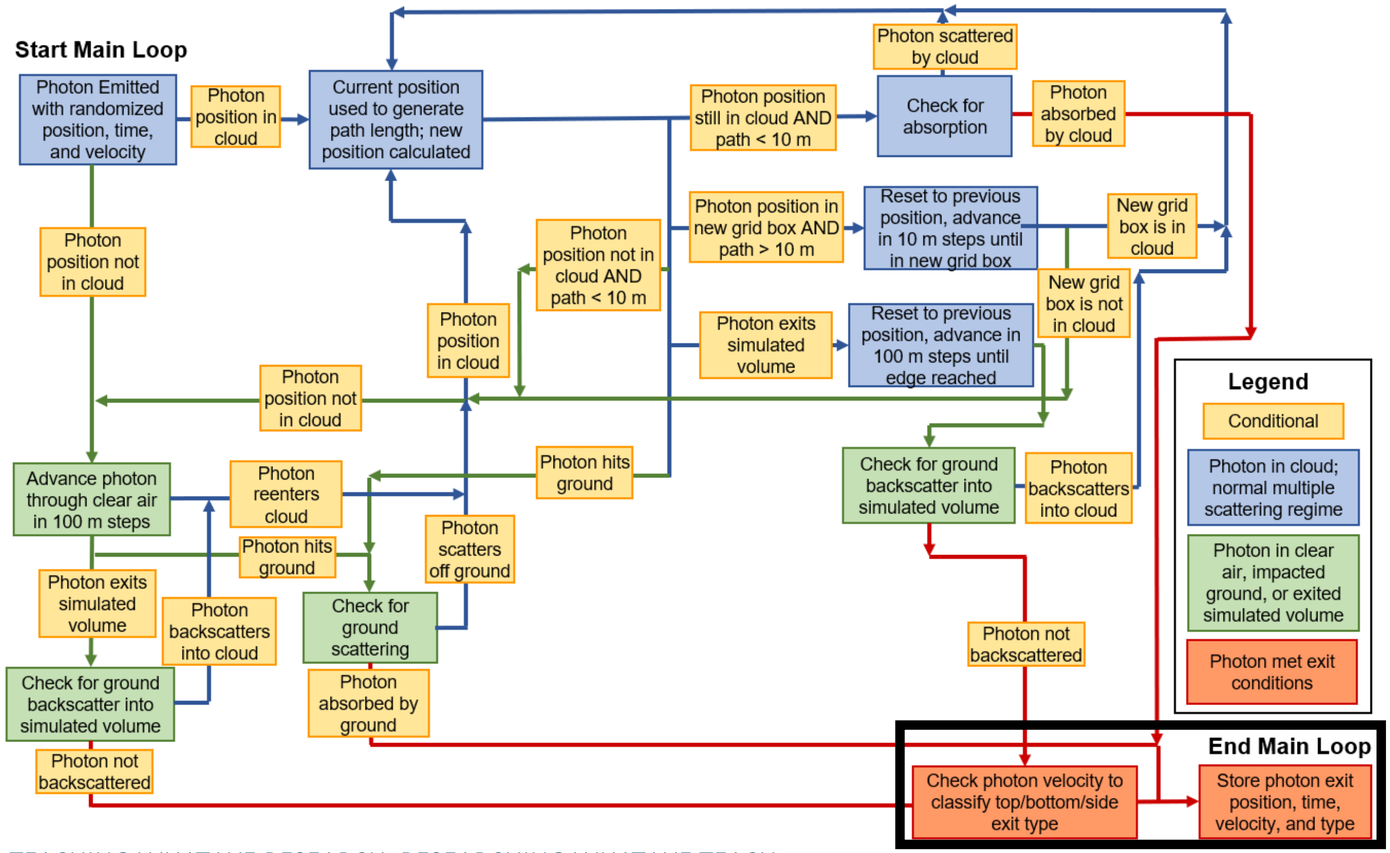
Methodology

Photon Transit Simulation – Exit Conditions

Photon has reached exit criteria

- Absorption immediately exits, classified by either ground or cloud absorption
- Exits from cloud edge are classified based on their direction of travel
- Position, direction of travel, time, and type of exit are logged

Repeat process for 100,000 (or desired number) photons



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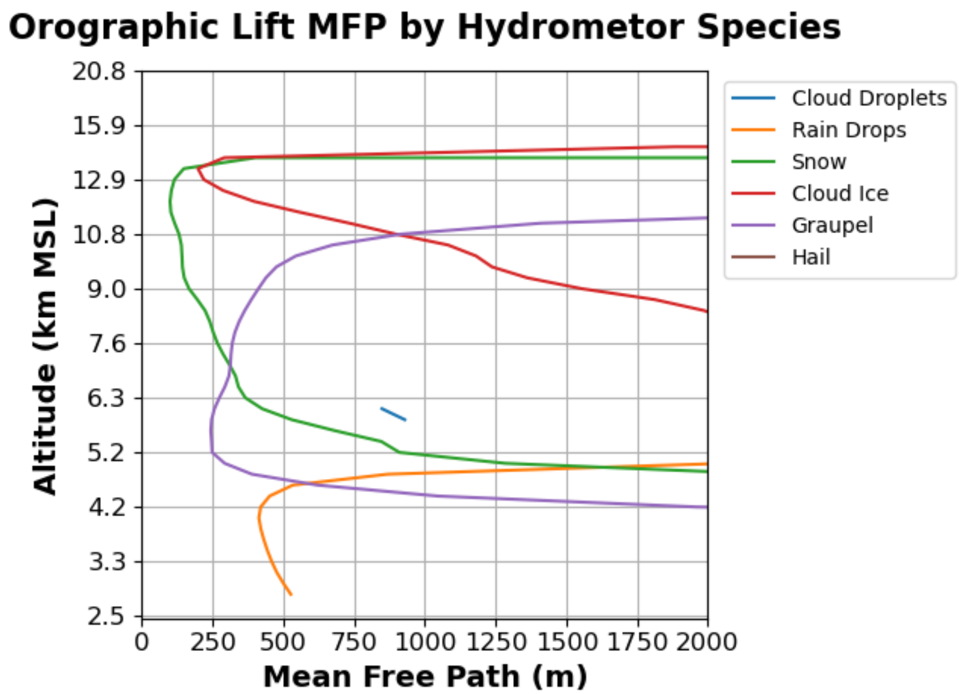
Results

