Modeling wildfire and air quality under climate change

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with contributions from

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CMAS annual meeting

October 5, 2015
Rationale

• It’s getting warm down here.

• Mean annual temperature rise may be stalling (but see 2014), but not hot extremes over land.

• More area is expected to burn.

• Fires set up dynamic feedbacks, including some large positive ones, from affected ecosystems!

• Problem is multiscale in space and time; understanding it needs integration across multiple science domains.

• Challenges to scientific understanding and for policy decisions on mitigation and adaptation.
Area burned in 11 Western states, 1916-2012

- Period of post-conquest fire
- Period of active fire suppression and fuel accumulation
- Period of fire increase

Expectation: Hotter and drier = more fire!
If we just look at fire climatology...

- Statistical fire-area regression models from temperature and precipitation.
- Ensemble projection of sub-regional climate expected with +1°C.
- Forested or mountain ecoprovinces increase more than shrubland and grassland.

the West burns up many times over.

Littell et al. (forthcoming)

(more to the story, but that's another talk)
The largest fires cause most of the trouble

2011 Las Conchas Fire, NM

2000 Cerro Grande Fire, NM

2014 Carleton Complex Fire, WA
Probability of megafires increases

Some ecoregions are affected more, e.g., Pacific Northwest

Big % changes in fire weather, even for RCP 4.5 in 2040s.

Stavros et al. (2014) Climatic Change 126:455–468
**Good news, bad news**

- The West is not burning up
  - Fires run out of real estate
  - “Hotter and drier = more fire” breaks down in the drier.

  *(Krawchuk & Moritz 2011, McKenzie & Littell 2011)*

- But unprecedented losses
  - Iconic ecosystems.
  - Increased probability of large destructive fires.

  *(Stavros et al. 2014)*

- Positive feedbacks
  - The West as a carbon source
  - Biomass-burning aerosols
  - Loss of ET cooling

• and the Southeast may see less fire
  ‣ Lightning-ignited fires will increase a bit.
  ‣ but human-ignited fires will decrease a bit more.

Prestemon et al. (2015) IJWF in review
Wildfire emissions affect daily-average PM$_{2.5}$

Courtesy of the Office of Research and Development, U.S. EPA
Relativized future “smoke potential”
based on megafire likelihood and simulated trajectories

Larkin et al. (2015)
Potential consequences for climate change (global) and human health (local)

- Fires increase ambient concentrations of *short-lived climate-forcing pollutants* (black carbon, organic aerosol, SO$_4$, O$_3$, NH$_3$).

- Impact on the global radiation budget (heating or cooling) is highly dependent on the land cover, e.g., forest vs. grass and woodland (Swann et al. 2012, Bond et al. 2013).

- PM chemical composition may play as important a role as concentrations in health impacts; PM from fires is particularly toxic (Wegesser et al. 2009).
Visibility impairment in pristine areas

Across the West, 20 worst days = wildfire
Framework for regional-scale modeling

Global climate $\rightarrow$ RCPs

Downscaling

Regional climate $\rightarrow$ Fire weather $\rightarrow$ GHGs $\rightarrow$ Chemistry & transport

Radiative feedbacks (GHGs, aerosols, clouds)

Emissions

Emissions from other natural sources

Biogenics

Anthropogenics (e.g., fossil fuels)

Vegetation $\rightarrow$ Fuels $\rightarrow$ Wildfires $\rightarrow$ Smoke

Ignition & behavior

Combustion

Mortality

LSFs $\rightarrow$ Growth

Much more detail in open-access review paper: type “earths future smoke consequences” into google search bar. :-)
Regional Climate Modeling

• Provide high spatial and temporal resolution for meteorological variables not available from GCMs.
• Provides more realistic representation of fire-related weather and extreme events (resolution- and scale-appropriate physics)
• Number of simulations (ensembles) limited by expense
• Typically atmosphere-only models, missing dynamic coupling to other components (e.g., surface hydrology, oceans, chemistry)
**Dynamic models**
- e.g., DGVMs, at regional scales.
- Vegetation limited to plant functional types.
- May include explicit modules for fire behavior and effects.
- No fire spread or other contagious processes.

