Quantitative Attribution of Wildfires on Summertime Ozone Concentrations along the Wasatch Front

In Response to the Utah Division of Air Quality:
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1.1. Abstract:

Wildfires can significantly enhance summertime ozone (O_3) and aerosol concentrations, which can degrade air quality and have adverse effects on human health. While air quality has improved across much of the U.S., the Western U.S. has seen more extreme air quality events, which can be partially attributed to an increase in wildfire activity. As wildfire events continue to increase in frequency across the region, it will become increasingly difficult for Utah to meet federal air quality standards for O_3 and $PM_{2.5}$. O_3 precursors can originate from a number of different sources including anthropogenic and biogenic emissions, as well as inter-basin air exchange processes, and long-range smoke transport. Therefore, it is crucial to investigate wildfire events to assess the contribution of the local fires and the long-range smoke transport to the extreme air quality in the Salt Lake Valley. It is also important to improve understanding on how wildfires interact with urban plumes to help with the implementation of effective regulatory policies and improve air quality modeling capabilities.

Several studies have examined the impacts of wildfires on air quality. However, quantifying the processes responsible for O_3 production is difficult. For example, recent studies found a dichotomy in smoke plume measurements where O_3 enhancements were observed in some plumes, while other plumes had near background or depleted concentrations of O_3. To clarify these discrepancies, sophisticated modeling-based frameworks are needed to elucidate processes behind degraded air quality events as a result of wildfire smoke. This requires a model being able to account for different sources of O_3 and its precursors, smoke aging processes, and chemical interactions between wildfire smoke and urban emissions. Furthermore, there are a variety of important fire-atmosphere interactions such as smoking shading from smoke aerosols and the buoyant fire plume rise that can impact local meteorology and smoke chemistry. Thus, a coupled fire-atmosphere-chemical model is often needed to resolve these types of interactions.

In this project we will leverage a comprehensive observational network along the Wasatch Front that includes in-situ and mobile air quality measurements, as well a novel high-density

ozone-monitoring network. We will deploy a coupled fire-atmosphere model with chemistry (WRF-SFIRE-CHEM) to simulate downwind transport of wildfire smoke and its interactions with urban emissions. This high-resolution modeling framework will simulate local and regional chemical transport processes, and complex fire-atmosphere interactions. Through an analysis of observational and model data, the proposed project will specifically address the following questions:

(1) What are the impacts of wildfires on ozone concentrations along the Wasatch Front relative to the contributions from anthropogenic sources?

(2) What are the relative contributions to ozone formation from local versus remote fires, and how does smoke shading from smoke plumes impact photochemistry?

(3) What is the spatial variability and sensitivity of smoke-enhanced ozone to different urban sources of ozone precursors?

We will specifically address the 6th item in the Utah Division of Air Quality's (UDAQ) Goal and Priorities section, which encourages research on "source contributions to summertime ozone". Through this project, we will be able to identify the role that wildfire plays towards enhancing summertime ozone (O_3) levels along the Wasatch Front, while also elucidating the complex chemical interactions between wildfire smoke and urban plumes. In addition, this project will also target the 1st and 3rd item in UDAQ's Goal and Priorities section, which seeks applicants that can improve air quality models and elucidate air exchange processes that involve pollutants.

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1. Scope of Work

1.1. Basis and rationale

Over the past century, anthropogenic emissions have altered the composition of the atmosphere, which has resulted in a degradation of air quality across the globe. An estimated 3.3 million deaths per year can be linked to poor air quality while 92% of the world's population lives in regions where air is considered unhealthy according to the World Health Organization (Silva et al. 2013, Lelieveld et al. 2015). Of these 3.3 million deaths, wildfire smoke is believed to be responsible for 5% of the deaths, respectively (Lelieveld et al. 2015). The number of wildfire events are expected to increase through the end of the 21st century as a consequence of climate change, which has resulted in warmer temperatures, more droughts, and declining snowpack (Westerling et al. 2006; Scalzetti et al. 2016; Seager and Hoerling 2014). As a result, degraded air quality associated with wildfires is projected to increase through the end of the 21st century (Spracklen et al. 2009; Liu et al. 2016).

Across the Western U.S., wildfire activity has already been steadily increasing since the early 1980s—especially the number of large wildfires (Westerling et al. 2006, Dennison et al. 2014). Climate change and past wildfire management practices are thought to be the primary drivers behind wildfire trends across the Western U.S. As the population across the Western U.S continues to expand into the Wildland-Urban Interface (U.S. Census Bureau 2010), the number of Americans exposed to wildfire smoke is a growing concern, especially as the impacts from climate change continues to intensify. This is especially problematic for Utah, which is the 3rd fastest growing state in the country (U.S. Census Bureau 2010).

McClure and Jaffe (2018) found a dichotomy in air quality observations across the U.S, where air quality across the Western U.S. was deteriorating relative to the eastern half of the U.S. These results are consistent with work from Hand et al. (2011; 2016), who also found an increase in aerosols across the Western U.S. Both studies concluded that these trends were likely being partially driven by more wildfires. A study carried out by Mallia et al. (2015), confirmed that degraded air quality across Utah during the summers of 2007 and 2012 was caused by wildfire smoke originating from fires across Idaho and Northern California.