Cloud Structure & Exit Types – Orographic Lift



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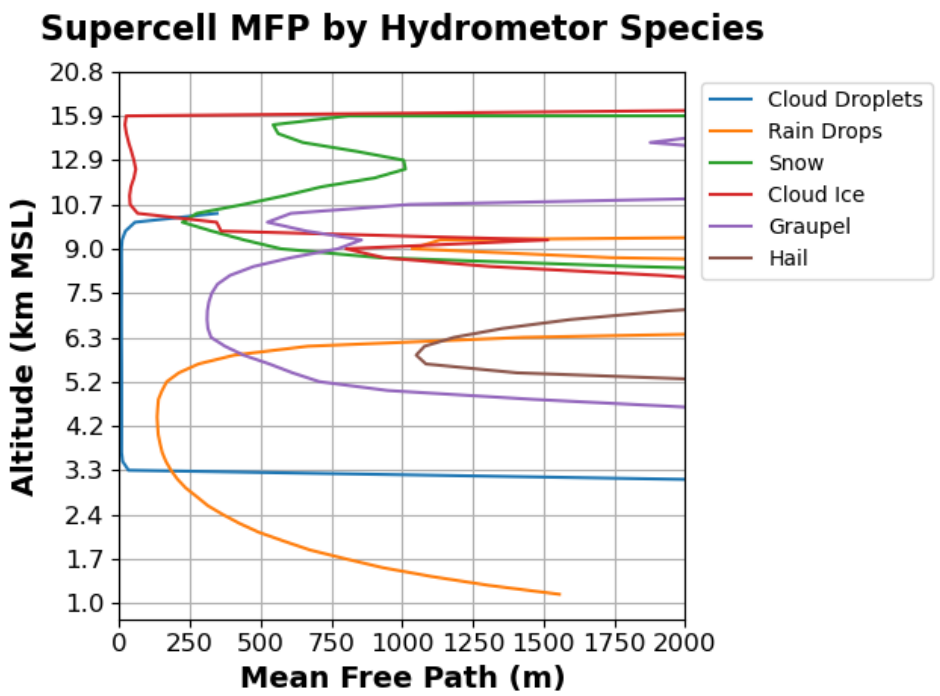
Results

Cloud Structure & Exit Types – Supercell



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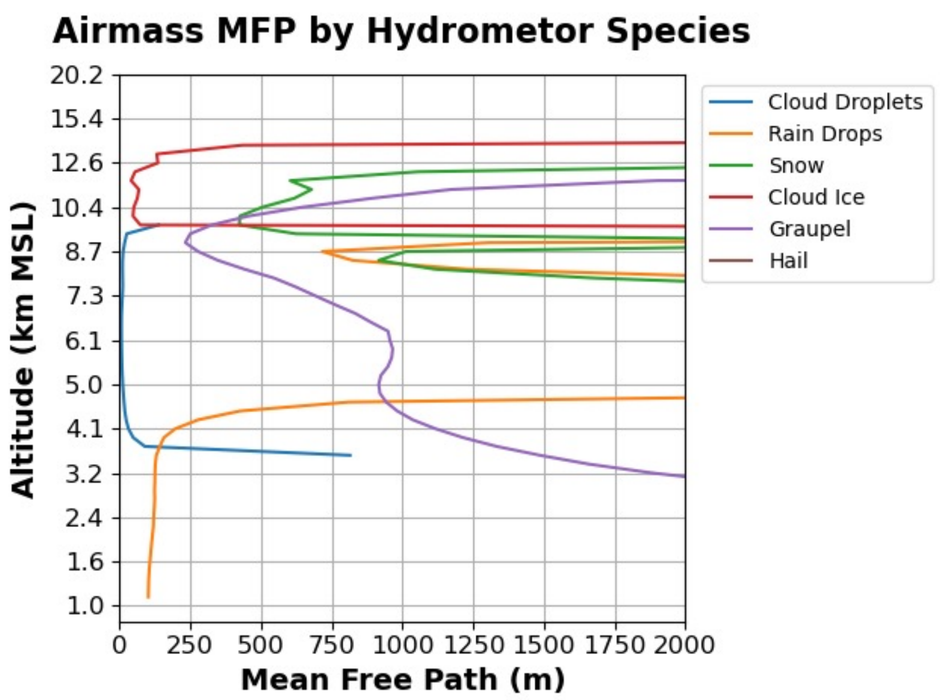
Results