**Empirical approaches**
- Bioclimatic envelope models.
- Species-level resolution.
- No dynamic changes in vegetation or feedbacks.

**Finer-scale landscape models**
- Species-level resolution.
- Fire spread, contagion.
- Not computationally feasible at regional scale.
• Variability at multiple scales.
• Crosswalks from vegetation.
• Need to update fuel from future vegetation. Models that use the current fuel layers are wrong from the start.
• Understory fuels difficult to estimate from overstory (visible via remote sensing).
• Scale mismatches make “validation” difficult.
Fire climatology

- Climatic controls on fire regimes.
- Top-down (climate) vs. bottom-up (topography, fuels) controls.
- Changing scales of inference: watersheds to ecoregions.

Fire weather

- Fire starts: convective storms, dry lightning.
- Fire spread: relative humidity, wind, fuel connectivity, slope.
- Fire duration & fire progression: consecutive days of fire weather.

Fire severity: patchy at local scales
### Fuel consumption
- Fuel condition (flammability ~ moisture)
- Fuel abundance
- Fuel connectivity

### Smoke emissions
- Combustion phase (flaming, smoldering, residual smoldering)
- Fuel chemistry
- Diurnal profile

#### Consumption and emissions
- **Global climate**
  - RCPs
  - Downscaling
- **Regional climate**
  - Fire weather
  - GHGs
- **Vegetation**
  - Fuels
  - Wildfires
- **Smoke**
  - Ignition & behavior
  - Mortality
  - Chemical & transport
- **Biogenics**

#### Emissions factors used in Consume

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Combustion</th>
<th>PM₁₀</th>
<th>PM₂.5</th>
<th>CO</th>
<th>CH₄</th>
<th>CH₃OH</th>
<th>CO₂</th>
<th>NMHC</th>
<th><strong>Flaming</strong></th>
<th><strong>Residual</strong></th>
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**NOx EMISSIONS FACTORS (e.g., fossil fuels)**

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*Flaring and smoldering sample sizes, respectively*
Speciated emissions of gas and aerosol precursors

- Deciduous trees (isoprene)
- Coniferous trees (terpenes)

Volcanic emissions
- \( \text{SO}_2 \)
- Ash
- \( \text{CO}_2 \)

Sea Spray
- Na
- Cl
- DMS

Wind-blown dust
- Si
- Fe
- Ca
- Mg
- Al
- etc.
Non-fire Source Emissions (2)

Power Generation
- SO₂ and SO₄ (SOₓ)
- NO and NO₂ (NOₓ)
- CO₂

Oil and gas refinement
- VOCs
- NOₓ

Vehicle exhaust
- NOₓ
- CO₂
- Soot

Cook stoves
- OC
- EC
- NH₃

Agricultural burning
- OC
- EC
- NH₃

and many more...

Global climate
- RCPs

Downscaling

Radiative feedbacks (GHGs, aerosols, clouds)

Chemistry & transport

Emissions from other natural sources

Anthropogenics (e.g., fossil fuels)
Feedbacks from vegetation to climate

- Changing radiation budgets with loss of cover or type conversion
  - May increase surface albedo (−)
  - May decrease carbon sink (+)
  - Air–surface exchange due to increased evaporation (+/−)
  - Biogenic secondary organic aerosol radiative feedback (−)

Feedbacks from fire to vegetation

- Depending on severity, fires can be a strong negative feedback on subsequent fires. (−)
- Dependent on vegetation type. (+/−)
- Time–dependent, because fire is.
- Possible conversion of vegetation type with changes in fire frequency or severity in response to climate. (+/−)
Feedbacks from chemistry to climate