A similar dichotomy has also been observed with O_3, where surface O_3 concentrations have been increasing throughout the Intermountain West (1990-2010) despite reductions in nitric oxides (NO_x) emissions (Jaffe et al. 2007; Cooper et al. 2012). On the other hand, O_3 has been steadily declining across the eastern U.S. While the increase in O_3 across the Western U.S. can be partially attributed to Asian emissions and global methane, these sources can only account for some of this increase (Fiore et al. 2002). Wildfires do not directly emit O_3; however, they often produce large quantities of NO_x, carbon monoxide (CO), and volatile organic compounds (VOCs), which are O_3 precursors (Yokelson et al. 2011). Jaffe et al. (2008) found a strong interannual correlation between high O_3 days and the wildfire burned area, suggesting that wildfires significantly contribute to worsening O_3 across the Western U.S. However, the quantification of wildfire contributions remains challenging.

An observational-based study by Verma et al. 2009 revealed significant variability in the O_3 concentrations in fire plumes. In some cases, O_3 concentrations were elevated by up to 90 ppb, while other case exhibited O_3 levels at or below background levels. Furthermore, this work found that in-plume ozone production can be very sensitive to the aerosol optical depth, with O_3 production being reduced by a factor of 4 due to the smoke shading (Verma et al. 2009). A more recent study by Sigh et al. 2010 found that Boreal and California forest fires had small impacts on the mean O_3 concentrations at high latitudes with perturbations less than <5ppb. However, when

smoke plumes mixed with urban emissions, there was more elevated O_3 production. Due to the complexity of underlying physical and chemical processes of smoke-enhanced O_3, the impact of fire emissions on tropospheric O_3 needs to be investigated on a case-by-case basis. Advanced numerical modeling is also needed, particularly for urban areas (Jaffe and Wigder 2011) where the applicability of classical observational-based analysis is challenging.

Based on the aforementioned studies, we hypothesize that wildfire enhanced O_3 episodes over Utah will exhibit significant variability on a case-by-case basis. It is suspected that this variability in smoke contribution to O_3 concentrations is related to the smoke origin, fire characteristics, time of year, and local meteorological patterns. We believe that Utah smoke events will fit into one of the two general scenarios, which outlines the potential pathways for wildfire smoke impacts on urban O_3. For cases of (1) long-range transport, where smoke originates from remote fires located outside of Utah, it is suspected that smoke aging processes are important for elevating O_3 concentrations, while more diffuse smoke plumes reduces the aerosol optical depth, thus increasing photochemical reactions. For cases associated with (2) local fires, we anticipate that incoming plumes will result in less O_3, due to limited reaction time, while less diffuse smoke plumes (thicker plumes) will inhibit photochemistry due to significant reductions in incoming solar radiation. However, local fires may still result in elevated O_3 and $PM_{2.5}$ concentrations in the Salt Lake Valley as a result of chemical interactions with urban emissions and inter-basin exchanges.

Despite decades of progress towards improving air quality, **increases in local and remote wildfire activity could inhibit Utah's ability to meet federal air quality standards**. In addition, changes in O_3, driven by increasing wildfire activity, could have a direct impact on visibility and air quality across Utah which **ties directly into UDAQ's mission of**: "*safeguarding human health and quality of life by protecting and enhancing the environment*". As the mechanisms associated with the smoke impact on O_3 concentrations are very complex (Jaffe and Wigder 2011), it is critical to improve our understanding of fire impacts on air quality across Utah and quantify their contribution towards elevated O_3 concentrations.

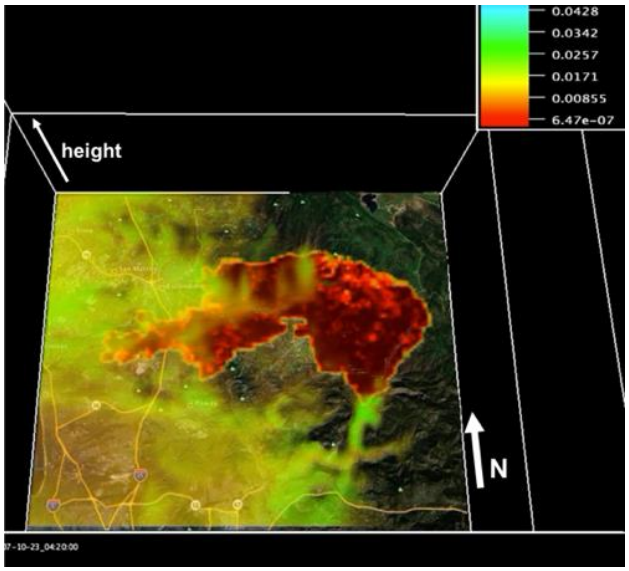


Figure 1. WRF-SFIRE-CHEM simulation of downwind ozone formation (yellow shading) associated with 2007 Santa Ana Fires in California (red polygon).

In order to meet these goals, we plan to utilize a wide range of observational data from a high-density O_3 monitoring network located along the Wasatch Front and deploy two sophisticated modeling frameworks specialized in modeling pollutants associated with wildfire events. A backward trajectory model (STILT) will be used to help identify wildfires with potentially large contributions towards observed O_3 events. This information will then be used to define the regions of influence for particular fires and to optimize the modeling domain for our coupled fire-atmosphere model (WRF-SFIRE-CHEM). WRF-SFIRE-CHEM will then be used to explicitly simulate fire progression, emissions, plume dynamics, smoke transport and chemistry. Coupled fire-atmosphere models like WRF-SFIRE-CHEM have already been used to carry out simulations of O_3 generated from the 2007 Santa Ana fires (Figure 1; Kochanski et al. 2015).

