The Development of a Lagrangian Cloud Physics Package in LANL's High Gradient (HiGrad) Model for Wildfire Simulations

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Abstract

In recent years, wildfires of devastating scales have taken center stage in international media. As they continue to intensify each year, we grow desperate to understand their underlying physical processes highlighting the importance of accurate and comprehensive wildfire models and simulations.

Large wildfires often produce thunderstorm clouds, called pyrocumulonimbus clouds (pyroCbs), exacerbating localized weather and causing more damage/loss in affected areas (Fig. 1). The current research aims to build a comprehensive cloud microphysics package for accurate representation of pyroCb development in HiGrad, LANL's parallel atmospheric hydrodynamics model, using a Lagrangian particle-based approach.

Fig 1. PyroCb from the Creek Fire in California from 2019 fire season. Credits: https://www.kvpr.org/science/2020-09-23/creek-fires-fire-breathing-cloud-to-aid-research-on-wildfires-and-climate

Introduction

- PyroCbs form when intensely heated air from fire rises through atmosphere and condenses water vapor due to adiabatic cooling
- Aerosol chemistry/physics are critical in the formation of pyroCbs
- Cloud microphysics better captured by Lagrangian methods over traditional Eulerian - allows explicit simulation of interactions between cloud and aerosol particles
- **Goal:** Develop wildfire model with capabilities for atmospheric aerosol release, cloud microphysical processes, and particulate fallout and/or injection into the stratosphere