Cloud Structure & Exit Types – Sea Breeze



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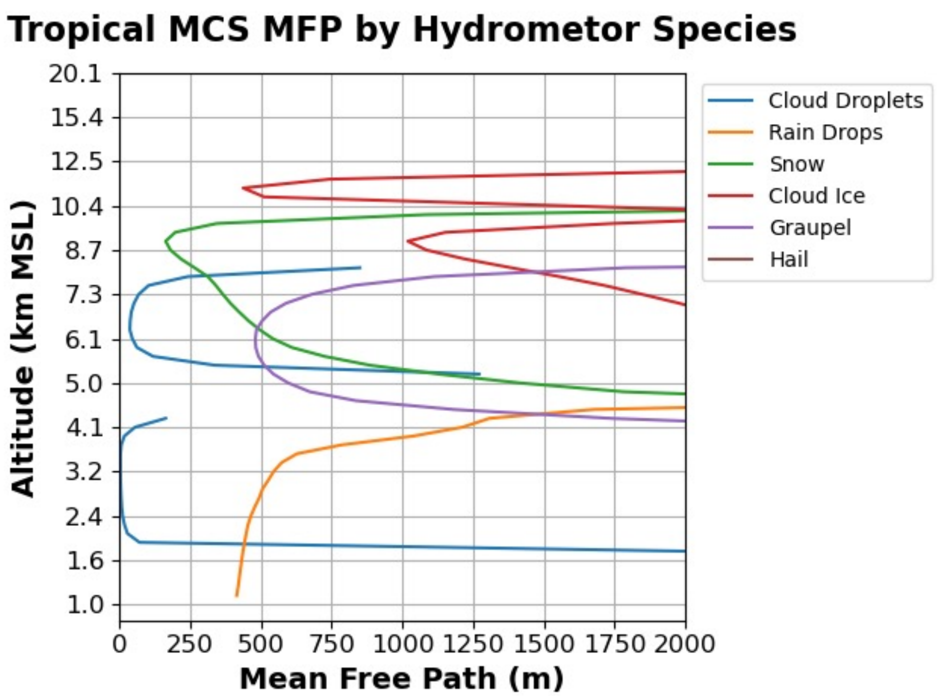
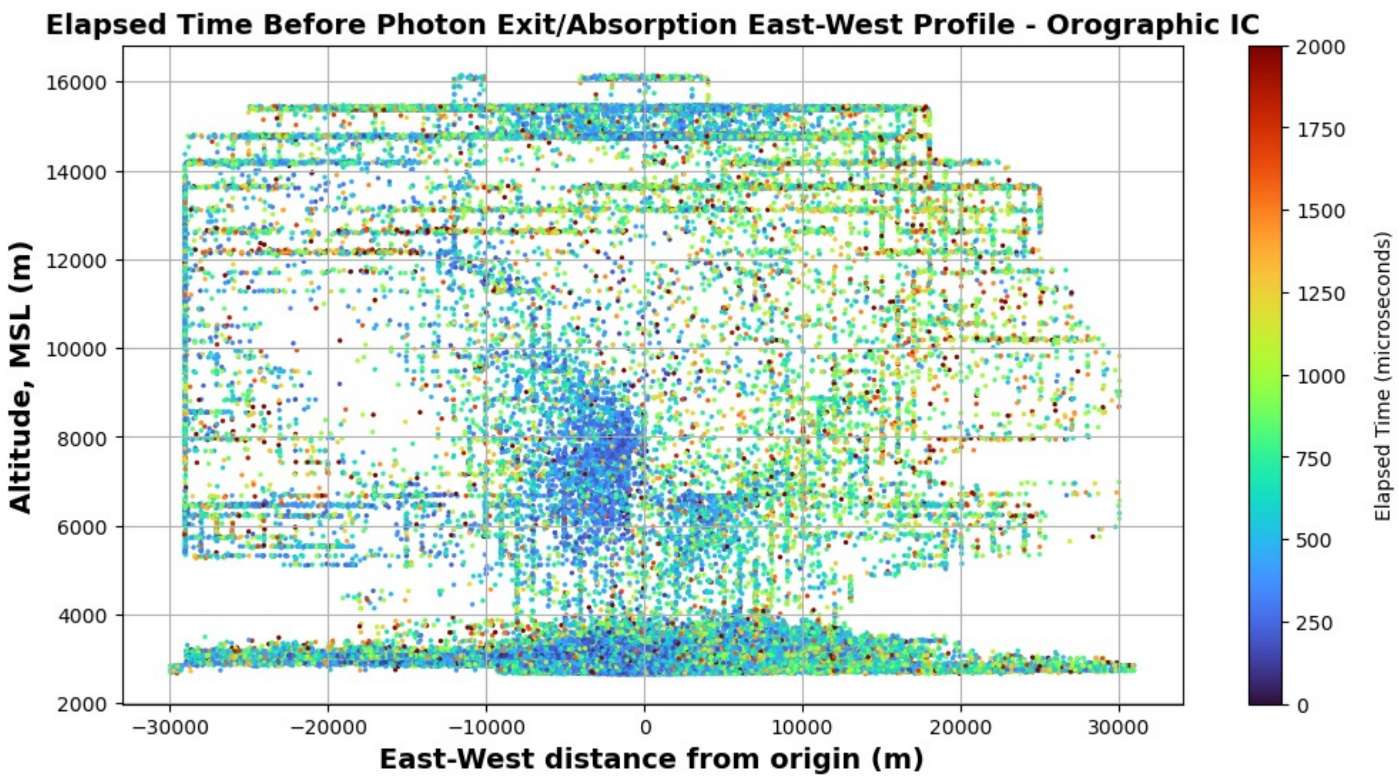
Results

