Investigation of the Effects of Changing Climate on Fires and the Consequences for U.S. Air Quality, Using a Hierarchy of Chemistry and Climate Models

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Funded by EPA: Fire, Climate, and Air Quality (RFA 2004 STAR-L1)
Objectives

Provide an integrated assessment of the effects of fires in a future climate on ozone and PM air quality in the United States:

- Explore relationship between climate and frequency/magnitude of wildfires in N. America
- Develop scenarios for future fires
- Analyze plume heights from forest fires from MISR data for 2000-2004
  - Quantify the dependence of air quality on height at which emissions are released
- Quantify the effect of present day fires on air quality in the U.S.
  - Examine how different scenarios for future fires will affect air quality in a future climate
- Assess uncertainty in results
Hayman fire caused worst air quality ever in Denver

- 56,000 ha, June 8-22, 2002
- 30 miles from Denver and Colorado Springs

<table>
<thead>
<tr>
<th>Date</th>
<th>PM$_{10}$</th>
<th>PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 8, 2002</td>
<td>40 µg/m$^3$</td>
<td>10 µg/m$^3$</td>
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<tr>
<td>June 9, 2002</td>
<td>372 µg/m$^3$</td>
<td>200 µg/m$^3$</td>
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Colorado Department of Public Health and Environment
Vedal et al., Env Res, 2006
Present day effects of wildfire emissions on ozone over the United States: a case study
(Morris et al., JGR, 2006)

In 2004, a blocking ridge set up over Canada and Alaska creating one of the largest fire seasons on record. In this event, ozone in Houston was the highest for the past four July months.

Blocking highs may last longer under a warming climate, making understanding fire behavior and air quality impacts from Canada and Alaska crucial.
Long-range transport of boreal wildfire emissions can also affect lower 48 states.
Area burned in Canada has increased since the 1960s, correlated with temp. increase.

Gillett et al., 2004

Increased fire frequency over western U.S. in recent decades – related to warmer temp., earlier snow melt.

Westerling et al., 2007
Mean area burned (1° x 1° grid) in 1980-2000 (Westerling et al., 2002)

Mean fuel consumed (Spracklen et al., 2008)

Where are the fires in the western U.S.?

The Pacific North West and Rocky Mountain Forests are most important for biomass consumption and emissions.

Large areas burned in CA and the southwest, but fuel burned is greater in forest than in shrub ecosystems.
Can we reproduce the effects of past fires on OC in the western United States?

- GEOS-Chem simulation of organic carbon from 1987-2004
- Assimilated meteorological data from NASA/Goddard GMAO
- Area burned on a 1°x1° grid (Westerling et al., 2007)
- Fuel loadings from FCCS for the U.S. (McKenzie et al. 2007)
- Fire severity based on analysis of large fires in 2002
- Fires outside the western U.S. were the same each year
- Evaluate results with IMPROVE observations
Wildfires drive interannual variability of organic carbon in the western U.S. in summer 
(Spracklen et al., GRL, 2007)

Model gives same variability as observed OC in summer at IMPROVE sites in the West

OC contribution to total fine aerosol:
40% in low fire years
55% in high fire years
How do we predict of fires in a future climate?

Approach used by Flannigan et al. (2005) for Canada

- Use a gridded data-base of area burned in the western U.S. for 24 years (Westerling et al., 2002).

- Determine the relationship between area burned and meteorology (temp., RH, wind speed, precip) and fire indicators from the Canadian Fire Weather Index (FWI) model, with linear regression.

- Use output from the GISS GCM for the IPCC A1B scenario to predict future meteorology.

- Use GISS output and regression relationships to predict future area burned.
GISS GCM METEROLOGICAL OUTPUT USED TO PROJECT FUTURE EMISSIONS AND AIR QUALITY CHANGES

GISS general circulation model → changing greenhouse gases (A1B scenario)

1950 Spin-up 2000 2025 2050 2075 2100

Area Burned Regressions

Predict Area Burned

Calculate emissions

GEOS-CHEM
Global chemistry model

archived met fields
Examples of area burned regressions for forest ecoregions

Best predictors are generally temperature and fuel moisture codes. R^2 values highest for forested ecosystems, lowest for shrub ecosystems with this approach.

Spracklen et al., in review, JGR, 2008
Available at www.as.harvard.edu/chemistry/trop
Changes in meteorology over the West from 1996-2005 to 2046-2055

- Temp. increases 1-3ºC across West
- Rainfall and RH increase slightly
- Wind speed decreases slightly
Predicted area burned in forested ecosystems

Note increase in area burned and in temperature, with variability.

Predicted area burned for 1995-2004 does not match observed areas on a yearly basis, as it is based on GCM output, but 10 year mean is the same.
Predicted biomass burned by fires in the West, 1996-2055

Results shown as the number of standard deviations away from the mean for 1996-2005.
Predicted changes in fires in the west from 1996-2005 to 2046-2055

<table>
<thead>
<tr>
<th>Increases in Area Burned:</th>
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<tbody>
<tr>
<td>Rocky Mountain Forest</td>
<td>175%</td>
</tr>
<tr>
<td>Pacific Northwest Forest</td>
<td>78%</td>
</tr>
<tr>
<td>California Coastal Shrub</td>
<td>38% (N.S.)</td>
</tr>
<tr>
<td>Desert Southwest</td>
<td>43%</td>
</tr>
<tr>
<td>Nevada Mtns/semi-desert</td>
<td>none</td>
</tr>
</tbody>
</table>

Increase in fuel consumption:
Total in West 91%
Predicted changes in OC and BC in 50 years from fires

Present Day

Change in 50 years
Effect of future fires in a future climate on organic carbon and black carbon in the western U.S.

