Modeling Smoke Plume Dynamics from Imagery

El HEAVN' : The Hearing, Exploring, And, Visualizing of Nubes

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Executive Summary

Forest Fires are natural processes that are necessary for healthy resilient forests. However, disasters can happen when wildfire spread is not understood and mitigated. Houses burn down, people are unable to evacuate, and wildlife and civilians can be trapped, injured, or killed. Mapping the spread patterns of wildfires makes it possible to efficiently contain active fires and predict future spread. In this project, we are observing, analyzing, and modeling smoke plumes from forest fires. The most cost-effective and safe method of locating the heat source of a fire is observing smoke and analyzing its behavior through computer modeling. A model such as the one we have created will help first responders react to forest fires in a more informed and effective manner based on camera observations of a smoke plume.

Introduction

a. Forest Fires

Forest fires are an increasingly common and unpredictable disaster. People who live in areas where forest fires are common are at great risk due to delayed evacuation alerts and information during a fire. In the United States in 2018 alone, there were 58,083 forest fires that destroyed over 25,000 structures (including 18,137 residences and 229 commercial structures) and burned 8,767,492 acres of forest (*Wildfires and Acres*, n.d.). These statistics have increased in the past 30 years, correlating to climate change across the United States.

In order for firefighters to successfully control a wildfire, they must have information about the fire location, movement, and areas that are at high risk. Unfortunately, this information is often unavailable to firefighters; they can find themselves going into a dangerous environment completely unaware of conditions and sometimes without the ability to communicate with their team members via radio in environments (Haynes & Madsen, 2017).

Using computer modeling to understand and visualize smoke plumes can be very beneficial when it comes to trying to predict the path, location, and attributes of fire. Specifically, plume imaging is a way to predict the behavior of a fire from afar. With this technology, firefighters will be safer and better able to protect at-risk areas in a forest fire.

b. Previous Approaches

When we began creating this model, the first thing we had to do was understand what a smoke plume is, how it forms, and what factors are most important to predicting the movement of a fire. We began by reading *Stormscapes: Simulating Cloud Dynamics in the Now* (Hadrich et. al.), which gave us an idea of how clouds form. From this paper, we were able to gain insight into the buoyancy, density, and mass that our modeled plume must have in order to accurately represent smoke from a forest fire.

Initially, we wanted to use this model as a basis for our project and create a simpler and more computationally efficient version directly for smoke plumes that could be used for field deployment. However, we soon discovered that each parameter within the model constituted its own complex derivation and simulation; therefore, any level of simplification would not be viable. Instead, we used the Stormscapes model to understand the principles for smoke and cloud formation and inform our agent-based model.

c. Project Goal

The goal of this project is to accurately model smoke plums, specifically the condensation of water vapor onto atmospheric debris, in order to map a wildfire through remote camera imagery. As trees are consumed by a moving wildfire, they combust. This means heat, sugar, and oxygen become carbon dioxide, water, soot, and ash in the fire. The soot and ash are cloud condensation nuclei (CCN). When combined with water vapor, CCN makes a smoke plume visible. By studying this process and modeling it with agent-based modeling in AgentScript (Densmore, 2012), we are able to gain an understanding of the behavior of smoke plumes and how they might reflect the location and movement of the wildfire.

Additionally, if the smoke plume from a real-world wildfire can be replicated by our model, then the model can be used in real-time to determine the behavior of an active fire.

Model Framework

a. Combustion

The most important aspect of a smoke plume model is the main molecular processes involved with a wildfire, which is combustion. The combustion of wood is a complex process that can vary with wood type, water content, and the temperature at which combustion is occurring. We used the following equation as the basis for combustion in the model:

$$C_6H_{10}O_5 + O_2 \rightarrow CO_2 + H_6O + CO + CCN$$

Figure 1. The unbalanced equation for the combustion of a tree

This assumes that the main component of wood is cellulose [1] and that some of the combustions will be incomplete, leaving behind carbon monoxide (*Chemical Composition*, n.d.).

b. Fuel

Combustion occurs at different rates based on the type of forest that is burning. By accounting for this, we are able to approximate the effects of wood type, water content, and temperature on combustion. The vegetation composition of the Santa Fe National Forest is as follows:

Classification	**%**	**Dominating Tree Types**
Timberland	64	Ponderosa-Pine, Douglas Fir
Woodland	36	Pinion, Juniper, Oak

Figure 2. Santa Fe National Forest Composition (Lambert, 2004, #)

Additionally, ponderosa-pine trees make up 22% of all land in the Santa Fe National Forest. Based on these statistics, our model assumes that the forest is entirely ponderosa-pine trees, as this will give an accurate approximation.