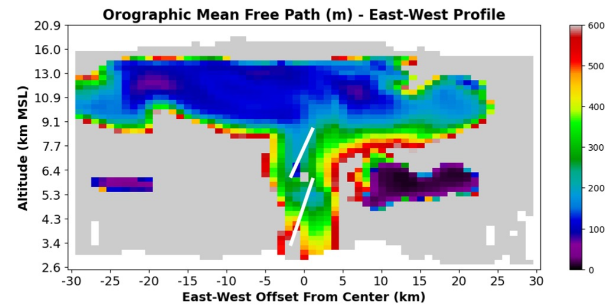
Cloud Structure & Exit Types – Tropical MCS



Results

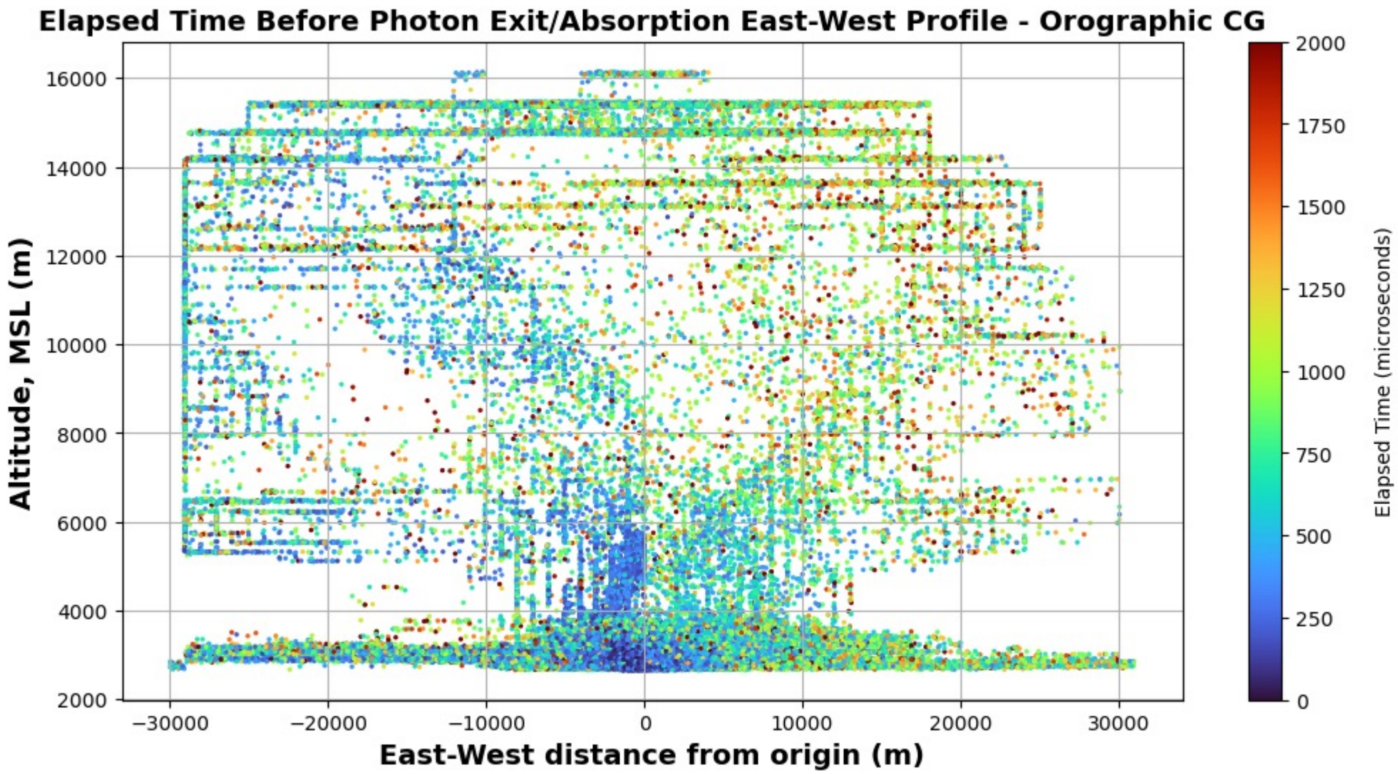
Photon Time to Exit – Orographic Lift IC

