Identifying and Quantifying the Impact of Wildfires and Dust Events on Utah's Air Quality

Utah Division of Air Quality Research Grant

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COLLEGE OF MINES AND EARTH SCIENCES | THE UNIVERSITY OF UTAH

DEPARTMENT OF ATMOSPHERIC SCIENCES

Project Background:

Biomass burning is known to be responsible for emitting large quantities of carbon monoxide (CO), particulate matter (PM), precursors of ozone (O_3), and other species relevant for air quality into the atmosphere. Effects of biomass burning not only affect the area local to the fire, but may also impact the air quality of regions downwind from the fire. The 2012 western U.S. wildfire season was characterized by significant wildfire activity across much of the American West, with potential adverse impacts on Utah's air quality. Previous studies have already shown that enhancement in CO, $PM_{2.5}$, and O_3 concentrations can occur at sites downstream of the wildfires [*DeBell et al.*, 2004; *Dempsey*, 2013; *Jaffe et al.*, 2013; *Jaffe and Wigder*, 2012; *Sapkota et al.*, 2005].

In addition to biomass burning, the emission and transport of dust can cause degraded air quality in Utah. *Hahnenberger and Nicoll* [2012] found that "dust events produced elevated PM_{10} exceeding NAAQS on 16 days since 1993, or 0.9 per year". *Steenburgh et al.* [2012], combining meteorological and satellite datasets, produced a climatology of dust events for the Wasatch Front. Both studies pointed to the southwestern U.S. as the origin of dust for the population centers along the Wasatch in northern Utah, but these studies did not develop a modeling framework capable of quantifying exactly how much impact each event affected the PM concentrations in northern Utah.

Elevated concentrations of O_3 and PM can cause significant health problems, especially to the elderly, young children, and people with lung and heart diseases [*Gauderman et al.*, 2004; *Weinmayr et al.*, 2010]. Exposure to adverse air quality caused by dust events and wildfires is expected to continue in the foreseeable future, with the rapid population rise taking place in Utah [*Utah Foundation*, 2014] and the general increase in wildfire activity across the Western U.S. [*Dennison et al.*, 2014], likely due to climate change [*Westerling et al.*, 2006]. This trend is anticipated to continue with the average maximum air temperature increasing for these regions even under the IPCC's moderate emission scenario [*IPCC*, 2007]. Dust production in the future will also likely increase, due to a combination of shifting climate [*Munson et al.*, 2011] and heightened anthropogenic activities (e.g., agriculture, energy exploration/development, recreation) [*Field et al.*, 2009; *Neff et al.*, 2008], which would arise from the increased population in the potential source region of dust to northern Utah. The U.S. Census has clearly identified Western U.S. as the region of the most rapid population growth in the nation [*U.S. Census Bureau*, 2010].

Despite advances in the published literature mentioned above, previous studies generally lacked the ability to provide a *quantitative assessment* of the impact of wildfires or dust events on air quality at selected receptors, instead relying upon statistical or qualitative approaches.

In the proposed study, we will use a source apportionment modeling method that will attempt to quantify the impact of dust emissions on population centers in northern Utah, as well