The average biomass of a ponderosa-pine tree for trees between 11 and 40 years old is 15.765 kilograms (Grulke & Retzlaff, 1999). Since ponderosa-pine is a softwood (Hardwoods, n.d.), most of the tree is composed of cellulose or $C_6H_{10}O_5$ and will burn in accordance with our combustion approximation (Rowell et al., 2012). The model is tuned to burn in accordance with these data points and can incorporate other fuel types as well given these parameters.

c. Initial NetLogo Model

The first iteration of our model was written in NetLogo 3D. It consists of a basic 3D space with oxygen (blue spheres) moving in Brownian motion. At random, trees combust (turn red), consuming oxygen and releasing water (orange spheres), which rises at an arbitrary rate.

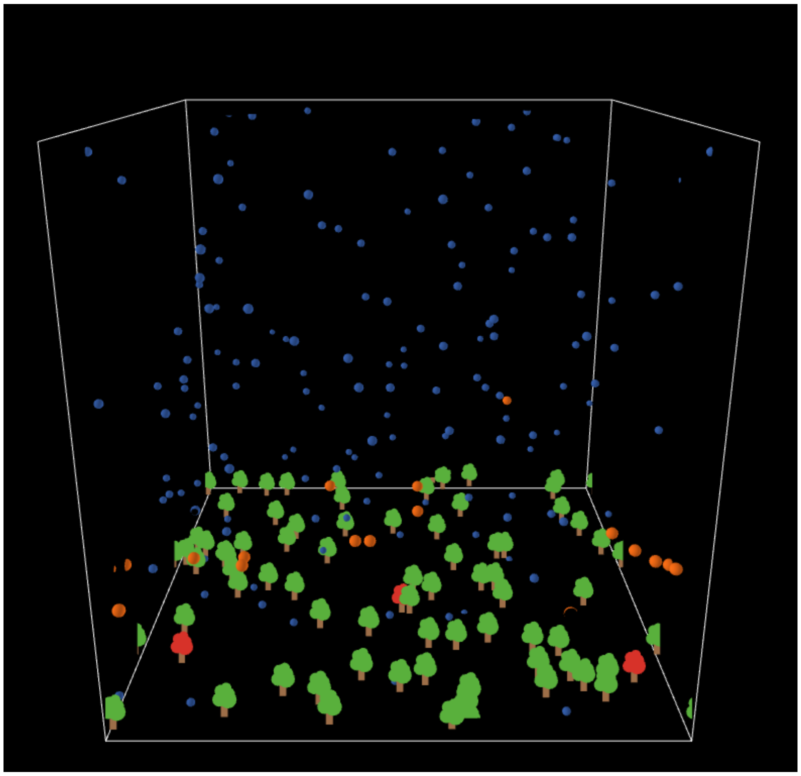


Figure 3. The original framework made in NetLogo 3D that we used as a base for our AgentScript Model

This served as a basic outline from which we could implement greater functionality; however, we quickly found that NetLogo may not be ideal for deployment. Though the framework is great for prototyping, the lack of typical programming conventions proved frustrating and inefficient. These pitfalls resulted in a model that would be difficult to expand. Additionally, despite its relative simplicity, the model is computationally demanding, indicating that it lacks scalability. These factors indicated that switching to a different framework may be the best approach for our project. With that in mind, we pivoted to writing the model in AgentScript. Using the framework of the original NetLogo3D model, we were able to make a more accurate forest and begin constructing the smoke plume.

Real-World Data

a. AlertWildfire Imaging Data

AlertWildfire is an imaging system with cameras all across the Southwest and the Western United States that aims to locate wildfires based on the location of their smoke plumes. The smoke plume is located in space and in relation to the surrounding territory through triangulation as facilitated by multiple camera angles.

Figures 4 and 5: AlertWildfire camera images of the Aztec Springs Prescribed Burn

The current technological capabilities of the AlertWildfire imaging system are to manually draw lines between observed points from the images (features on the smoke plume) and known points shared with a model (geographical features like mountains or stars). Each camera is calibrated by this process and the error is corrected using the Levenberg-Marquardt algorithm. (*Alert Wildfire*, n.d.)