Present day fires in black, 1996-2000
Future fires in red, 2046-2050

OC increases by 40%, EC increases by 20%.

For OC, 75% of increase is from fire emissions, 25% from higher biogenic emissions in a warmer climate.
Effect of future fires in a future climate on ozone in the western U.S.

- We are doing the same type of simulations for ozone

- Results for one year simulations for present day and future
  - Five year runs planned
Predicted total Western US NO$_x$ emissions

2045-2054 emissions are >50% larger than during 1996-2004
Predicted mean ozone increase due to fires in the West is 3-6 ppb (for 1-5 pm, July) – preliminary! Need 5 years of model simulation.

Effect of fires in ozone in July

- Ozone increases by >5 ppbv at highest concentrations
- *note: Changes due to climate change alone have been subtracted out

[Hudman et al., in prep.]
Multi-angle Imaging SpectroRadiometer- MISR

David Diner, Ralph Kahn, David Nelson, JPL

9 view angles at Earth surface: nadir to 70.5º forward and backward

Continuous pole-to-pole coverage on orbit dayside

360-km swath
9 day coverage at equator
2 day coverage at poles

Overpass around local noon time in high and mid-latitudes

275 m - 1.1 km sampling

In polar orbit aboard Terra since December 1999
Analysis of Fire Plumes: MISR INteractive eXplorer (MINX)

Smoke plume over central Alaska

Cross-section of heights as a function of distance from the source

Histogram of heights retrieved by MINX

www.openchannelsoftware.org
~3000 smoke plumes digitalized over North America

2002
N = 480

2005
N = 980

2004
N = 690

2006
N = 463

2007
N = 580
Height distribution of plumes from MISR

Most plumes are at relatively low altitude at ~noon, but a few are as high as 6 km

We examined the relationship to boundary layer height and stability.
Distribution of (MISR heights-BL height) for smoke plumes

Val Martin et al., in prep.

5-30% smoke plumes are above the boundary layer
Most plumes above the boundary layer are in a stable layer – example shown for one large plume.
**Downscaling of GISS GCM to Regional Scale Model (MM5)**

Daewon Byun

### “GISS2MM5” Model Configuration Comparison

<table>
<thead>
<tr>
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<th>GISS</th>
<th>MM5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HGRID</strong></td>
<td>Arakawa A (scalar) and B (wind)</td>
<td>Arakawa B</td>
</tr>
<tr>
<td><strong>VGRID</strong></td>
<td>Hybrid (Sigma and Pressure)</td>
<td>Sigma</td>
</tr>
<tr>
<td><strong>PROJECTION</strong></td>
<td>Lat./Lon.</td>
<td>Lambert Conformal</td>
</tr>
<tr>
<td><strong>RESOLUTION</strong></td>
<td>4 x 5 degrees</td>
<td>108 or 36 km</td>
</tr>
<tr>
<td><strong># of LAYERS</strong></td>
<td>23</td>
<td>43</td>
</tr>
</tbody>
</table>
Surface Temperature JJA 2000 ("current year")

- Averaged 1st layer temperatures for summer (Jun., Jul. & Aug.)
- Note GISS and MM5 have different layer definitions
  GISS layer 1 ($\sigma : 1.0 \sim 0.971$)
  MM5 layer 1 ($\sigma : 1.0 \sim 0.996$)
Surface Temperature JJA 2050 ("future year")

2050 is much warmer than 2000

Regional details of changes could be different from GCM predictions
Surface Temperature difference JJA 2050 - 2000

- General patterns are well inherited during downscaling, but detailed locations and intensities are re-distributed by finer resolution surface LULC and its own dynamics
Future work on effects of fires in a future climate on air quality (1)

- Improve predictions of fires in shrub and grass ecosystems (CA and southwest)
  - include meteorology the year before, drought indices (PDSI)
  - rain the previous year causes more fuel to be available for the next fire season

- Improve prediction of boreal fires in Canada
  - effect of increasing precipitation, predicted in many GCMS
  - several groups have difficulty obtaining good regressions in eastern Canada
Regressions for Alaska

Area burned (black) and regression fit (red); fit includes observed 500 hPa geopotential height from Fairbanks

Boreal Interior

R² = 53%

Cordillera

R² = 57%

Preliminary results for Alaska

[Hudman et al., in prep.]
Canada - regressions capture variability in some regions

Most GCMS predict increases in rain for high latitudes. What will be the effects on fires? Fuel moisture is crucial. Examine …
Future work on effects of fires in a future climate on air quality (2)

- Effects of changes in lightning on fire ignition?
- Potential increases in length of fire season?
- Impacts of changing climate on fire severity?
- Impacts of land cover changes on fuels?

- Uncertainty analysis using multiple scenarios and models (GCMs)
- Improve calculation of air quality effects using 2°x2.5° GISS GCM and GEOS-Chem with nesting to 1°x1°
Conclusions

- Interannual variability in OC in summer in the western U.S. is driven by variability in fires.
- Regressions of annual area burned in western U.S. capture ~50% of interannual variability. Temperature and fuel moisture are best predictors.
- Using GISS GCM output, forest fire emissions of OC are predicted to double by 2045-2055 resulting in mean increases in OC of ~40%.
- Ozone is likely to increase by a few ppb as a result of the increases in fires.
- Further work is needed on changes in shrub ecosystems (CA and the southwest) and on changes in Canadian forest fires.

- Still to come – finish ozone simulations with GEOS-Chem
- CMAQ simulations at U. Houston.