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MEGAFIRES AND SMOKE EXPOSURE UNDER FUTURE CLIMATE SCENARIOS IN THE CONTIGUOUS UNITED STATES

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1. INTRODUCTION

Over the past several years, large high-intensity fires, or "megafires," have set records for the greatest burn area and most costly fires in several U.S. states. In a short period of time, very large wildfires (VLFs) can release many tons of fine particles and other pollutants that are hazardous to human health. Observed increases in VLF occurrence have heightened concerns about widespread air quality impacts. In addition, VLF occurrence is expected to increase in many regions of the United States as the future climate in those regions is likely to be warmer and drier. The danger of smoke exposure from future VLFs depends on several spatial factors, including the likelihood of VLF occurrence, fuel loading and consumption, emission rates, air transport patterns, and population density.

We combined climatological transport modeling, fire emission rates, and population density to determine the areas within the United States where a VLF would result in the greatest human exposure to smoke. To corroborate results from this trajectory-based analysis, we performed a large ensemble of dispersion modeling simulations to estimate probabilistic smoke impacts for select areas identified as high-risk for future VLFs. Coupled with a synthesis of recent studies on the likelihood of VLF occurrence under future climate scenarios, these results provide a view of future smoke management and emergency response needs.

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2. LITERATURE REVIEW OF FUTURE VLFs

We conducted a literature search to identify where VLFs are likely to occur in the United States through the year 2100. Several studies provided forecasts of long-term fire potential (fire size, fire occurrence, fire frequency, and area burned) and spatially explicit information on future VLF occurrence. We used these studies to develop a gridded map of forecasted fire potential and increased probability of VLFs (Fig. 1).

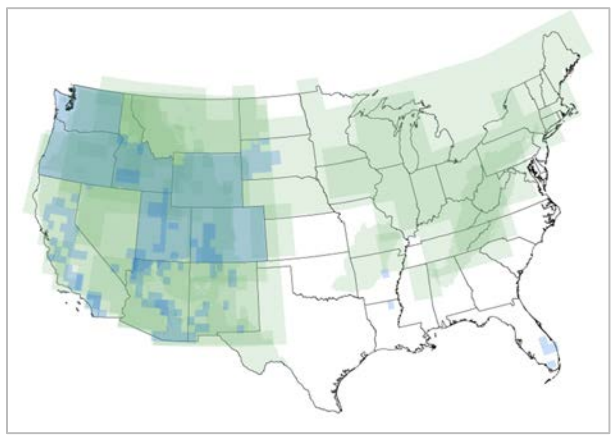

Fig. 1. Spatial area forecasts of increased fire potential and an elevated chance of VLFs. Darker shades indicate more studies forecasting increased fire potential.

These studies suggest a higher potential for increased fire probability, including VLFs, in the Southwest, parts of California, the Pacific Northwest, the interior Mountain West, and along the Rocky Mountains. For the eastern United States, increased future fire potential was forecast throughout Appalachia, the Ozarks, South Florida, and much of the upper Midwest.

3. SMOKE IMPACT POTENTIAL

To assess the potential for smoke from a fire at a given location to impact populations, we created monthly maps of smoke impact potential by combining smoke emissions maps with transfer functions and populations. The smoke impact potential is a qualitative index with nonphysical units that addresses two factors: the amount of smoke that would be generated by a hypothetical VLF, and the number of people who might be exposed to that smoke.

Mathematically, the smoke impact potential score at a given source fire location *l* and grid cell *ij* was determined by

$$\sum_{ij}\left(t_{l,ij} \times p_{ij}\right) \times ER_l \quad (1)$$

where $t_{l,ij}$ is the normalized (1 at source cell, < 1 elsewhere) transfer function value for source location *l* for grid cell *ij*; p_{ij} is the total population within grid cell *ij*, based on 2010 zip code census; and ER_l is the wildfire small particulate matter ($PM_{2.5}$) emissions rate for location *l*. The gridded emission rates and smoke transfer functions are discussed in Sections 3.1 and 3.2. Sample results are shown in Section 3.3.

3.1 Emissions

We developed a gridded map of wildfire emission rates of $PM_{2.5}$ for the continental United States (CONUS) for use in the smoke impact potential calculations. Consume 4.0 (Prichard et al., 2006) was applied with climatologically representative fuel moisture values under dry fuel conditions to predict fuel consumption and emissions for a 100-acre fire set in each grid of a 1-km fuelbed. The fuelbed is a crosswalk between the Fuel Characteristics Classification System (FCCS) and Landscape Fire and Resource Management Planning Tools Project (LANDFIRE) (McKenzie et al., 2012). These emission estimates were generated as part of the "Fire Everywhere" test case from the Smoke and Emissions Model Intercomparison Project (SEMIP) (Larkin et al., 2012). The final emissions data were averaged to a half-resolution version (64 km) of the North American Regional Reanalysis (NARR) grid. The resulting emission map is shown in Fig. 2.