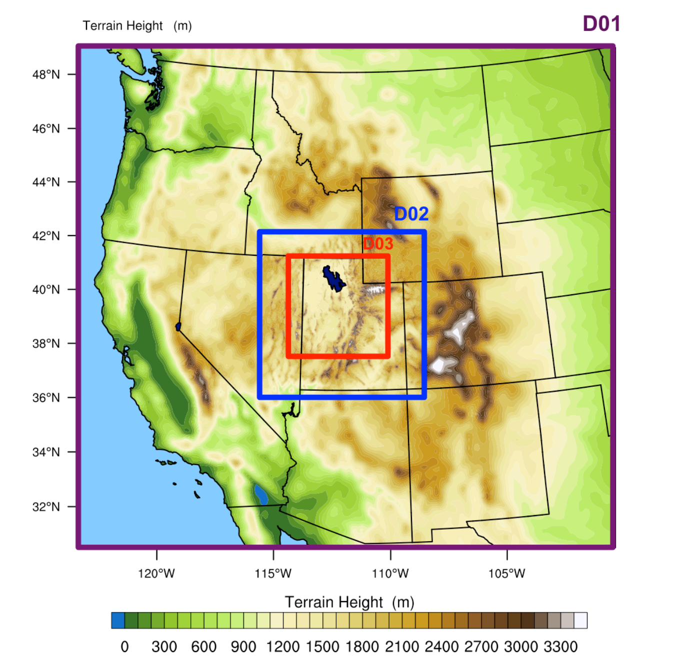

Figure 1. The WRF domain used for this study with surface and upper-air observations used for our WRF run comparisons. The horizontal grid spacing is 12-km for D01, 4-km for D02 and 1.333 km for D03.

as separate the impacts of non-wildfire emissions from wildfire-emitted CO, $PM_{2.5}$ and secondary species that aid in the formation of O_3 and $PM_{2.5}$. This modeling framework will make use of the Stochastic Time-Inverted Lagrangian Transport (STILT) model [*Lin et al.*, 2003], which will be driven by wind fields generated from the Weather Research and Forecasting (WRF)-ARW model[*Nehrkorn et al.*, 2010; *Skamarock and Klemp*, 2008]. Using a receptor-orientated framework, information from the STILT trajectories coupled with wildfire emission inventories + a dust parameterization can be used to determine the direct influences of upstream wildfire and dust emissions. The Lagrangian modeling framework represented by WRF-STILT could make for a valuable tool for understanding events in violation of NAAQS and yield quantitative evidence for demonstrating exceptional events.

Objective:

The objective of the proposed work is to construct and apply a modeling framework that combines Lagrangian atmospheric modeling with emission inventories and dust parameterizations in order to determine the contributions of wildfires and dust emissions to the air quality of the population centers of northern Utah.

Task Descriptions:

Driven by WRF meteorology, the Stochastic Time-Inverted Lagrangian Transport (STILT) model [*Lin et al.*, 2003] will be used to examine the origins of air parcels arriving at the monitoring sites ("receptors") along the Wasatch. The model simulates backward trajectories of air parcels, incorporating the effect of atmospheric turbulence as well as the variations of the windfield in 4D, as predicted by WRF.

At least 5 receptors will be selected, with a minimum of 1 receptor in each of the 5 counties along the Front Range—Cache, Weber, Davis, Salt Lake, and Utah counties. Each receptor would be co-located with an urban air quality monitoring site within each of the following population centers: Logan, Ogden, Bountiful, Salt Lake City, and Provo.

The specific tasks to be carried are:

1. Determine the optimal WRF configuration for simulating atmospheric flows and meteorological conditions during the 2012 western U.S. wildfire season (May~Sept.)
2. Quantify the impacts of *primary* fire emissions on observation sites across the Wasatch Front by running the WRF-STILT model for CO and $PM_{2.5}$
3. Incorporate a wildfire plume rise model within the WRF-STILT model developed from a complementary project

4. Incorporate non-linear chemical reactions within the modeling framework (WRF-STILT-Chem), and quantify the impact of wildfire emissions on O_3 for the 2012 western U.S. wildfire season
5. Develop dust emission module that can be coupled to the WRF-STILT model

Each of the tasks above will be described in detail below.

1. Determine the optimal WRF configuration for simulating atmospheric flows and meteorological conditions during the 2012 western U.S. wildfire season (May~Sept.)

Over the past year, we have already carried out an evaluation of a nested WRF domain centered over northern Utah (Fig. 1), with different settings within WRF (Table 1). We will test some additional WRF features (e.g., MYNN PBL scheme, alternative land schemes).