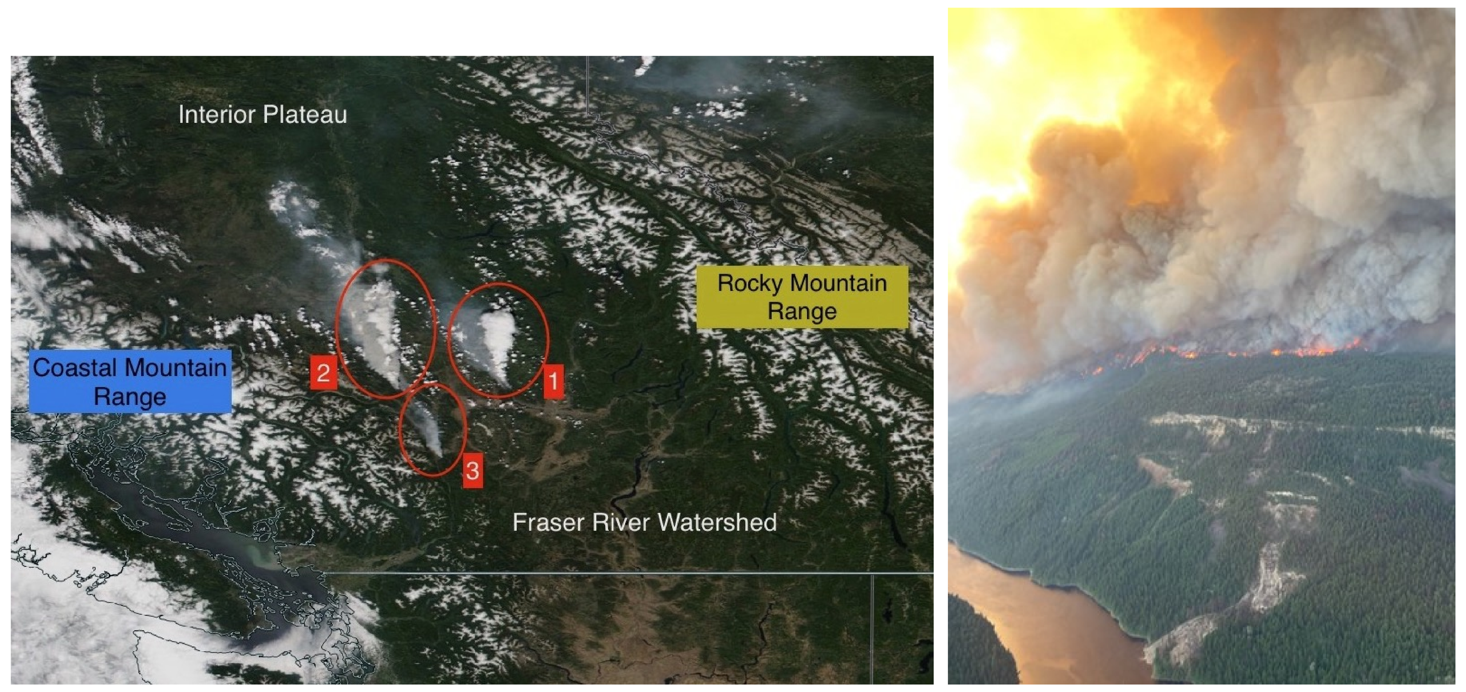

Fig 2. Left: Satellite image of Sparks Lake (1), McKay Creek (2), and Lytton Creek (3) fires on June 30th displaying pyroCb clouds over the Sparks Lake (1) and McKay Creek (2) fires in British Columbia; Right: Sparks Lake fire front on June 30th, 2021. Credits: NASA Worldview, British Columbia Fire Database.

Methods and Equations

Lagrangian Cloud Model

- Eulerian flow-field + Lagrangian approach using "super-droplet method" by Shima et al. (2009) (Fig. 3)
- Aerosol activation happens when water condenses onto aerosol
  - Diffusional growth of droplet by condensation:

$$\frac{dr}{dt} = \frac{GSF}{r} \qquad (1)$$

$$G = \frac{1}{F_k + F_d} \qquad F_k = \left(\frac{l_v}{R_v T} - 1\right)\frac{l_v}{qT} \qquad F_d = \frac{R_v T}{D e_s(T)} \qquad (2)$$

  - Black Carbon and Organic Aerosol: Background Aerosol and Ice:

$$S = \frac{q_v}{q_{vs}} - a_w e^{\frac{A}{r}} \qquad S = \frac{q_v}{q_{vs}} - 1 \qquad (3)$$

- All features tested with simulation of Sparks Lake Fire from British Columbia 2021 fire season (Fig. 2, 4-5)

F	Reynold's ventilation factor
F_k	Thermal diffusion coefficient
F_d	Vapor diffusion coefficient
S	Supersaturation
l_v	Latent heat of vaporization
R_v	Moist gas constant
T	Temperature
q	Thermal conductivity of water
D	Diffusivity of water vapor
e_s	Saturation vapor pressure
ρ_w	Density of liquid water
q_v	Water vapor mixing ratio
q_{vs}	Saturation mixing ratio
a_w	Water activity
r	Particle radius

Tab 1. Variable definitions for equations 1-3.