However, the imaging system is limited to manually relating known geographical points in a model of the area to observed points. Our work is to automate the process by which a smoke plume is correlated with a ground location that will increase the response time of such an imaging system. A model like ours will facilitate a more rapid determination of the location of a fire in order to provide that information to first responders and reduce damage and casualties.

b. Controlled Burn Data

After using the AlertWildfire Data to understand the process by which smoke plumes can be observed and measured, one of the obstacles we came across was figuring out how quickly smoke rises, which is an unpredictable and varying number. We completed a controlled burn of our own to gather specific data about fire and smoke behavior. We used a combination of dead needles and live branches of a ponderosa pine tree in the school parking lot to simulate a forest fire in a very small and controlled manner. The wind during this experiment was moving at a relatively average speed for Santa Fe (7mph) and the setting for the experiment was in an unsheltered location (*US Wind Climatology*, n.d.).

Figure 6: Controlled burn still images

We took measurements of the velocity of smoke with camera footage shot in 4K at 30fps by analyzing several different sections of burn videos in Davinci Resolve 17. Using this tool we were able to visually and manually identify how many distinct features in the plume moved per frame. The speed at which the smoke moved was approximately 60cm/s (2cm/frame). In creating a physical experiment, we were able to implement the data for how fast the smoke rose on average into our computer model.

Smoke Plume Model and Implementation

a. Burning Process

The trees in our model are all based on ponderosa-pine trees as discussed in the Fuel section. These are softwood trees, are the most common trees in New Mexico forests, and are commonly burned in wildfires. The patches in the model are each 100m^2 and the fire spreads from patch to patch. Based on the fire spread model developed in the 2019 New Mexico School for the Arts Supercomputing Challenge project, “It’s ‘Bout To Get Lit Up In Here: Modeling Forest Fire Risks in Northern New Mexico,” the fire in our model takes 15,000 seconds (250 minutes) to spread from one patch to the next given that the slope between each of the two patches is 0. Each fire begins on the center patch and will ignite any neighboring patch of trees that have not yet caught fire.

This framework makes it very simple to implement wind and slope as factors that affect fire spread; however, we moved on to focus on modeling the smoke plume.

b. Plume Formation

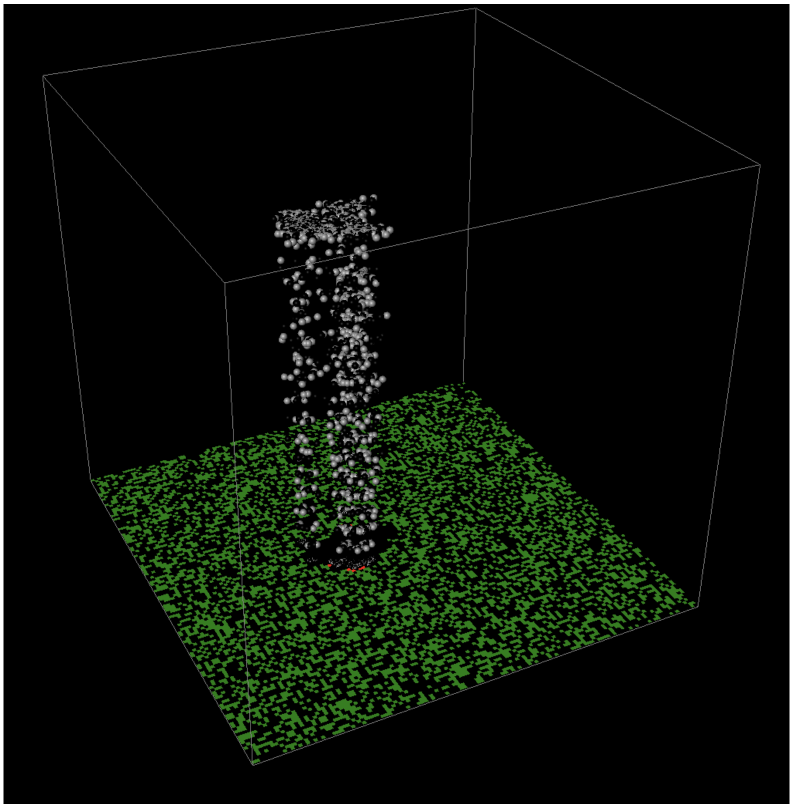
After forming a rudimentary model of the burning forest, we set out to accurately construct our plume. A study on the “Characterization of Combustion Aerosols for Haze and Cloud Formation” (Hallett et al., 2007) found that ponderosa-pine wood burns at a rate of about 10g/100s. This indicates that the average ponderosa-pine tree (15.765kg) will take approximately 43 hours to burn entirely and will release smoke for that entire duration (Hallett et al., 2007). The concentration of condensation nuclei (CN), all particulate matter in clouds that includes hydrophilic and hydrophobic particles in the smoke from a ponderosa-pine tree, is 50,000 to 500,000 CN / cm^3 (Schmale et al., 2017). The ratio of CCN/CN in smoke is 0.72; therefore, the density of CCN in smoke can be estimated at 162,000 CCN/cm^3. This smoke, with a CCN density of 162,000/cm^3, rises at a rate of 1 Liter/second (Hallett et al., 2007).