- Changing radiation budgets with fire emissions
  - Radiative forcing (RF) of CO₂, O₃ and H₂O (+) emitted directly or formed from precursors in smoke plumes
  - Direct RF of black carbon (+), brown carbon aerosol (+/-)
  - Indirect RF of aerosols from enhancing cloud albedo, lifetime (-)
  - Semi–direct effect of black carbon on clouds (+/-)
  - Short atmospheric lifetime for O₃ and aerosols compared to CO₂ → a high degree of spatial and temporal variability

Feedbacks from vegetation to chemistry

- Changing atmospheric composition with vegetation
  - As vegetation types change emission fluxes of isoprene, terpenes would change
  - May shut down biogenic emissions in burn scar areas
  - Affects oxidant and SOA budgets
Human-related feedbacks

Changes in the wildland-urban interface (WUI)

• Spatial pattern and complexity within WUI.
• Demographics and broader-scale patterns.
• Effects on fire suppression.

Feedbacks to fire probability

• Predictors of arson.
• Recreational land use.
• Commercial logging and thinning, or explicit fuel treatments, can change fire probability in the WUI and elsewhere.

Photos by Ahodges7 & U8oL0 (Wikimedia)

Figure 3—Share of wildfire areas, lightning, and other wildfire ignitions on national forests, 1970-2004. (Source: USDA Forest Service 2007)

Prestemon & Butry (2007)
Model evaluation (1)

✦ Four broad criteria for acceptable performance from the system

• Minimizing the cumulative effects of errors, uncertainties, and biases, e.g., scale mismatch

• Algorithmic and computational feasibility

• Transparency of outcomes: did you get the right answer for the right reasons?

• Robustness to future projections

✦ Ultimately the system needs to match the needs of the assessment (obviously no model fits all)

these 3 slides are “IMHO”
Model evaluation (2)

What to do in the absence of observations:
with some lessons learned from the IPCC

✦ Embrace uncertainty
  • Take advantage of model differences.
  • Ensembles or model averaging.
  • Decide which uncertainties you can live with.

✦ Use multiple lines of evidence
  • e.g., Holocene fire, historical fire, fire observations.
  • Evaluate outcomes at multiple scales.

✦ Don’t expect added complexity to reduce uncertainty.
  • Tradeoffs between complexity and replication.
  • Cumulative error may increase, but confidence in error bounds also increases.
Modeling Guidelines

- Coupled is better than disconnected, especially in modeling vegetation, fuel, and fire emissions in an evolving climate

- Distributions are better than points
  - But don’t regress away the extremes
  - Decide when to use ensemble means rather than preserve the variability

- Watch out for scale mismatches

- Keep it as simple as possible but no simpler

these 3 slides are “IMHO”
Research needs (1): fire and vegetation

- Representing processes across scales
  - Contagion, fire spread, fire-fuel interactions on landscapes.
  - Species-specific responses of vegetation.
  - Key processes intractable to model at regional scales.

- Account for thresholds and tipping points
  - Proposed indicators of both cover a small percentage of (less interesting) cases.
  - Fire-vegetation interactions and feedbacks produce non-linear behavior.
  - Evaluate outcomes at multiple scales (e.g., thresholds may appear only at certain scales, by certain metrics).
Research needs (2): air quality and climate

✦ Better observations of short–lived climate forcers.
  • Brown carbon and other emissions from fires.
  • Role of biogenic emissions in surface cooling (e.g., NOAA SE nexus).

✦ Probabilistic evaluation of air–quality models.
  • Stochastic variation within ensembles, and Bayesian model averaging.
  • Incorporating feedbacks in ensembles with coupled modeling.

✦ Regional climate feedbacks to the larger circulations.
  • Next–generation RCMs with hexagonal grids might address this?
  • Need better coupling to ocean circulations in RCMs.

Photo: S. Urbanski
Dennis et al. (2010)

Skamarock et al. (2011) (NCAR)
The end