1.2. Technical Approach

1.2.1. Challenges

Simulating smoke transport is often difficult, as there are number of uncertainties related to the wildfire plume rise, emissions, and fire-atmosphere feedbacks, that most standard atmospheric and chemical transport models fail to account for. For example, regional air quality models often have limited resolution, which prevents explicit representation of the wildfire plume dynamics. As a result, these models rely on simplistic plume parameterizations like Briggs (1975) to vertically distribute fire emissions. However, these plume-rise parameterizations often perform poorly when compared to satellite-derived plume heights (Val Martin et. 2012). This can be problematic, especially at local scales where the accurate representation the vertical plume evolution is crucial for realistically simulating smoke transport. The temporal variability of fire emissions is also important when modeling wildfire smoke. While explicitly resolving the temporal variability of remote fires may be inconsequential, there are cases where wind-driven fire events do not conform to the typical diurnal wildfire activity profile, which assumes that emissions are maximized during the afternoon. Meteorology over northern Utah can also be complex, as this region is covered by a number of mountain ranges and basins, which can further complicate air transport across the area. Inter-basin exchanges can have significant impacts on the transport of pollutants, precursors and oxidants (Baasandorj et al. 2018).

Simulating O_3 requires a careful representation of emissions (especially non-methane organic compounds), radical production, radiative effects, and internal plume dynamics which can be difficult to resolve. Work carried out by Jaffe and Wigder (2011) found that modeled O_3 concentrations are particularly sensitive to mixing and dilution. For example, chemical transport models tend to underestimate O_3 production at coarse resolutions as a result of fire emissions being diluted across large grid cells. Coupled fire-atmosphere models such as WRF-SFIRE-CHEM are well equipped to deal with the challenges associated wildfire and O_3 modeling as they often use multi-domain configurations that utilize high-resolution grid spacing over selected sub-regions. This allows coupled fire-atmosphere models to realistically represent fine-scale mixing, dilution, and fine-scale circulations found across complex terrain.

Finally, the availability of observational data is critical for identifying high-ozone events, elucidating key processes responsible for elevating O_3, and validating atmospheric and chemical transport models. Observations with an appropriate network density are also needed to adequately resolve strong spatial concentration gradients often associated with complex flow patterns.

1.2.2. Experimental design

The first step (Phase 1; Figure 2) of the project will be to identify wildfire events that resulted in degraded air quality along Wasatch Front during the summertime using an extensive observation network. This network will include observations from UDAQ and Mountain Meteorology air quality stations, measurements from a mobile measurement platform installed on TRAX, and instruments from Co-PI Kerry Kelly's AirU network, which have been recently calibrated to make O_3 measurements. Through the synthesis of these air quality networks, we plan to develop a high-density observation data set, which can validate atmospheric and chemical transport models, identify smoke events, and elucidate key processes behind the formation of urban O_3 during wildfire smoke events. Fire observations will also be used to setup and validate model simulations. More technical details on these observation networks can be found in Technical Details section (Section 1.2.3.1).

Once potential smoke events have been identified, the next phase (Phase 2; Figure 2) of

the project will use backward trajectory model (STILT; Lin et al. 2003) to locate contributing wildfires (Section 1.2.3.2). Here, we will select events that were affected by (1) remote/regional wildfires and (2) local wildfire to quantify the role of smoke plume aging and dilution on downwind O_3 formation. STILT model output will also be used to determine the domain configuration for the more computationally intensive WRF-SFIRE-CHEM simulations, which will include smoke production, transport and chemistry. More technical details behind STILT and its inputs can be reviewed in Section 1.2.3.2.

The next phase of the project (Phase 3; Figure 2) will focus on simulating wildfire smoke events identified using STILT. These events will include cases where regional/remote wildfires impacted local air quality through long-range transport, as well as the cases when smoke from nearby Utah wildfires degraded air quality because of the local inter-basin air exchange. For each case study, high-resolution WRF-SFIRE-CHEM simulations with and without fire emissions will be carried out to quantify the impacts of urban emissions on O_3 formation within smoke plumes. This sensitivity analysis will consist of three simulations that will include **(1) wildfire + anthropogenic emission sources**, **(2) wildfire emissions only**, and **(3) anthropogenic emissions only**. This test will also be carried out for specific emission sources (i.e on-road emissions) to determine whether specific urban sources are responsible for further enhancing O_3 formation within smoke plumes. An additional sensitivity analysis will also be carried out that will include and exclude aerosol radiative feedbacks to quantify the impact of smoke shading on O_3. Smoke shading has been hypothesized as being an important process for limiting O_3 formation. Results here will be validated against a high-density air quality network discussed in Phase 1. More details behind WRF-SFIRE-CHEM modeling efforts can be reviewed in Section 1.2.3.3.