Model run	Nudging	Microphysical	Cumulus	PBL	Urban?	Landuse?
WRF #1	Spectral nudging above PBL	New Thompson	Kain-Fritsch	YSU	No	No
WRF #2	Spectral nudging above PBL	New Thompson	Kain-Fritsch	YSU	No	No
WRF #3	No nudging	New Thompson	Kain-Fritsch	YSU	No	No
WRF #4	No nudging	WSM 3-class	Kain-Fritsch	MYJ	Yes	No
WRF #5	No nudging	New Thompson	Betts-Miller-Janjić	MYJ	Yes	No
WRF #6	Grid nudging applied	Purdue Lin	Grell-Devenyi Ens.	YSU	Yes	No
WRF #7	Grid nudging applied	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	No
WRF #8	Grid nudging applied	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	Yes
WRF #9	Spectral nudging above PBL	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	Yes
WRF #10	No nudging	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	Yes

TABLE 1: Overview of the WRF configurations tested for the WRF simulations centered over Salt Lake City, Utah. All of these simulations used the RRTMG longwave and shortwave radiation schemes, NOAH land-surface model, and had a similar domain with 41 vertical levels.

2. Quantify the impacts of primary fire emissions on observation sites across the Wasatch Front by running the WRF-STILT model, using primary emissions of CO and $PM_{2.5}$

We will couple the atmospheric transport as simulated by WRF-STILT with a state-of-the-science biomass burning emissions inventory—the enhanced version of the Wildland Fire Emissions Inventory (WFEI; [*Urbanski et al.*, 2011]) (Fig. 2). The enhanced version of the WFEI includes numerous improvements not found within *Urbanski et al.* [2011] and is supported by PI Lin's grant from NOAA (see "Related Projects" below)

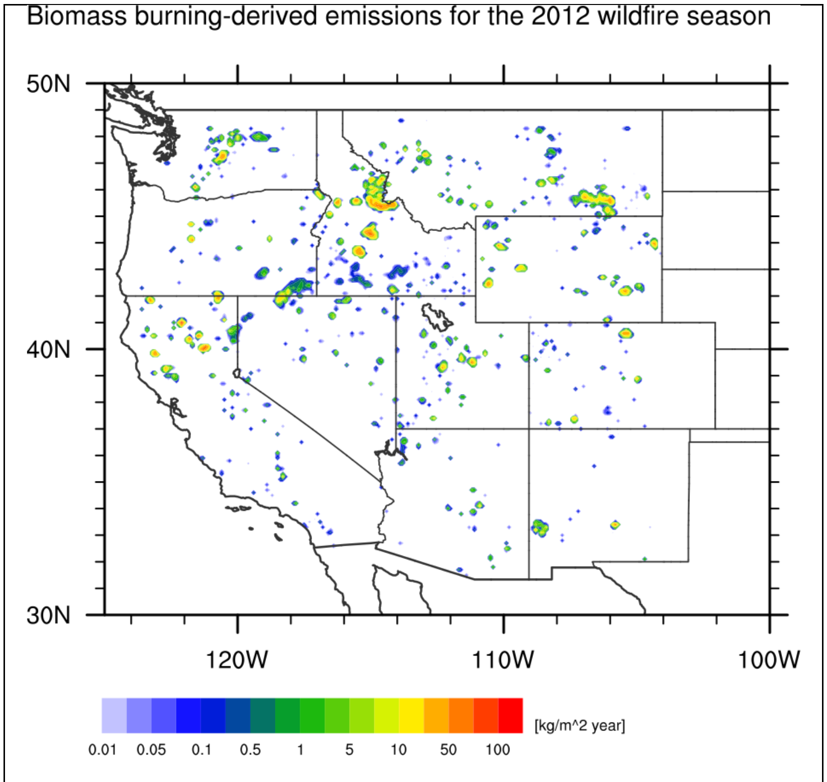

Figure 2. Total wildfire emissions for the 2012 western U.S. wildfire season, as derived from the enhanced version of the Wildland Fire Emissions Inventory (WFEI) [*Urbanski et al.*, 2011].