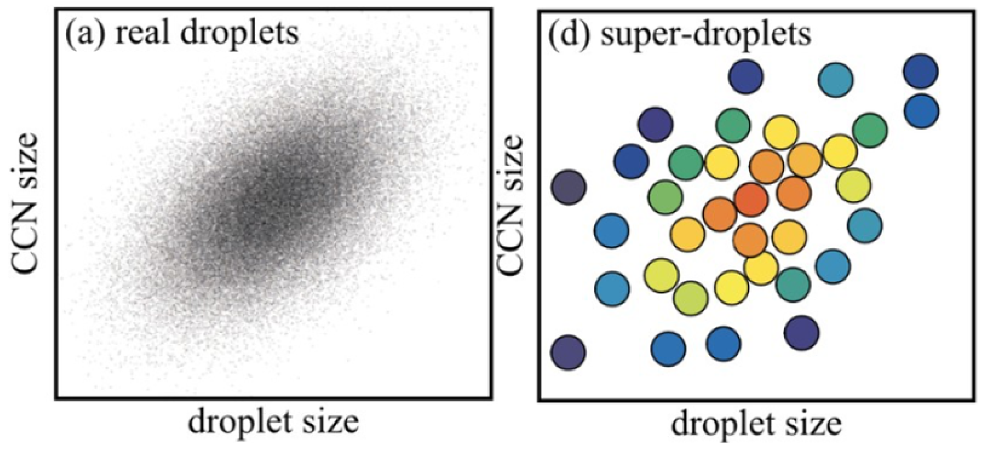

Fig 3. The Super-Droplet Method is used to represent the enormous number of aerosol and cloud particles inside the grid cell of a cloud model. Super-droplets are traced in physical space and they experience all of the microphysical processes represented in the model (condensation/evaporation, freezing/melting). Each super-droplet represents a specific number of particles (multiplicity).[1]

Results

Simulation of BC21 Sparks Lake Fire using Lagrangian Cloud Model

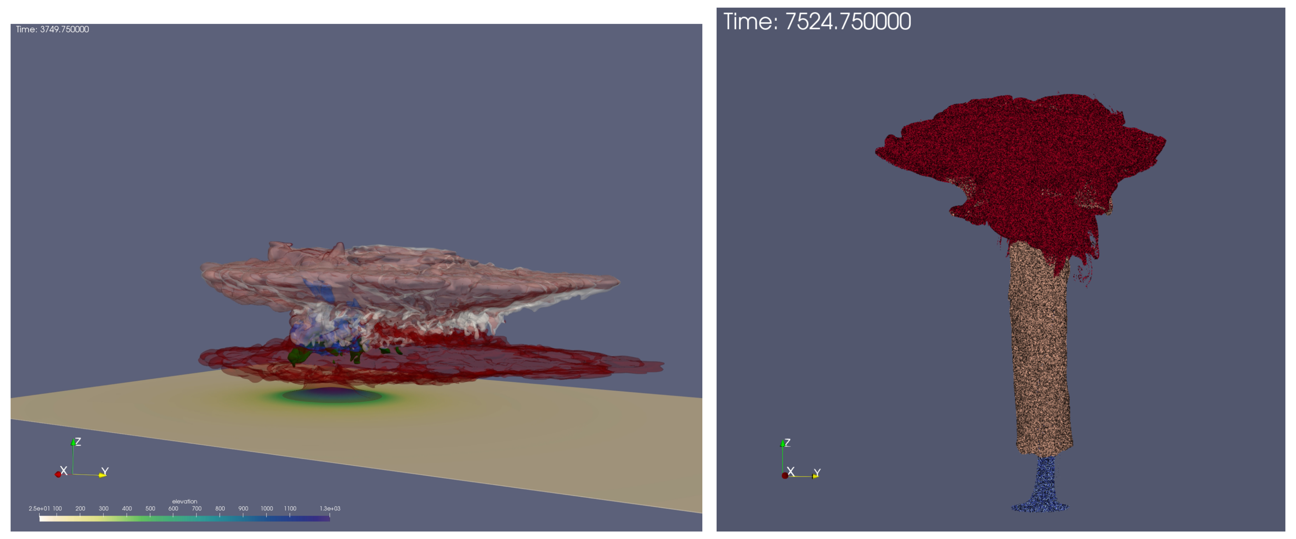

Fig 4. Left: Simulation of Sparks Lake fire from BC21 using Eulerian bulk scheme (ice - white, cloud water - blue, rain - green, aerosol - red) reached an injection height of 16 km; Right: Simulation of Sparks Lake fire from BC21 using Lagrangian particle-based scheme (ice - red, cloud water - peach, black carbon - light blue, organic aerosol - dark blue).