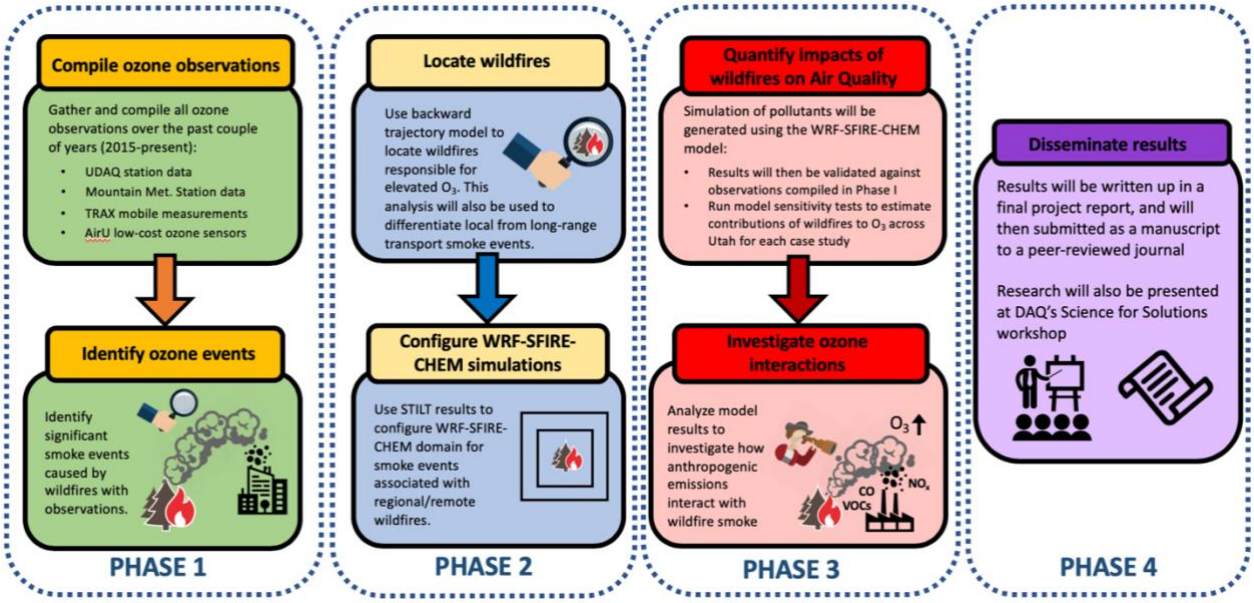


Figure 2. A schematic illustrating the different phases of the experimental design of this project.

This analysis will provide detailed information needed for an application for an exceptional event. Additionally, this project will help *improve the understanding behind (1) wildfire smoke influences on O_3 concentration along the Wasatch Front,* (2) *how the wildfire smoke plume is impacted by urban emissions*, and (3) *whether there are specific sources of anthropogenic emissions that promotes O_3 formation in smoke plumes*. Finally, we would also like to address the impacts of (4) *the smoke plume age (—e.g. long-range vs. local smoke transport) on the formation of O_3 in large urban centers like Salt Lake City*.

1.2.3. Technical details

1.2.3.1. Observations

Utah has a comprehensive observation network that spans across the Wasatch Front. This network consists of a number of UDAQ in-situ sites that monitor O_3, $PM_{2.5}$ and other chemical species relevant to air quality. A time series of a smoke event identified by the UDAQ Hawthorne station can be seen in Figure 3. Here, the time series shows elevated concentrations of $PM_{2.5}$ and CO from regional wildfires that corresponds with enhancements in O_3, that exceeded 80 ppb on August 24th, 2018 from regional wildfires over the Pacific Northwest. In addition to the UDAQ network, several other air quality sites are located in West Valley, Daybreak, Sandy, Sugarhouse, and Salt Lake City, which are maintained by MesoWest (Horel et al., 2002) and the University of Utah's Atmospheric Trace gas and Air Quality (U-ATAQ) lab.

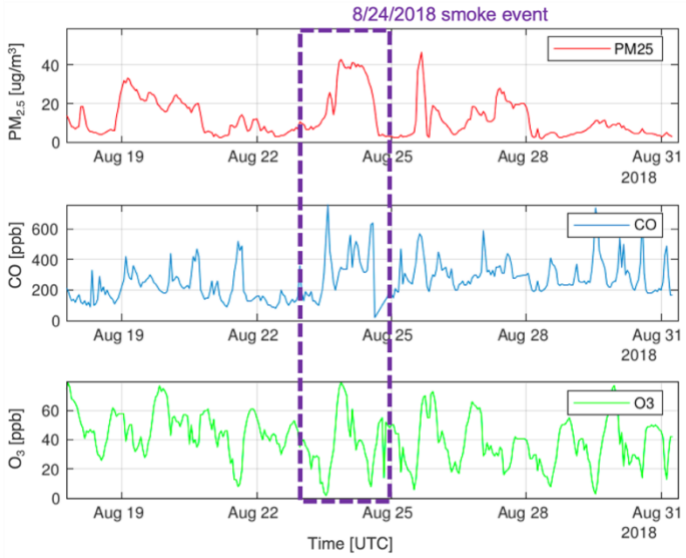


Figure 3. Time series of $PM_{2.5}$, CO, and O_3 concentrations from August 18-31st 2018 at Hawthorne UDAQ site.

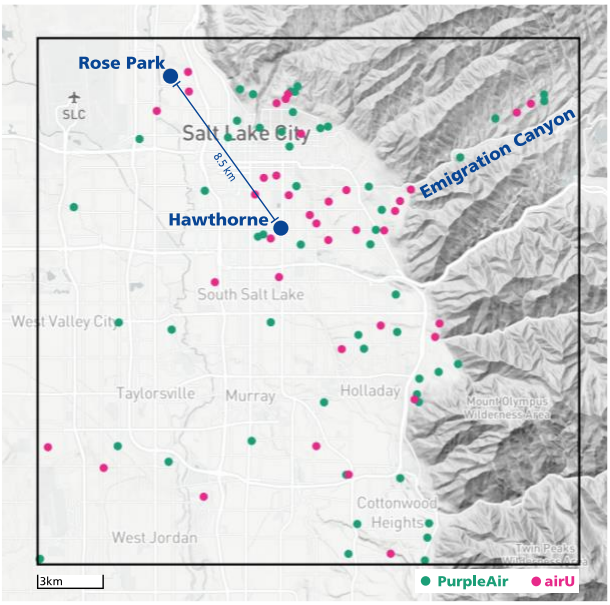


Figure 4. AirU sensing platform (top, left) and AirU sensor in housing (bottom, left). Map of AirU and PurpleAir sensors deployed, July 5, 2018. Note that some sensors provide data, but the sensor hosts have requested that their sensors be hidden on maps.