3. Incorporate a wildfire plume rise model within the WRF-STILT

Due to the additional buoyancy generated by heat released in wildfires, pollutants could be injected to the atmosphere at altitudes much higher than the ground surface. We will assess the sensitivity of the simulation to this atmospheric phenomenon by leveraging a Forest Service-supported project (see "Related Projects"), which will test and assess plume rise models within the WRF-STILT framework.

4. Incorporate non-linear chemical reactions within the modeling framework, and quantify the impact of wildfire emissions on O_3 for the 2012 western U.S. wildfire season

In order to simulate ozone (O_3), we will make use of a chemistry-version of STILT (STILT-Chem) that incorporates non-linear chemical reactions which will modify concentrations of different chemically-active species as they are transported along the parcel trajectories [*Wen et al.*, 2012; *Wen et al.*, 2013]. Thus we will assess the impact of the enhanced input of ozone precursors (NO_x, VOC) from the fires in elevating O_3 along the Wasatch Front, in 2012.

5. Develop dust emission module that can be coupled to the WRF-STILT model

We will develop a dust emissions module that can be coupled to the WRF-STILT modeling framework, which would then be applied to quantify contributions to air quality in northern Utah from dust events during May~Sept. 2012. We will assess published parameterizations of dust emissions—based on such variables as threshold friction velocity, roughness length, soil moisture, and soil properties [*Darmenova et al.*, 2009]. From the dust source regions, the WRF-STILT model will transport dust towards the receptors, accounting for loss from gravitational settling, as well as dry/wet deposition. Dry/wet deposition processes for aerosols are already simulated within STILT [*Wen et al.*, 2013]; for gravitational settling, the scheme of *Zender et al.* [2003] will be adopted.

Deliverables:

- Model-based, spatially-explicit estimates of the contributions of wildfires to CO, O_3, and $PM_{2.5}$ concentrations along with Wasatch Front for the 2012 western U.S. wildfire season
- Include model uncertainties to the above results due to transport error, particle numbers, and emission grid-spacing

- Weight-of-Evidence (WOE) analysis using the 2012 primary aerosols modeling to be included as an addendum to DAQ's exceptional events documentation for the 2012 wildfire season
- Final report containing the methodology and results of STILT and STILT-Chem modeling for ozone from wildfires and windblown dust during dust storms.
- Interim progress reports on project development at regular intervals during the course of the project

Schedule and Project Milestones:

- **September 2014**: Determine the optimal WRF configuration for simulating atmospheric flows and meteorological conditions during the 2012 western U.S. wildfire season (May~Sept.)
- **October 2014**: DAQ will provide gridded, time-varying emission inventories in Utah for May~September of 2012.
- **January 2015**: Quantify the impacts of primary fire emissions on observation sites across the Wasatch Front by running the WRF-STILT model for CO and $PM_{2.5}$
- **March 2015**: Incorporate a wildfire plume rise model within the WRF-STILT model developed from a complimentary project
- **July 2015**: Incorporate non-linear chemical reactions within the modeling framework (WRF-STILT-Chem), and quantify the impact of wildfire emissions on O_3 for the 2012 western U.S. wildfire season
- **January 2016**: Develop dust emission module that can be coupled to the WRF-STILT model

Complementary Projects:

The following are 3 funded projects that complement the present proposal to DAQ:

1. *Improving biomass burning emissions in CarbonTracker: Imposing the multi-species atmospheric constraint (PI; NOAA-OAR-CPO-2013-2003445)*

This NOAA project focuses on determining the amount of carbon emitted from biomass burning across North America, with a goal towards improving NOAA's CarbonTracker system (http://carbontracker.noaa.gov/). This grant also supports the development of the enhanced Wildfire Emissions Inventory (WFEI) that our proposed project will leverage, at no cost to DAQ.