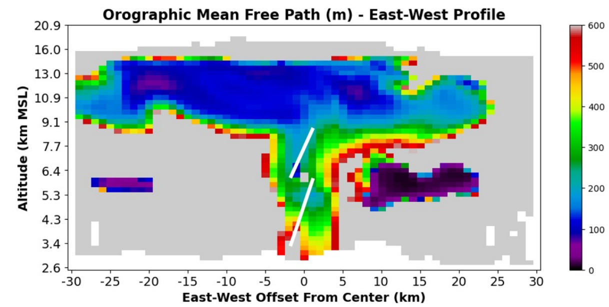




Results

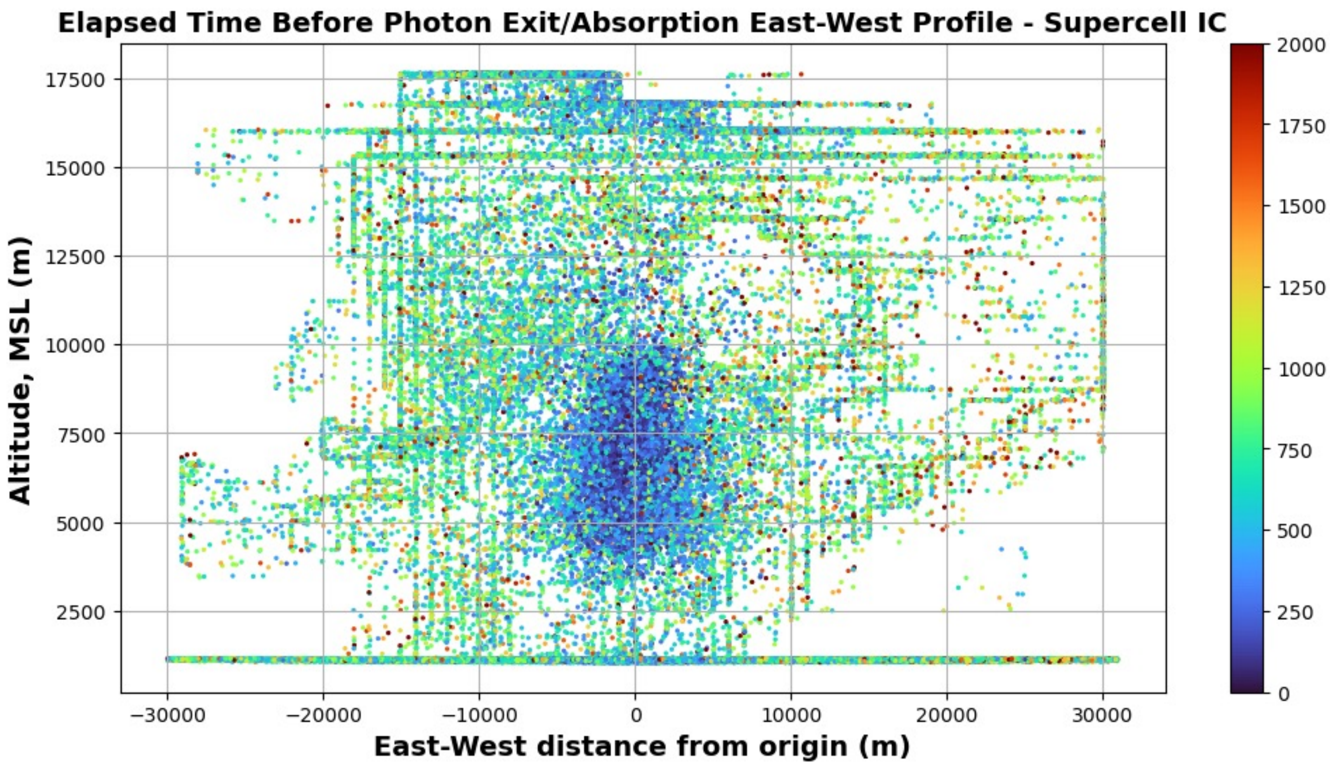
Photon Time to Exit – Orographic Lift CG