Mobile measurements of O_3, Nitrogen Oxide (NO_2), and $PM_{2.5}$ are also being collected along Salt Lake City's public transit light rail system (TRAX), which spans across the Salt Lake Valley. O_3 data is collected with a 2 B Technologies Model 2015 Ozone Monitor, which can make measurements every 2 seconds while NO_2 measurements are made every second with a Los Gatos Research Analyzer. $PM_{2.5}$ is measured using a Met One Instruments E-Sampler, which has a sampling interval of 1 minute. (Mitchell et al. 2018). Mobile networks are ideal for spatially resolving air quality data (Mitchell et al. 2018), especially when trying to identify smoke and dust plumes, which can exhibit significant spatial heterogeneity across local scales (Mallia et al. 2018).

A critical observational component of the project is the AirU platform, which was developed at the University of Utah with support from the National Science Foundation by Dr. Kelly and her colleagues (Figure 4). This platform includes sensors for temperature and relative humidity (HDC 1080), visible light (OPT3001), oxidizing and reducing gas species (SGX Sensor Tech MiCS-4514), GPS location and altitude (Adafruit Ultimate GPS Module), and PM (Plantower PMS 3003) (Figure 4, left panel). The AirU platform has a 56-cm_2 footprint on a custom 4-layer PCB that is designed around a TI CC3200 micro-controller, with a 32-bit ARM Cortex-M4 Core. The CC3200 has WiFi capabilities to upload data to the cloud, and it can also operate with battery power. Currently, the University of Utah has approximately 120 AirU's deployed in the Salt Lake Valley, and during the summer of 2018 we had approximately 60 sensors deployed (Figure 4, right panel). The AirU platforms collect a complete set of measurements every 15 seconds, averaged to one minute, and pushes the data to an online database and web portal every 5 minutes.

Dr. Kelly has been developing strategies to address low-cost sensor performance challenges, including hybrid field-laboratory calibration strategies to improve sensor accuracy and precision (Sayahi et al. 2019a, Kelly et al. 2017). Her work showed that, in general, each AirU and PurpleAir PM sensor provides $PM_{2.5}$ concentrations that are well correlated with reference instrumentation and that the instrument response is reproducible over more than one year although sensor response varies with particle properties and season (Sayahi et al. 2019a, Kelly et al. 2017). Dr. Kelly has also designed and validated a calibration chamber to calibrate multiple low-cost PM sensors at one time (Sayahi et al. 2019b).

It has also been determined that the AirU's oxidizing gas sensor exhibits highly correlated, reproducible laboratory performance for measuring ozone concentration. Furthermore, Dr. Kelly has been developing machine-learning strategies to predict O_3 concentrations from the oxidizing gas sensor in outdoor environments. Figure 5 demonstrates the use of a feed-forward artificial neural network with one layer and 30 nodes in predicting O_3 concentration at the UDAQ's Hawthorne and Rose Park stations. The key input parameters to the model include the oxidizing sensor's readings, relative humidity, and solar radiation. The training period was one year (October 2018 to October 2019) with 70% of the data randomly selected for training and 30% of the data used for testing (Figure 5, left panel). Two sensors were held out from the training and testing, and Figure 5 (right panel) demonstrates the high correlation R_2> 0.9 for these held out sensors in predicting ozone concentrations compared to UDAQ's reference ozone measurements (one sensor at Rose Park and one at Hawthorne). As a result, we are confident in being able to provide geospatially distributed O_3 measure

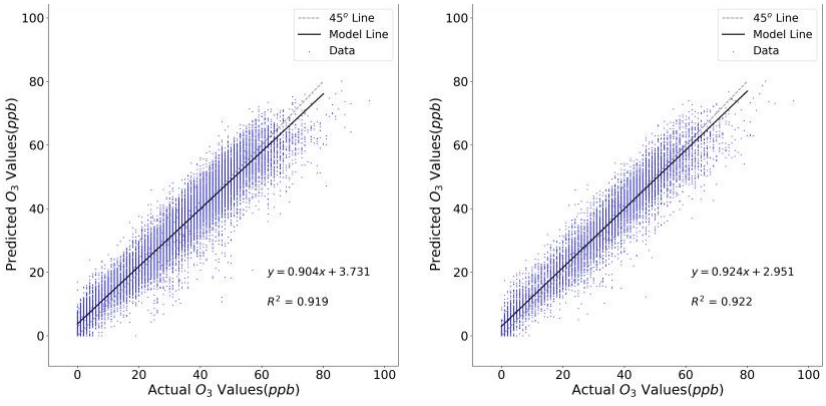


Figure 5. Right panel: Test data from the machine-learning prediction of hourly ambient O_3 concentration (measured with 2B 106L at the Hawthorne and Rose Park monitoring station) based on AirU platform measurements including oxidizing sensor readings, relative humidity, and solar radiation, during October 2018 to October 2019. The left panel shows the results for two sensors held out from the training and testing data (one held-out sensor at Hawthorne and one held-out sensor at Rose Park).

-ments that complement the existing regulatory and research-grade measurements in the Salt Lake Valley.

