Smoke Models and Applications

Patricia Azike

Computing PhD

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Overview

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Introduction

Wildfires are unexpected fires that start in rural or urban regions and can last long over a vast area of land.

Wildfires emit smoke which contains pollutants such as: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM)

Figure: Wildfire and smoke in Los Angeles National Forest, California

https://daily.jstor.org/a-recipe-for-ancient-wildfires/

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Seed Papers

- Paper I: Modelling smoke transport from wildland fires: a review (Goodrick et al., 2013 [1]).
- Paper II: Analyses of BlueSky Gateway $PM_{2.5}$ predictions during the 2007 southern and 2008 northern California fires (Strand et al., 2012 [5]).
- Paper III: Evaluating a fire smoke simulation algorithm in the National Air Quality Forecast Capability (NAQFC) by using multiple observation data sets during the Southeast Nexus (SENEX) field campaign (Pan et al., 2020 [3]).
- Paper IV: Ash3d: A finite-volume, conservative numerical model for ash transport and tephra deposition (Schwaiger et al., 2012 [4]).

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Smoke Models

Box Models

The box model is the most fundamental method for forecasting emission concentrations in an airshed [1, 2].

Assumptions

- pollutants are instantly and uniformly spread
- concentrations can be simulated over coarse temporal scales
- wind speed is not necessary

Applications

- predicts short- and long-term thermal and PM changes
- Ventilated Valley Box Model (VALBOX)
- analyzed the total smoke loading in a valley [1]

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Smoke Models

Plume Models

Gaussian plume models specify the emissions source as a point containing the fire [1].

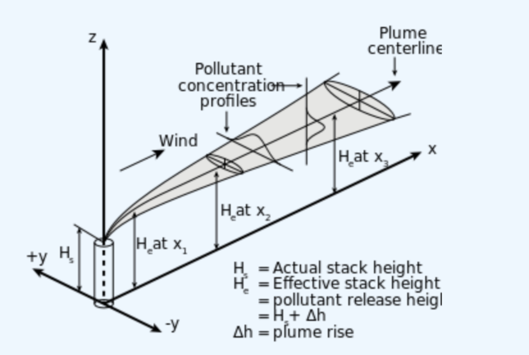

Figure: Visualization of a buoyant Gaussian plume

https://www.envis.org/technology/air-pollution/

Smoke Models

Plume Models

The dispersion of a smoke pollutant is calculated as

$$C = \frac{Q}{u} \cdot \frac{f}{\sigma_y \sqrt{2\pi}} \cdot \frac{g}{\sigma_z \sqrt{2\pi}} \tag{1}$$

- transport of smoke is determined by trajectory winds
- do not require so much weather information
- assumes that smoke moves in a straight line
- do not detect altering trajectories
- applied to the Simple Approach Smoke Estimation Model (SASEM)

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Smoke Models

Puff Models

Puff models simulate smoke dispersion by creating a sequence of puffs.

- have highly varying winds
- account for complex terrains
- address time-varying variables
- inability to adequately calculate plume rise

CALPUFF is a generalized non-steady-state air quality modeling system

- simulates dispersion processes using the output of 3-D modeling domain
- disadvantaged due to undocumented activities regarding burns

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Smoke Models

Particle Models

Predict variations of a fixed number of particles as they are advected throughout the model domain

- employ coordinate systems that effectively track particles
- HYSPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory model
  - a hybrid model used to calculate the dispersion and deposition of air pollutants
  - employs a technique involving puffs, particles, or both
- FLEXPART
  - simulates the transport and dispersion of passive tracers in the planetary boundary layer (PBL)
  - includes a density-correction term

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Smoke Models

Eulerian Models

Calculate the transport and dispersion of smoke pollutants using coordinates fixed in space.

- allow for a more straightforward evaluation of the cumulative consequences of several plumes
- evaluate the effects of chemical changes
- CMAQ
  - simulates dispersion, and deposition
  - often been used to educate key stakeholders
  - has inherent biases
  - corrected using the constant air quality model performance (CAMP)

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Smoke Models

Eulerian Models: Ash3d

Ash3d is a three-dimensional novel Eulerian advection and dispersion model

- solves for mass conservation in the atmosphere
- is intended for operational settings
- defined method for calculating source term

$$\frac{dS}{dz} = S(z)\frac{k^2\left(1-\frac{z}{H}\right)\exp\left[k\left(\frac{z}{H}-1\right)\right]}{H\left[1-(1+k)\exp(-k)\right]}, \tag{2}$$

where H is the plume height, S is the erupted mass at a given time, z is the vertical height, and mass distribution over height is controlled by k [4].