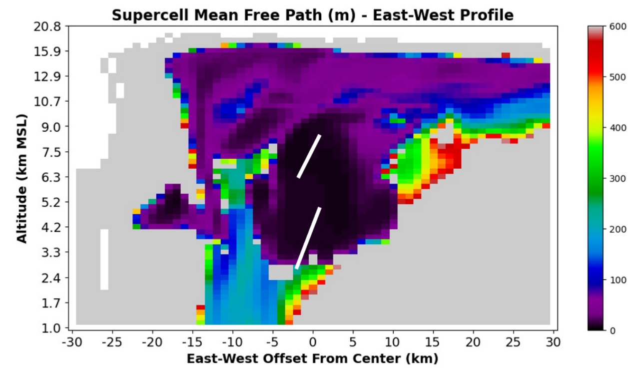




Results

Photon Time to Exit – Supercell IC





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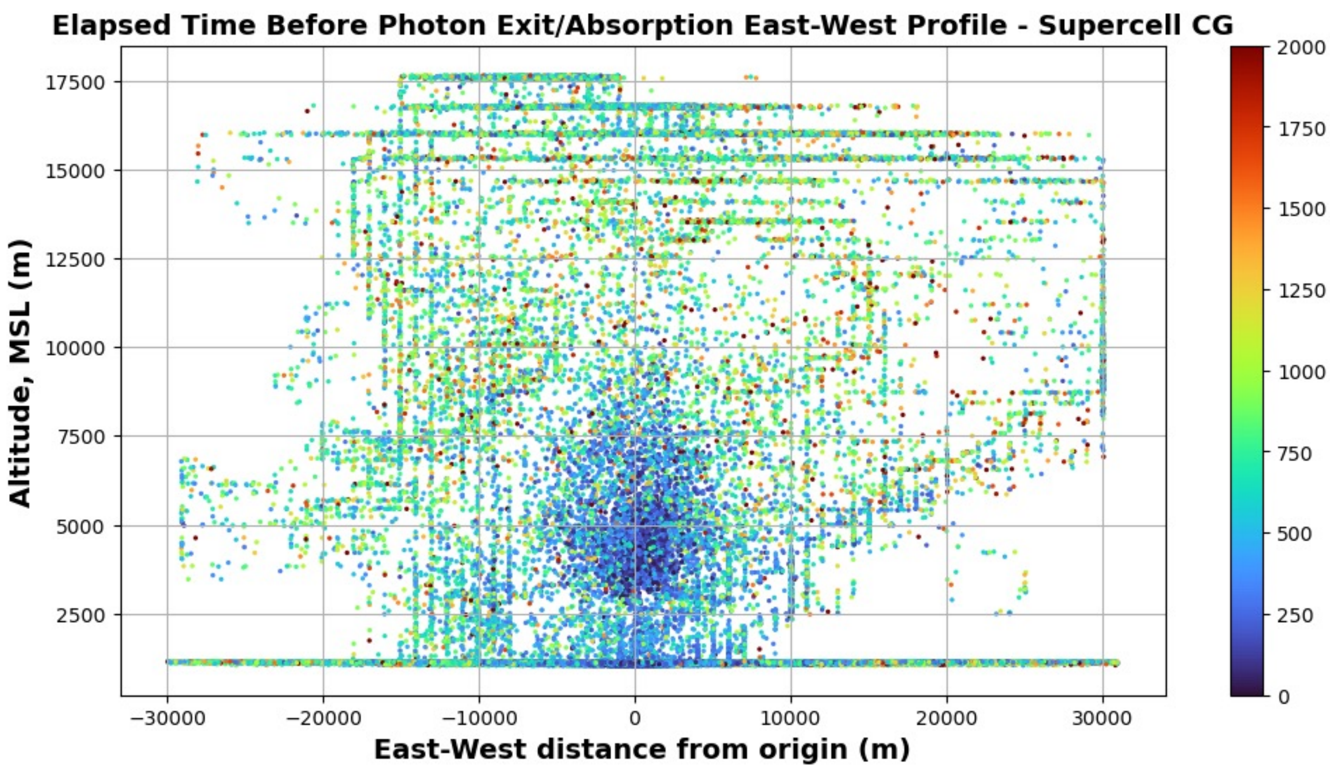
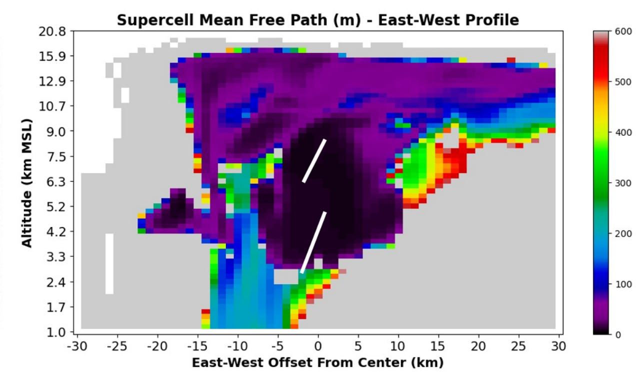
Results

Photon Time to Exit – Supercell CG





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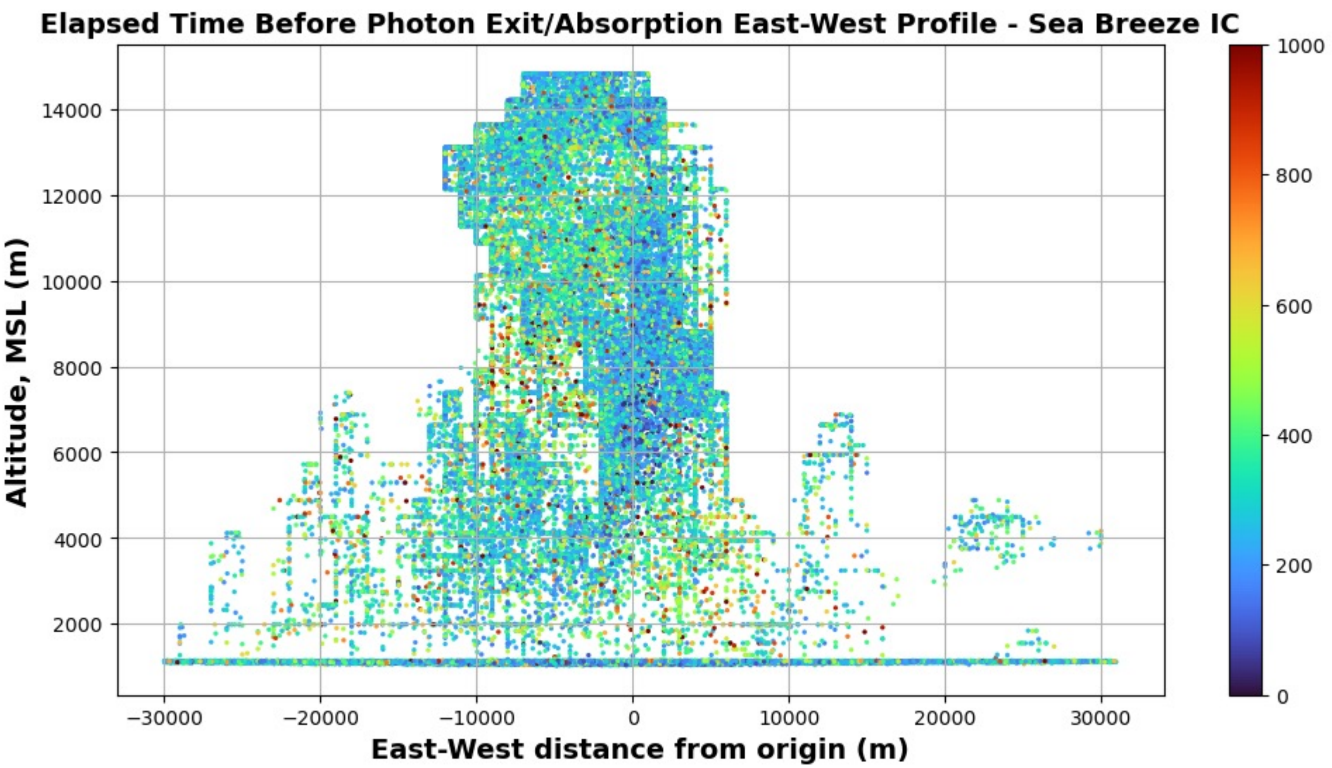
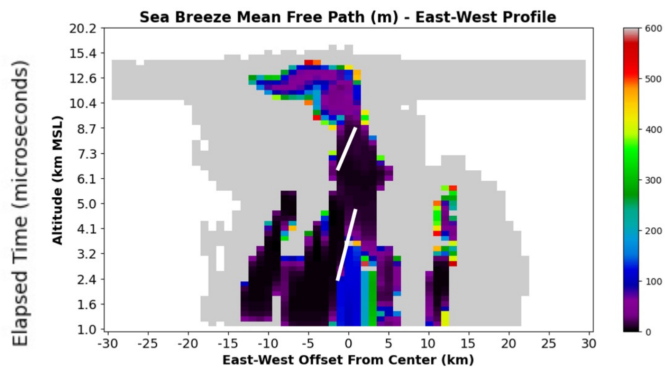
Results