1.2.3.2. STILT modeling

STILT is a time-reversed Lagrangian Particle Dispersion Model (LPDM) that simulates atmospheric transport with an ensemble of backward trajectories released at a receptor location — e.g., the receptor-oriented framework. In this case, regions along the Wasatch Front would be defined as our receptor locations. STILT trajectories disperse over time as a result of turbulent motions that often characterize the planetary boundary layer (PBL). In the case of STILT, subgrid-scale turbulence is parameterized as a Markov Chain (Lin et al. 2003). Each STILT trajectory represents a parcel of air, which is small enough where its physical properties are similar to that of the surrounding air and is unaffected by gravitational settling or buoyancy.

Using the receptor-oriented framework, STILT can link upwind emissions to concentration changes at the receptor through the STILT "footprint", which defines the area upwind of the receptor along with its strength of influence. An example of the STILT footprint for receptors along the Wasatch Front can be seen in Figure 6. This modeling framework was previously used by Mallia et al. (2015; 2018) to quantify the impacts of regional wildfires on air quality across Northern Utah. Recent work by Mallia et al. (2018) also updated STILT to include a plume rise parameterization for vertically lofting smoke emissions.

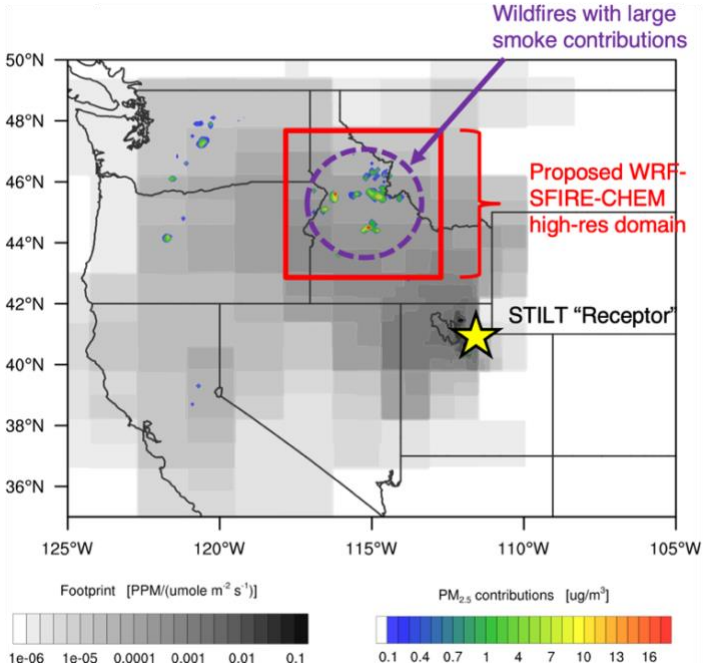


Figure 6. STILT averaged footprint (gray) and smoke contributions (colored) towards SLC and Brigham City on 10-21 August 2018. The purple circle indicates fires with large contributions of $PM_{2.5}$ to the Wasatch Front and the red box highlights the high-resolution domain that would likely be configured for the WRF-SFIRE-CHEM simulation.

Combining STILT with a fire emissions inventory (e.g. Fire Inventory from NCAR; Wiedinmyer et. al. 2011) will enable us to *locate and identifying wildfires* with the largest smoke contributions to the poor air quality along the Wasatch Front (Figure 6). This framework will also allow us to separate smoke episodes associated with long-range and local transport. This information will then be used to determine the optimal location of WRF-SFIRE-CHEM regional domains, which would be centered on the fires with large smoke contributions to the Wasatch Front. The WRF domain configuration defined by STILT would likely vary on a case-by-case basis and would be dependent on the location of the largest fires upwind of the Wasatch Front, along with the synoptic-scale wind patterns.

1.2.3.3. Coupled fire-atmosphere-chemistry model WRF-SFIRE-CHEM

Once wildfires have been identified with our backward trajectory model outlined in the previous section, WRF-SFIRE-CHEM will be used to generate simulations of O_3 for the events of interest. WRF-SFIRE-CHEM is an extension of the WRF-SFIRE (Mandel et al. 2011), which

couples WRF (Weather Research Forecasting System: Skamarock et al. 2008) with a fire spread rate model (SFIRE) that utiles a semi-empirical fire spread formula (Rothermel 1972). In WRF-SFIRE, fire behavior can be driven by a realistic meteorological large-scale forcing, while heat and moisture fluxes at the fireline are fed back into the atmospheric core, altering local air temperature, humidity, and winds (Figure 7). The fire-affected local flow is then used to compute the fire's rate of spread, fuel consumption and smoke dispersion, resulting in a two-way atmosphere-fire coupling. Additional functionality has been added to WRF-SFIRE-CHEM to constrain fire growth using existing infrared fire perimeters and satellite fire detections from VIIRS and MODIS.

WRF-SFIRE has been coupled (Kochanski et al. 2016) with WRF-CHEM (Grell et al. 2011) so that fire progression can be simulated along with the fire emissions and smoke chemistry (Figure 9). WRF-SFIRE-CHEM provides fire emissions and plume rise based on the fire behavior, fuel moisture, and atmospheric conditions computed at each WRF time step (Figure 7). Combustion rates are computed based on the mass of fuel consumed within each fire-grid point. Emission fluxes are the products of the combustion rates and fuel-specific emission factors. Emission factor derived from Urbanski et al. (2014) will be used to compute fire emissions. Smoke emissions are represented as a sum of fluxes of WRF-CHEM-compatible chemical species and are emitted into the lowest WRF model layer.