2. *The Development and Application of Top-down Methods for Constraining Biomass Burning Emissions Sources (PI; 14-JV-11221637-027)*

The focus of this work—supported by the U.S. Forest Service—is to utilize data from the RxCADRE prescribed burn field campaign (http://www.firelab.org/research-projects/physical-fire/205-rxcadre) and demonstrate that the STILT model can constrain biomass burning emissions when provided with high precision aircraft measurements of CO and CH_4. It also supports the development of a plume rise parameterization within STILT that will be used in our proposal.

3. *Confronting models with regional CO_2 observations to improve interpretation of drought stress and emissions (anthropogenic and fire) (Co-PI; DOE ER65543 SC#: SC0010624)*

This Dept. of Energy project seeks to understand regional-scale CO_2 budgets, focusing on the mountainous area extending from eastern Utah to western Colorado. It supports measurements from the Univ. of Utah mobile laboratory (a.k.a. "Nerdmobile") that will be driven near wildfires, thereby helping to constrain fire-based emissions.

Budget:

Postdoctoral Researcher Adam Kochanski (8 months)	$40,000
Graduate student (10 months)	$22,500
Fringe Benefits (37% for Postdoctoral researcher; 14% for student)	$17,950
RAID disk storage + tape backup	$3000
Publication cost	$1000
Travel- Meetings within Utah	$400
Total Direct	**$84,850**
Direct Costs for F&A Calculation	$84,850
Indirect (F&A) Cost (10%)	**$8,485**
Grand Total	**$93,335**

Cited References:

Darmenova, K., I. N. Sokolik, Y. Shao, B. Marticorena, and G. Bergametti (2009), Development of a physically based dust emission module within the Weather Research and Forecasting (WRF) model: assessment of dust emission parameterizations and input parameters for source regions in Central and East Asia, *Journal of Geophysical Research*, *114*(D14201), doi:10.1029/2008JD011236.

DeBell, L. J., R. W. Talbot, J. E. Dibb, J. W. Munger, E. V. Fischer, and S. E. Frolking (2004), A major regional air pollution event in the northeastern United States caused by extensive forest fires in Quebec, Canada, *Journal of Geophysical Research-Atmospheres*, *109*(D19).

Dempsey, F. (2013), Forest fire effects on air quality in Ontario: evaluation of several recent examples, *Bulletin of the American Meteorological Society*, *94*, 1059-1064.

Dennison, P. E., S. C. Brewer, J. D. Arnold, and M. A. Moritz (2014), Large wildfire trends in the western United States, 1984–2011, *Geophysical Research Letters*, 2928-2933, doi:doi://10.1002/2014GL059576.

Field, J. P., J. Belnap, D. D. Breshears, J. C. Neff, G. S. Okin, J. J. Whicker, T. H. Painter, S. Ravi, M. C. Reheis, and R. L. Reynolds (2009), The ecology of dust, *Frontiers in Ecology and the Environment*, *8*(8), 423-430, doi:10.1890/090050.

Gauderman, W. J., E. Avol, F. Gilliland, H. Vora, D. Thomas, and K. Berhane (2004), The effect of air pollution on lung development from 10 to 18 years of age, *New England Journal of Medicine*, *351*, 1057-1067.

Hahnenberger, M., and K. Nicoll (2012), Meteorological characteristics of dust storm events in the eastern Great Basin of Utah, U.S.A., *Atmospheric Environment*, *60*, 601-612.

IPCC (2007), *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*, Cambridge University Press.

Jaffe, D. A., N. Wigder, N. Downey, G. Pfister, A. Boynard, and S. B. Reid (2013), Impact of Wildfires on Ozone Exceptional Events in the Western U.S., *Environmental Science & Technology*, *47*, 11065-11072.