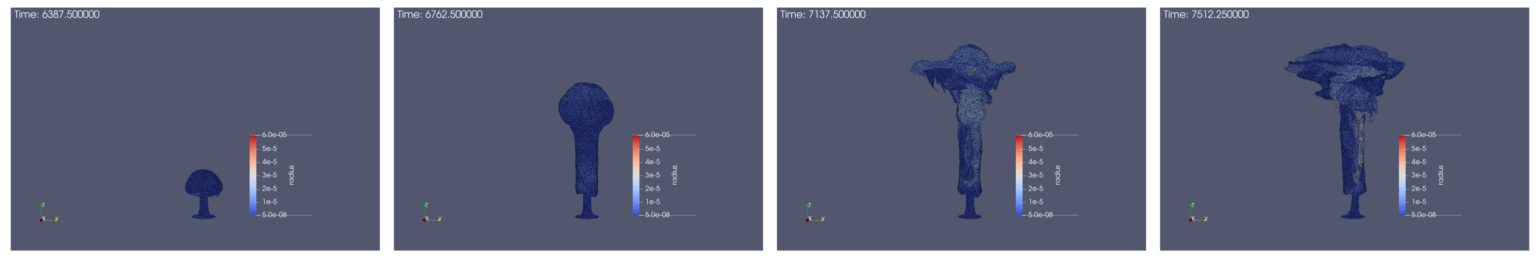

Fig 5. Time lapse of the pyroCb simulation of the Sparks Lake fire. The simulation plume rises to over 14km. The Sparks Lake fire had a record injection height of 16km.

Results

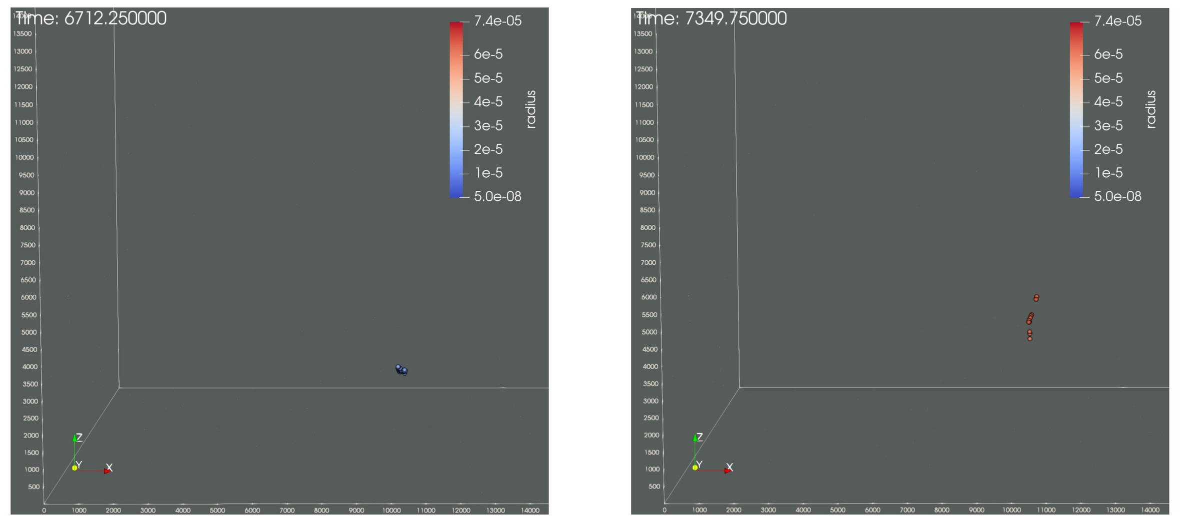

Fig 6. Particle-tracking is enabled using unique IDs to follow particles of interest as they are activated and grow in time and space.