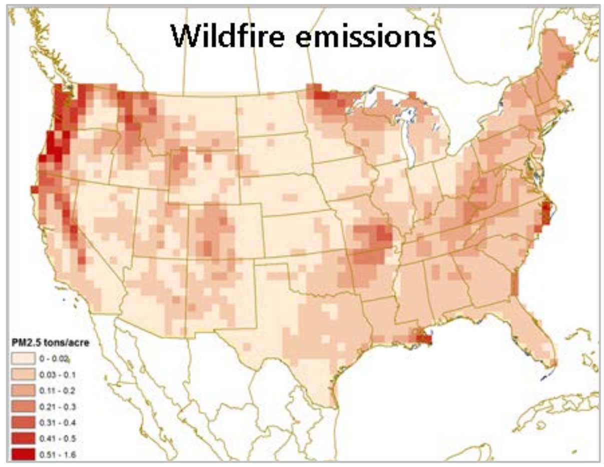

Fig. 2. Average $PM_{2.5}$ emissions in tons/acre based on the FCCS-LANDFIRE 1-km fuelbed map and Consume 4.0 from the SEMIP Fire Everywhere test case.

3.2 Transfer Function

To determine the likelihood of smoke transport from a fire source location to all other points, we used the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1997) to employ "transfer functions." For each starting location shown in Fig. 3, we modeled four trajectories per day at three starting heights (500 m, 1000 m, and 1500 m above ground level) from 1979 to 2008. HYSPLIT trajectories were driven by gridded meteorological fields from the NARR, and were calculated forward in time for five days.

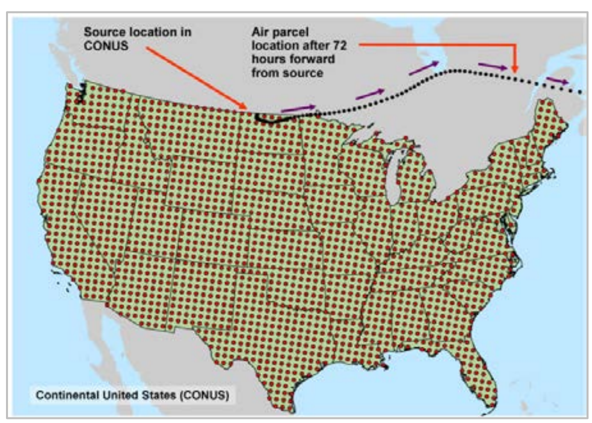

Fig. 3. HYSPLIT trajectory locations (red dots) and single-trajectory example output (black dots).

We converted trajectories to transfer functions for each site by combining all trajectories within a single climatological week (e.g., January 1–7 across all years), counting hourly trajectory points within each 64-km^2 analysis grid cell on the half-resolution NARR grid, and normalizing the resulting counts by the maximum count. We combined weekly transport functions to produce monthly results. Fig. 4 shows transfer functions for grid cells in the northern Sierra Nevada and New Jersey Pine Barrens. These potential VLF regions are the subjects of ensemble dispersion modeling case studies in Section 4.

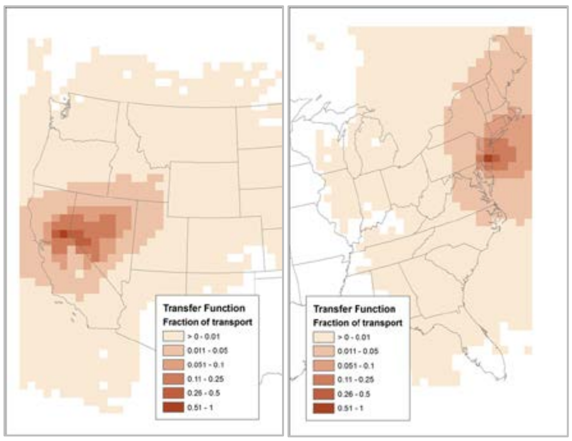

Fig. 4. Transfer functions showing fraction of transport from fires originating from the northern Sierra Nevada in June (left) and New Jersey Pine Barrens in July (right).