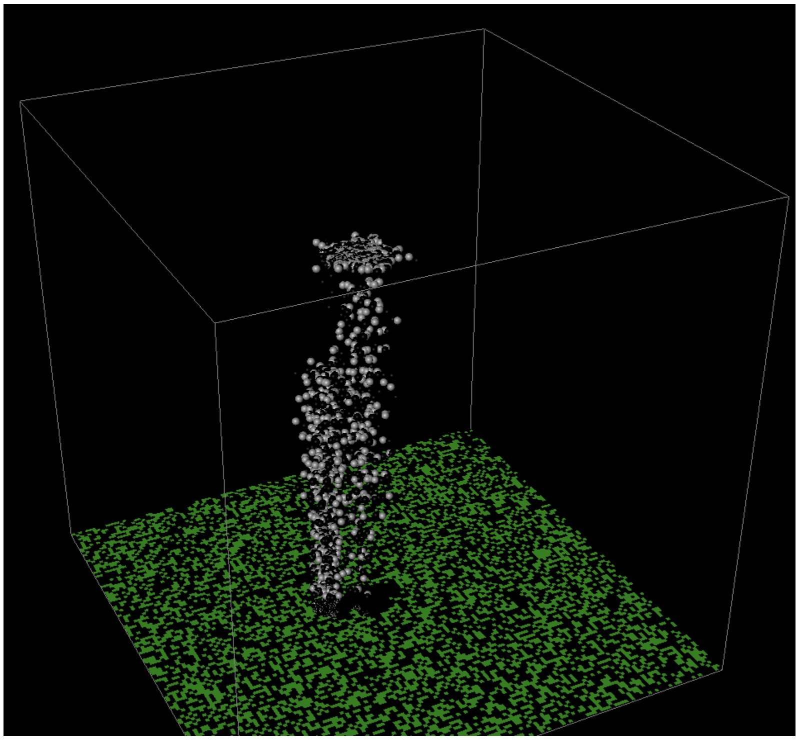
Scaling all of this information to the size of the model produces the following values: each tick is 1,000 seconds, burning patches will release 2,430,000,000,000 CCN particles each tick, and burning patches will release 0.7166 liters of water each tick. These quantities of CCN and water are represented by a single black sphere and a single gray sphere respectively in the model. The smoke rises at a rate of 600m/tick, as informed by our controlled burn.

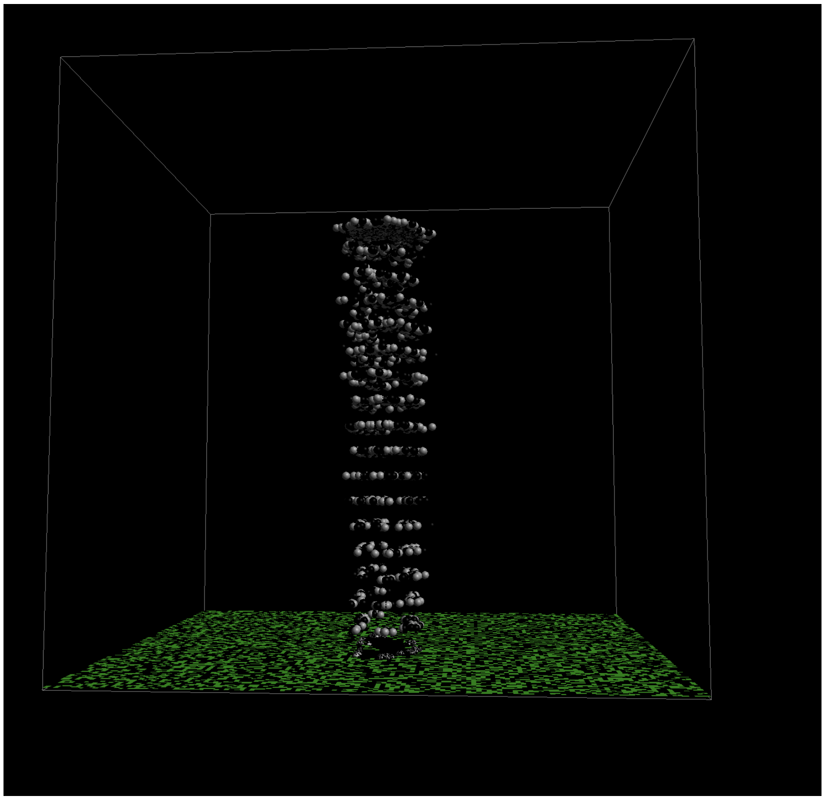
The fire smoke cools at 1 degree Celsius per 100 meters of altitude (Curtis, n.d.). The smoke stops rising when the temperature reaches the dew point of -2 degrees Celsius, which is the yearly average for Santa Fe (*Climate & Weather Averages in Santa Fe, New Mexico, USA*, n.d.). Currently, we assume that the temperature of the smoke plume begins at 100 degrees Celsius immediately after the water within the tree vaporizes and is released as smoke. The implementation of these parameters into our model creates a functional smoke plume in our model that resembles the behavior of smoke plumes for real-world wildfires.