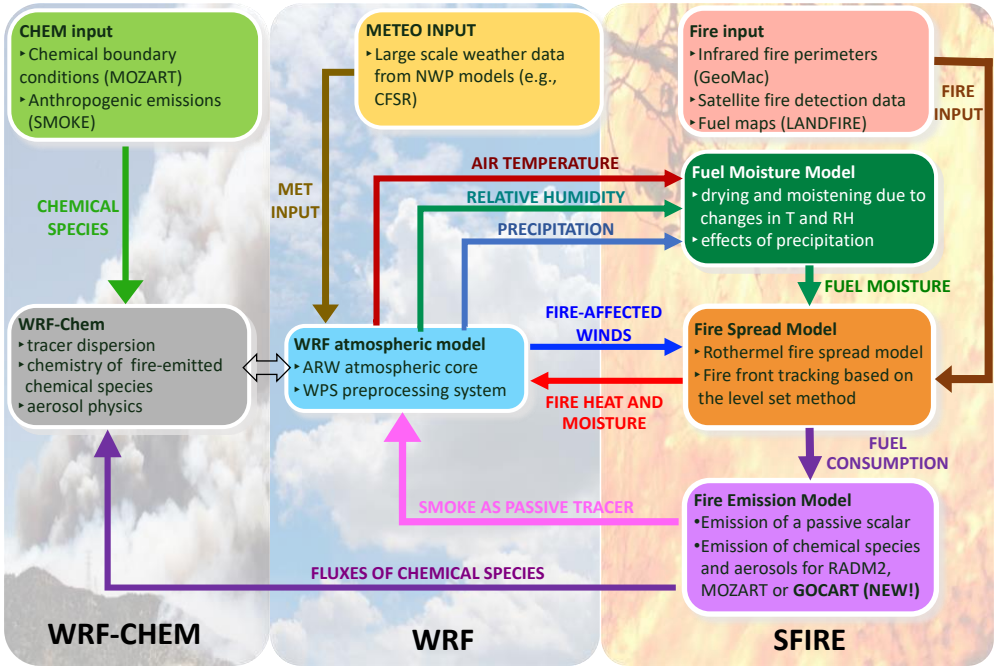


Figure 7. Data flow in the WRF-SFIRE-CHEM modeling system.

Smoke emissions generated from WRF-SFIRE-CHEM will be transported via winds from the atmosphere model (WRF) while WRF-CHEM's chemical mechanisms will be responsible for simulating smoke plume chemistry and interactions between the smoke plume and anthropogenic emissions. An earlier study, which focused on O_3 chemistry, found that WRF-SFIRE-CHEM was also able to simulate elevated concentrations of O_3, NO_x and $PM_{2.5}$ downwind of fire in Southern California (Kochanski et al. 2015). Smoke emissions will also be linked to an aerosol model (GOCART), which can interact with solar radiation and microphysics. Recent work by Kochanski et al. (2019) found that smoke aerosols can significantly impact the surface energy budget via smoke shading, which can affect near-surface winds, temperature, and stability. WRF-SFIRE-CHEM's capability to resolve the impacts of aerosol-radiative feedbacks allowed us to identify a positive feedback mechanism where smoke shading increased atmospheric stability, inhibited vertical mixing, and further increased near-surface smoke concentrations. Through this framework

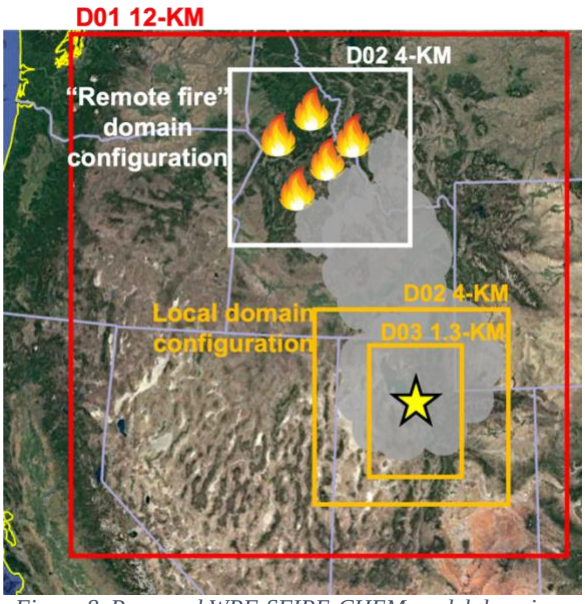


Figure 8. Proposed WRF-SFIRE-CHEM model domain centered over the Wasatch Front and remote fires (hypothetical case). Flame symbols represent remote fire locations, while the gray shaded region illustrates smoke.

we would also explore the impacts of smoke shading on O_3 photochemistry.

In order to run WRF-SFIRE-CHEM for smoke-induced air quality events, a number of inputs are needed. These inputs include meteorological and chemical boundary conditions, anthropogenic emissions, and fire data inputs such as: fuel maps, fuel moisture, infrared fire perimeters and/or satellite fire detections. The atmospheric forcing and boundary condition data needed to initialize and drive WRF model simulations will come from the Climate Forecast System Reanalysis (CFSR, Saha et. al 2010) dataset, while NASA's MOZART-5/GEOS-5 will be used for chemical boundary conditions (https://www.acom.ucar.edu). Anthropogenic emissions within our domain of interest will be obtained using the Sparse Matrix Operator Kernel (SMOKE) Modeling System.