3.3 Results

Fire-season smoke impact potentials, calculated using the methodology presented above, are shown in Fig. 5. The darker colors represent areas where fires would result in greater smoke impacts on populations. Results show a balance between emissions-driven and population-driven fire source locations that would generate high smoke impact. Fire source locations with the 100 highest smoke impact potentials are labeled in Fig. 5. Fire locations that result in the highest smoke impact potentials include areas where fuel loadings are high in California, Oregon, and Minnesota, as well as areas upwind of large population centers, such as West Virginia and Missouri.

4. ENSEMBLE DISPERSION MODELING

The fire source regions with the highest smoke impact potentials (Fig. 5) correspond closely with the regions of expected VLF occurrence identified in the literature review (Fig. 1). These regions where future VLFs are likely to result in significant human exposure to smoke were the focus of additional dispersion modeling to further assess potential smoke impacts from future VLFs.

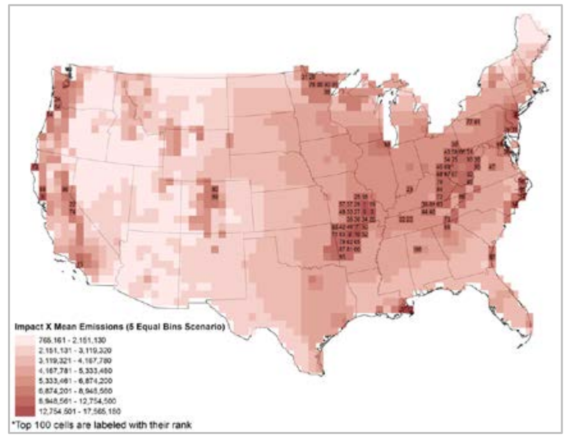

Fig. 5. Smoke impact potentials.

4.1 Methods

We used the BlueSky Framework version 3-5-1 (Larkin et al., 2009) and the HYSPLIT dispersion model, driven by the gridded NARR meteorological re-analysis (Mesinger et al., 2006) to develop probabilistic smoke impact analyses for eight hypothetical VLF scenarios. Results from two scenarios, the northern Sierra Nevada and New Jersey Pine Barrens, are presented here.

For each VLF scenario, the smoke impacts from a 10,000-acre wildfire ignited at midnight local time were modeled each day from 1979 to 2008 during July, the month in which a VLF is most likely to occur in the northern Sierra Nevada and New Jersey Pine Barrens regions, as identified regionally through evaluation of Monitoring Trends in Burn Severity (MTBS) fire perimeter data. Although a VLF might burn 50,000 acres or more over the course of several days or weeks, we selected 10,000 acres as a reasonable estimate of burn area for the first day of a VLF event, based on the behavior and spread of VLF events that have occurred in the past. In extreme circumstances, this estimate would be highly conservative. For example, the September 2015 Valley Fire in Lake County, California, consumed 10,000 acres during the first three hours.

We ran each HYSPLIT simulation in the ensemble (up to 930 simulations per scenario) in full particle mode for 48 hours, with all the fire emissions occurring within the first 24 hours. During the final 24 hours, fire emissions were set to zero while smoke previously injected into the modeling system continued to be transported and dispersed. This approach simulated potential smoke impacts over a 48-hour period from a one-day burn cycle of a VLF.

Smoke emissions for the HYSPLIT model runs were computed with the BlueSky Framework; we used fuel loadings from FCCS (McKenzie et al., 2007), consumption from Consume 4.0, and emissions from the Fire Emissions Prediction Simulator (FEPS) (Andersen et al., 2004). Lofted smoke emissions were released at the midpoint between the plume bottom and plume top values estimated by the FEPS plume rise module, which implements the Briggs plume rise formulation. Smoldering emissions, as well as the surface component of the flaming emissions, were released at 10 m above ground level (AGL). Smoke concentrations at ground level were predicted on a 0.2 by 0.2 degree (approximately 20 km resolution) receptor grid covering a geographic area likely to be impacted by smoke within 48 hours of a fire ignition.

Each HYSPLIT simulation in a VLF modeling scenario is identical except for the meteorological data used. The result is an ensemble of hourly smoke impact predictions based on climatological transport patterns during the month in which a VLF is most likely to occur. The ensemble model output is aggregated to develop a statistical analysis of potential smoke impacts due to smoke from a VLF scenario. Results from two metrics are shown in Figs. 6–9. The maximum impact represents the maximum hourly $PM_{2.5}$ concentration predicted in the ensemble at each receptor and represents the maximum short-term air quality impact that might be expected from a VLF. The probability of impact represents the percentage of simulations in the ensemble in which the $PM_{2.5}$ concentration exceeded 1 µg/m^3 for at least one hour.