Jaffe, D. A., and N. L. Wigder (2012), Ozone production from wildfires: A critical review, *Atmospheric Environment*, *51*, 1-10.

Lin, J. C., C. Gerbig, S. C. Wofsy, A. E. Andrews, B. C. Daube, K. J. Davis, and C. A. Grainger (2003), A near-field tool for simulating the upstream influence of atmospheric observations: the Stochastic Time-Inverted Lagrangian Transport (STILT) model, *Journal of Geophysical Research*, *108*(4493), doi:10.1029/2002JD003161.

Munson, S. M., J. Belnap, and G. S. Okin (2011), Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau, *Proceedings of the National Academy of Sciences*, *108*(10), 3854-3859, doi:10.1073/pnas.1014947108.

Neff, J. C., A. P. Ballantyne, G. L. Farmer, N. M. Mahowald, J. L. Conroy, C. C. Landry, J. T. Overpeck, T. H. Painter, C. R. Lawrence, and R. L. Reynolds (2008), Increasing eolian dust deposition in the western United States linked to human activity, *Nature Geoscience*, *1*(3), 189-195, doi:10.1038/ngeo133.

Nehrkorn, T., J. Eluszkiewicz, S. C. Wofsy, J. C. Lin, C. Gerbig, M. Longo, and S. Freitas (2010), Coupled Weather Research and Forecasting–Stochastic Time-Inverted Lagrangian Transport (WRF–STILT) model, *Meteorology and Atmospheric Physics*, *107*, 51-64.

Sapkota, A., J. M. Symons, J. Kleissl, L. Wang, M. B. Parlange, J. Ondov, P. N. Breysse, G. B. Diette, P. A. Eggleston, and T. Buckley (2005), Impacts of the 2002 Canadian forest fires on particulate matter air quality in Baltimore City, *Environmental Science and Technology*, *39*(1), 24-32.
Skamarock, W. C., and J. B. Klemp (2008), A time-split nonhydrostatic atmospheric model for weather research and forecasting applications, *Journal of Computational Physics*, *227*(7), 3465-3485.
Steenburgh, W. J., J. D. Massey, and T. H. Painter (2012), Episodic Dust Events of Utah's Wasatch Front and Adjoining Region, *Journal of Applied Meteorology and Climatology*, *51*, 1654-1669.
U.S. Census Bureau (2010), United States Census 2010. Geographic products and information, edited.
Urbanski, S. P., W. M. Hao, and B. Nordgren (2011), The wildland fire emission inventory: western United States emission estimates and an evaluation of uncertainty, *Atmospheric Chemistry and Physics*, *11*, 12973-13000.
Utah Foundation (2014), A snapshot of 2050: An Analysis of the projected population change in Utah*Rep. 721*, 19 pp, Utah Foundation, Salt Lake City, UT.
Weinmayr, G., L. Romeo, M. De Sario, S. K. Weiland, and F. Forastiere (2010), Short-term effects of PM10 and NO2 on respiratory health among children with asthma or asthma-like symptoms: a systematic review and meta-analysis, *Environmental Health Perspectives*, *118*, 449-457.
Wen, D., J. C. Lin, D. Millet, A. Stein, and R. Draxler (2012), A backward-time stochastic Lagrangian air quality model, *Atmospheric Environment*, *54*, 373-386.
Wen, D., J. C. Lin, L. Zhang, R. Vet, and M. D. Moran (2013), Modeling atmospheric ammonia and ammonium using a stochastic Lagrangian air quality model (STILT-Chem v0.7), *Geoscientific Model Development*, *6*, 327-344.
Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006), Warming and earlier spring increase western U.S. forest wildfire activity, *Science*, *313*, 940-943.
Zender, C. S., H. Bian, and D. Newman (2003), Mineral dust entrainment and deposition (DEAD) model: description and 1990s dust climatology, *Journal of Geophysical Research*, *108*(4416), doi:10.1029/2002JD002775.