Results

Our final plume model correlates to the spread of a forest fire. We were able to test the applicability of our model framework by altering parameters, such as the density of the forest (percentage of trees, or number of 100m^2 patches that contain trees), the vertical velocity of the smoke, the initial temperature of the smoke (how hot the fire is burning), the dew point (to correspond to a particular day), the characteristics of the trees in the model (for example, juniper instead of pine trees), and the speed of fire spread.







Figures 7, 8, and 9: Three different angles of the smoke plume from a ponderosa pine tree forest where CNN are black spheres and Water is gray spheres

After successfully being able to burn our forest and model a plume, we are able to begin analyzing its movement and try to decipher the heat source. When a smoke plume rises above a fire, the concentration, visual appearance, and movement of the plume correlate to the location of the fire and its movement. Just as we were able to determine the location of a plume by beginning with information about the fire, the model can be reverse engineered to begin with information about a plume and determine the characteristics of a fire. Being able to analyze this backwards in the model proved challenging; therefore, our ability to obtain data about the effectiveness of the model in this particular application was hindered. Many of the environmental and computational aspects of our plume were more complex than we had anticipated. As a result, we plan to continue working to analyze our plume and forest fire in order to make this possible.

Even so, we were able to implement all of the computational structures for this model and have created a useful structure for fire spread prediction in the field. The model can be used as an educational tool for understanding fire spread and can be tuned to fit specific conditions in other forests.

Conclusion

a. Takeaways

In conclusion, we were able to make a functional plume and model a forest fire in AgentScript that can be used as an educational resource for discussing and learning about wildfire spread and a framework for automating the translation of smoke plume imagery into real-time data about the location of a wildfire. Through several iterations of our model, we were able to identify and model the most impactful parameters for smoke formation: tree composition, atmospheric dew point, smoke particle temperature, and vertical velocity of smoke particles. Finally, the work that we completed fostered a greater understanding of scientific and computational practices, laying a strong foundation for future work and research.

b. Limitations and Errors

Complex systems such as wind, condensation onto CCN, and smoke plume dispersion could not be feasibly implemented due to the scope and timeline of our project. Currently, there is no representation for wind in the model, and water condensation is approximated by ceasing the vertical motion of particles when said particles reach the dew point. Modeling the dispersion of smoke particles is computationally demanding and further optimization will be required to account for all the particles produced during a wildfire. At the moment, the number of smoke particles visible in the model is limited to maintain functionality. With further research and work, we hope to implement these systems.

c. Future Plans

As our timeline permits it, we intend to implement the systems mentioned in our limitations and errors section. These systems of wind, condensation, and particle dispersion will increase the accuracy and applicability of our model. Additionally, we hope to implement more ground fire spread aspects into our model based on the framework developed in “It’s ‘Bout To Get Lit Up In Here: Modeling Forest Fire Risks in Northern New Mexico.” These aspects include terrain slope, GIS compatibility, and wind speed effect on ground fire spread. This will allow us to simulate smoke plumes in real-world environments, such as the Santa Fe National Forest.

We would also like to improve the current visualization abilities that our model provides. While the model currently visualizes the structure of the smoke plume functionally, this model would best develop into a more computationally advanced version that could more accurately predict movement and hear heat sources within the smoke.

Finally, we want to eventually add sound to our model through sonification, perhaps as a project in future years. We looked at several different examples where scientists are already using sonication to display data. One example of this is the solar wind radio made with parameter mapping (*Sonification: Data Like You've Never Heard Before*, 2013). Parameter mapping refers to relating specific aspects of the data back to a specific variable in the music. The size and spread of the fire could be directly related back to the tempo and pitch of the music and then communicated in the form of music to firefighters in the field (*What Is Sonification? | Arts and Architecture Research*, n.d.).

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