4.2 Results

4.2.1 Case Study 1: Northern Sierra Nevada

The northern Sierra Nevada VLF is located in Amador County, California, at 4,500 feet in elevation and approximately 40 miles southwest of Lake Tahoe. The predominant fuels in the VLF region are Jeffrey pine, ponderosa pine, Douglas-fir, and black oak forest.

Fig. 6 shows the maximum $PM_{2.5}$ impact predicted for the northern Sierra Nevada VLF. The highest potential impacts are located in the foothills west of the fire ignition, likely due to easterly nocturnal drainage flow into the Sacramento Valley. These peak impacts affect numerous foothill communities, as well as larger cities such as Stockton and Sacramento. Significant peak impacts also extend down the east side of the San Joaquin Valley. Westerly flow conditions produce a potential for significant peak impacts in South Lake Tahoe and east of the Sierra Nevada in Reno and Carson City.

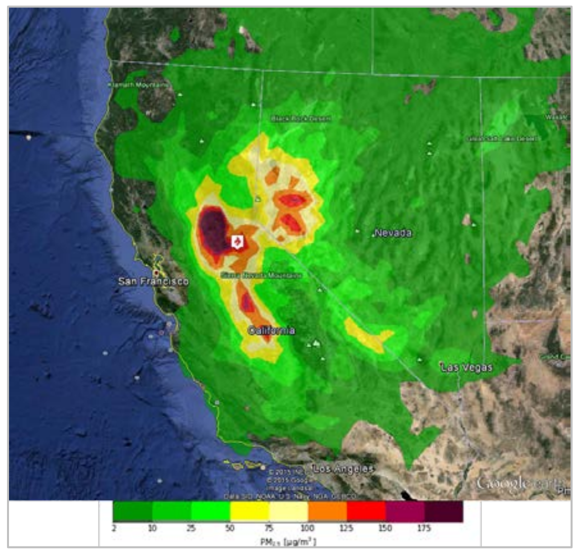

Fig. 6. Maximum predicted $PM_{2.5}$ concentration (µg/m^3) from a northern Sierra Nevada VLF in July. Fire symbol indicates the VLF location.

Fig. 7 shows the probability that a VLF in the northern Sierra Nevada in July would produce a measurable $PM_{2.5}$ impact. The highest probability of smoke impact occurs in the VLF burn area and in a lobe extending northeast over Lake Tahoe and into western Nevada. This is the result of westerly flow that is predominant in the region during July. A lobe of lower impact probability extends southward down the San Joaquin Valley. The effects of terrain blocking by the taller mountains southeast of the VLF are apparent. The general spatial patterns from this ensemble modeling analysis are consistent with the transfer function (Fig. 4), with the majority of smoke impact northeast of the VLF location and smaller impacts to the south.

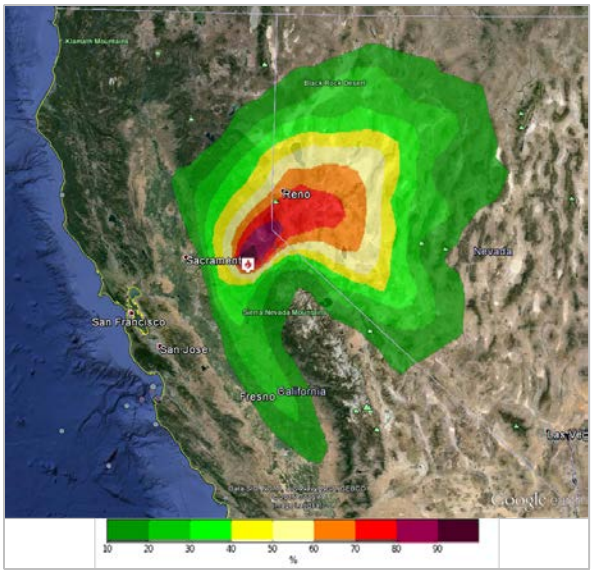

Fig. 7. Probability of a 1 μg/m^3 impact from a northern Sierra Nevada VLF in July.

4.2.2 Case Study 2: New Jersey Pine Barrens

The New Jersey Pine Barrens VLF is located in Burlington County, in close proximity to the highly urbanized I-95 corridor. The predominant fuels in the VLF region are pitch pine and scrub oak forest.