Photon Time to Exit – Sea Breeze IC

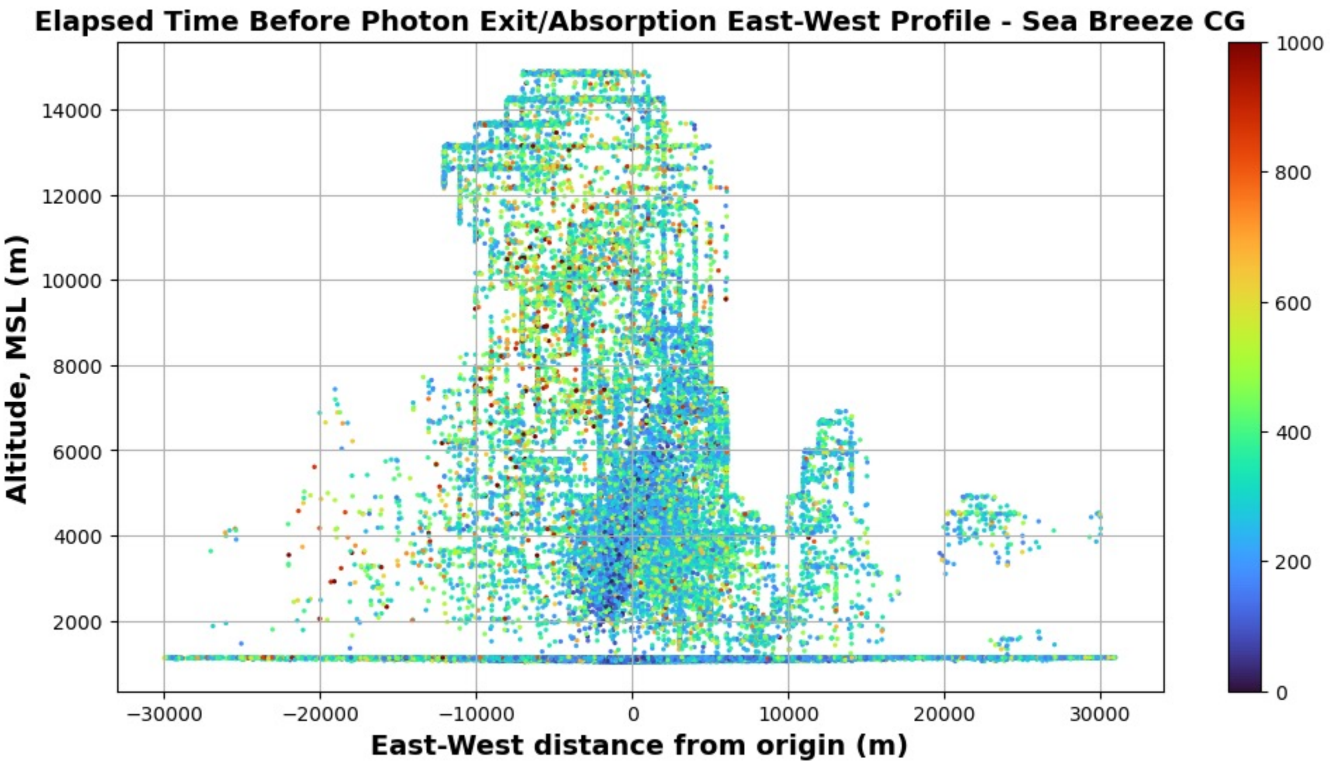


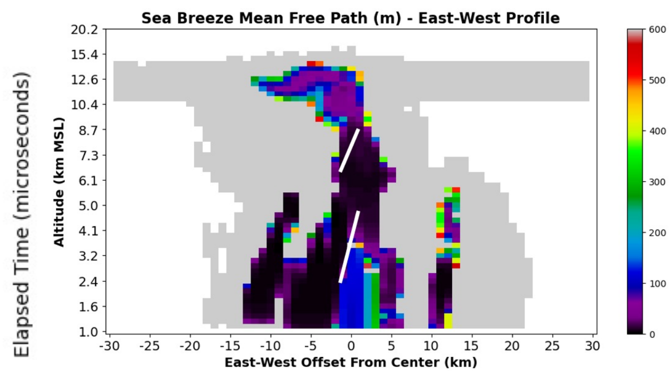


TEACHING WHAT WE RESEARCH. RESEARCHING WHAT WE TEACH.