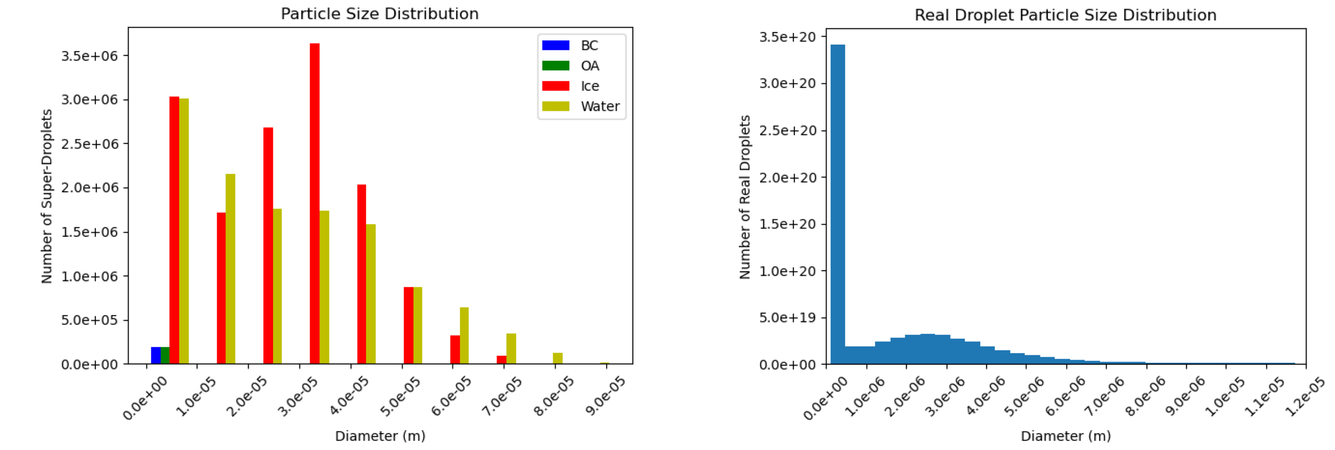

Fig 7. Particle size distribution (PSD) of super-droplets by particle type (left) and particle size distribution of the "real" particles being represented in the multiplicity of the super-droplets (right) for Sparks Lake fire simulation (Fig. 5) after 4500 timesteps.

Conclusions and Future Work

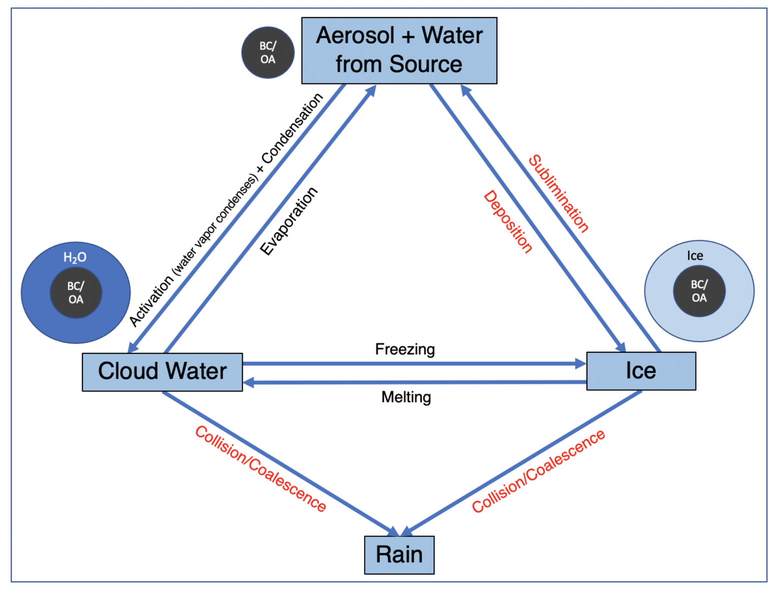

Fig 8. Summary of phases and processes represented in the current Lagrangian Cloud Model with depictions of how particles undergo each phase change. The processes in black are represented in the results presented on this poster. The processes in red are currently being implemented.

- Lagrangian approach calculates transport and growth of particles individually using ODEs → no numerical diffusion
- More accurate representation of micro-scale cloud processes in large-scale wildfires
- Lagrangian framework enables particle tracking in time + space
- Implementation of collision/coalescence physics will allow precipitation and lightning
- Studying interactions of additional fire products (ash, dust, etc.)
- Comparison to observational data

References

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Acknowledgements

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