Fig. 8 shows the maximum $PM_{2.5}$ impact predicted for a potential VLF in the New Jersey Pine Barrens in July. The highest potential impacts are located in central and southern New Jersey, with significant impacts affecting several large cities, including Philadelphia and New York City. Peak impacts greater than 50 μg/m^3 are confined mostly to the Atlantic Coast, but smaller peak impacts extend throughout the Northeast.

Fig. 9 shows the probability that a VLF in the New Jersey Pine Barrens in July would produce at least a 1 μg/m^3 $PM_{2.5}$ impact. The highest probability of smoke impact occurs in a lobe extending northeast from the VLF burn area, due to the climatological southwest flow in July. This spatial pattern is consistent with the transfer functions for this VLF shown in Fig. 4. Smoke impact probabilities of greater than 40% occur from Atlantic City to New York City and Long Island, with impact probabilities of at least 10% extending farther northeast into New England. Cities that are generally upwind of the Pine Barrens in July, such as Philadelphia, have a relatively low probability of significant smoke impacts from a Pine Barrens VLF; however, the peak impact map (Fig. 8) suggests that these locations could experience significant smoke impacts if a VLF occurred during climatologically abnormal conditions (for example, southeasterly flow).

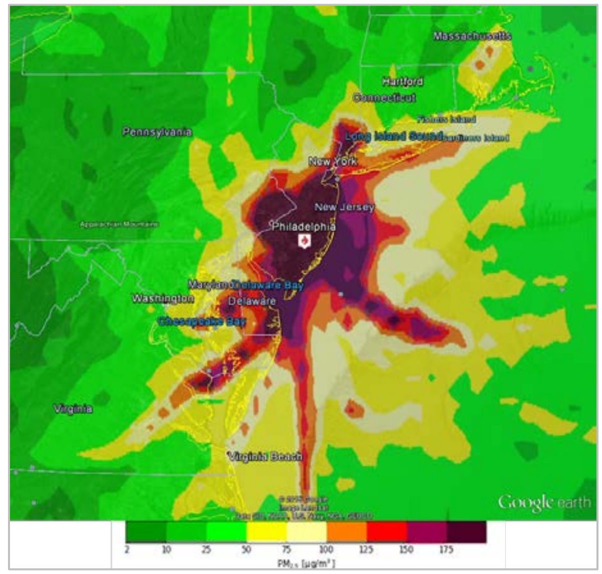

Fig. 8. Maximum predicted $PM_{2.5}$ concentration (μg/m^3) from a VLF in the New Jersey Pine Barrens in July. Fire symbol indicates the VLF location.

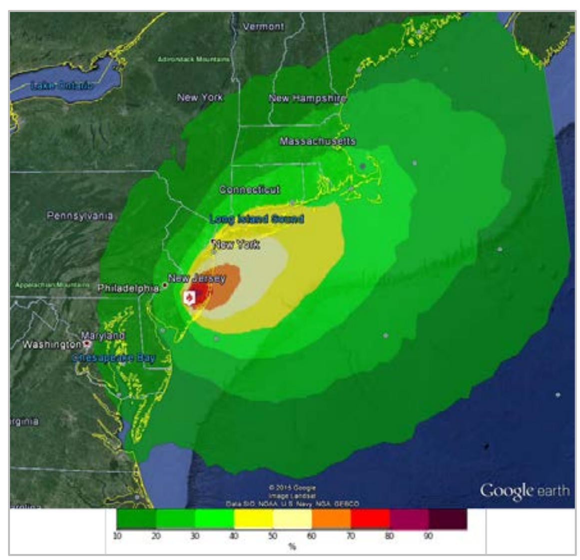

Fig. 9. Probability of a 1 μg/m^3 impact from a VLF in the New Jersey Pine Barrens in July.

5. CONCLUSION

We combined fire emission rates, population density, and climatological trajectory-based transport modeling to determine the areas within the United States where a VLF would result in the greatest human exposure to smoke. The Sierra Nevada (and California generally), the Cascades, northern Minnesota, northern Utah, and the Ozarks were identified as areas where VLFs are likely to produce significant smoke impacts on populations. Since the trajectory-based analysis does not account for the effects of smoke plume dispersion, we corroborated the results from this analysis with dispersion modeling. We developed an ensemble of dispersion modeling results with HYSPLIT using meteorological data over 30 years to estimate probabilistic smoke impacts for select areas identified as high-risk for future VLFs. The probabilistic smoke impact analysis indicated that significant regional air quality impacts from future VLFs in highly populated regions are likely. Coupled with a synthesis of recent studies on the likelihood of VLF occurrence under future climate scenarios, these results provide information that can be used to help prioritize management actions to mitigate megafire risk.

6. REFERENCES

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