Results

Photon Time to Exit – Sea Breeze CG

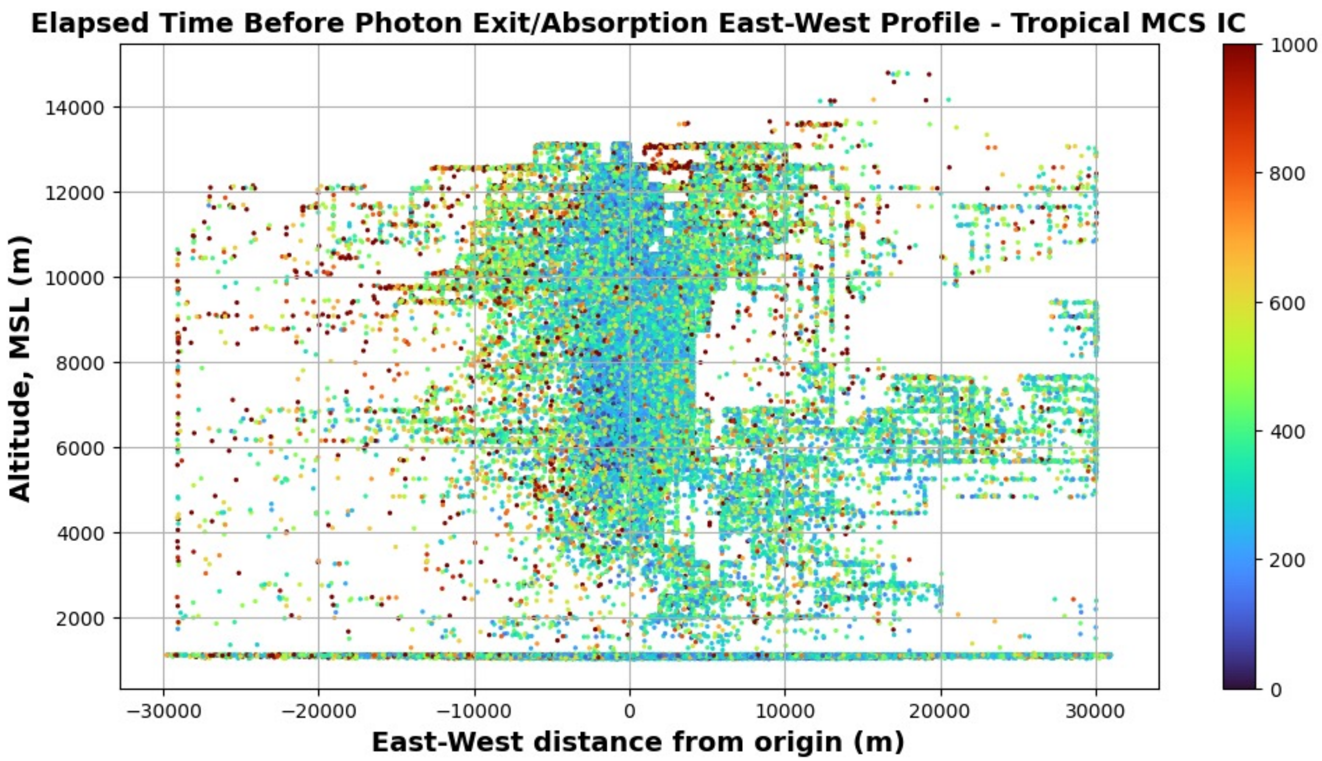


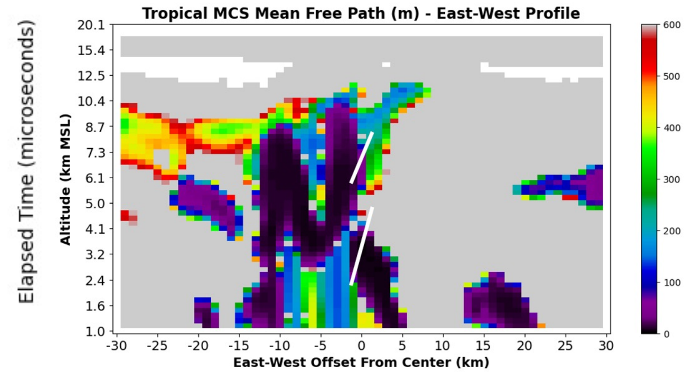


TEACHING WHAT WE RESEARCH. RESEARCHING WHAT WE TEACH.

Results

Photon Time to Exit – Tropical MCS IC





TEACHING WHAT WE RESEARCH. RESEARCHING WHAT WE TEACH.

Results

Photon Time to Exit – Tropical MCS CG