Grid models are constrained by grid sizes.

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Smoke Modeling Frameworks

BlueSky

- BlueSky combines a smoke transport and dispersion model with other components
- estimates $PM_{2.5}$ impacts from a single fire and the cumulative effects from numerous fires

Pathways

presents the various components from fire information to dispersion models used

Strand et al., 2012 [5] determined BlueSky's predictions using observations from the 2007 southern California and 2008 northern California fires.

- southern California: underestimated
- northern California: performed well

Smoke Modeling Frameworks

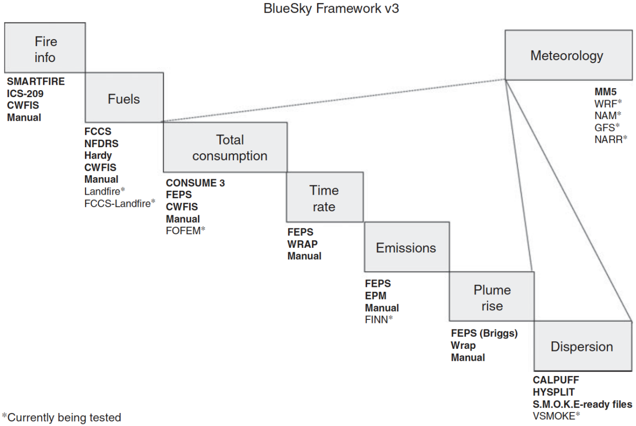

Figure: [1]

Smoke Modeling Frameworks

NAQFC

The National Air Quality Forecasting Capability is fire signal-capturing algorithm that utilizes multiple models and observations

- depends on BlueSky for emissions data
- Hazard Mapping System (HMS) fire detection algorithm
- employs the US EPA Sparse Matrix Operator Kernel Emission (SMOKE) to calculate plume rise
- NOAA National Weather Service's (NWS) North American Multi-scale Model (NAM) and CMAQ for meteorological forecasts and chemical transport models
- identifies the location of wildfires and analyzes their magnitude
- adequately describing fire emissions and their impact on air quality is particularly difficult for NAQFC

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Research Challenges

Characterization of the emissions

- assumptions
- reliance on constant emission rates
- smoke monitors are limited by location

Meteorological information

- forecasts with wide error margins
- weather-imposed constraints
- inability to calculate fire size from aerial measurements
- discrepancies in the temporal resolution

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Future Work

- include more fundamental physics
- use box model for emissions
- employ adaptive mesh refinement (AMR) to simulate smoke on large domains

References

[1] S. L. Goodrick, G. L. Achtemeier, N. K. Larkin, Y. Liu, and T. M. Strand. Modelling smoke transport from wildland fires: a review. *International Journal of Wildland Fire*, 22(1):83–94, 2013.

[2] H. H. Lettau. Physical and meteorological basis for mathematical models of urban diffusion processes. *Proceedings, Symposium on Multiple Source Urban Diffusion Models US EPA*, 28(AP-86):2.1–2.26, 1970.

[3] L. Pan, H. Kim, P. Lee, R. Saylor, Y. Tang, D. Tong, B. Baker, S Kondrugata, C. Xu, M. Ruminski, W. Chen, J. Mcqueen, and I. Stajner. Evaluating a fire smoke simulation algorithm in the National Air Quality Forecast Capability (NAQFC) by using multiple observation data sets during the Southeast Nexus (SENEX) field campaign. *Geoscientific Model Development*, 13(5):2169–2184, 2020.

[4] H. F. Schwaiger, R. P. Denlinger, and L. G. Mastin. Ash3d: A finite-volume, conservative numerical model for ash transport and tephra deposition. *Journal of Geophysical Research*, 117(B4):450 pp, 2012.

[5] T. M. Strand, N. Larkin, K. Craig, S. Raffuse, D. Sullivan, R. Solomon, M. Rorig, N. Wheeler, and D. Pryden. Analyses of BlueSky Gateway PM2.5 predictions during the 2007 southern and 2008 northern California fires. *Journal of Geophysical Research*, 117(D17), 2012.

Thank You!