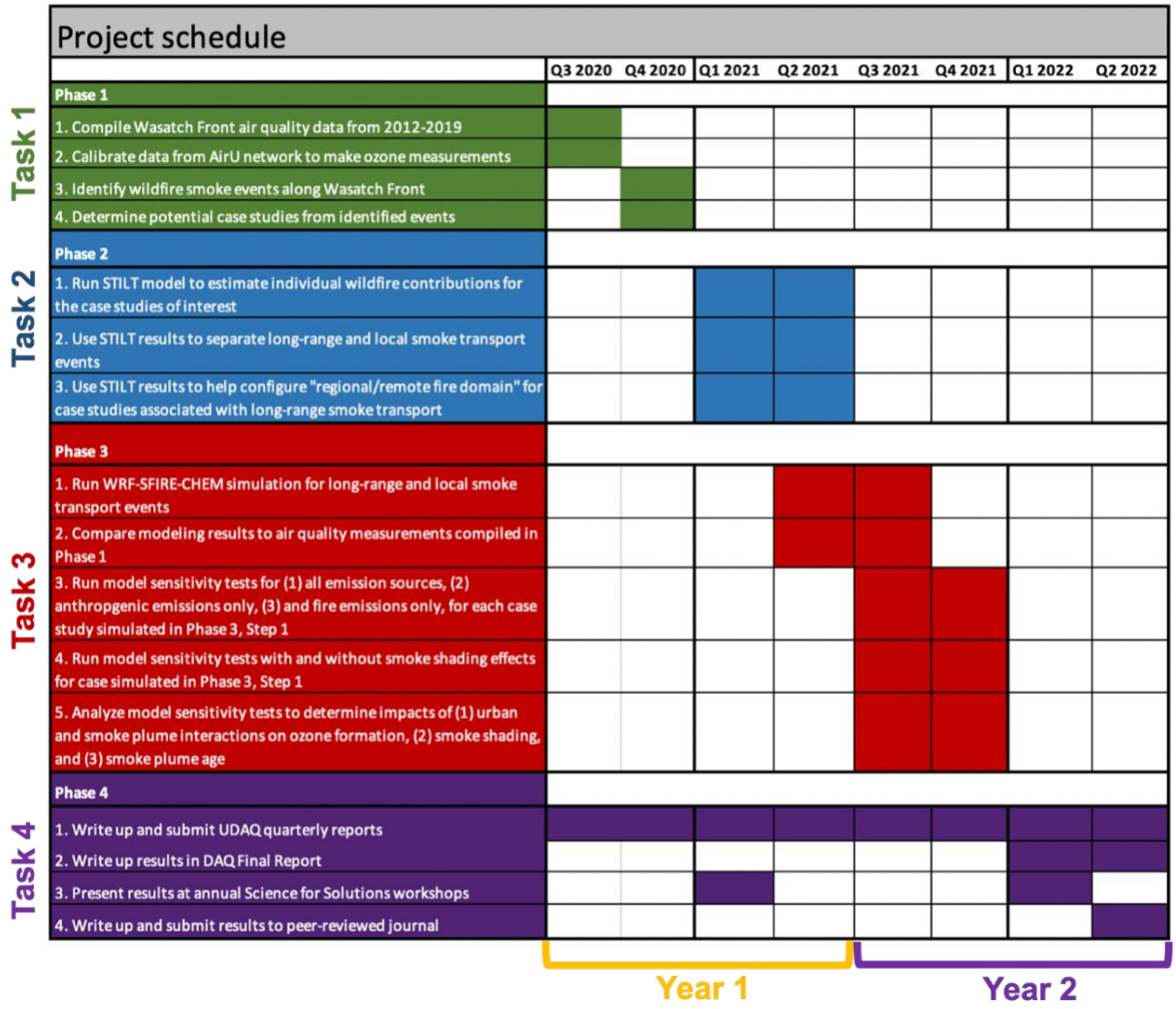
USGS GeoMac infrared fire perimeters (https://www.geomac.gov) will be used to initialize fires within the WRF-SFIRE-CHEM modeling framework and to constrain the daily growth of these fires. This method will prevent model simulations from over and underestimating daily fire growth, which will translate to more accurate fire emissions. This method was previously used in Kochanski et al. (2019) to simulate extreme smoke events across Northern California during the summer of 201. For cases where daily airborne infrared fire perimeters are not available, we will assimilate level 2 VIIRS (375, and 750m) and MOIDS fire detections encoded as spatial fire arrival maps to constrain fire growth within WRF-SFIRE-CHEM. Static data for fire modeling, such as fuel maps and topography, will be obtained from the LANDFIRE database. This data will be ingested within WRF-SFIRE-CHEM to determine the amount and type of fuels that are being consumed by the fire, which are needed to estimate fire heat fluxes and emissions.

To simulate O_3, we will use combination of the MOZART chemical mechanism (Emmons et al. 2014) and an aerosol scheme. This configuration will allow WRF-SFIRE-CHEM to simulate the transport of O_3, and other relevant species for O_3 chemistry. Aerosol radiation feedbacks will be turned on within WRF-SFIRE-CHEM, which will allow aerosols to interact with RRTMG longwave and shortwave scheme within WRF.

A multiscale domain configuration will be used to simulate wildfire smoke impacts across Utah (Figure 8). An outer 12-km resolution domain will be designed to encompass the Western U.S. Two additional high-resolution nested domains will be centered over the fire regions of interest and Northern Utah. This domain setup will be dynamic, in the sense that the domain placement will be dependent on the event of interest. The proposed high-resolution model configuration is intended to help the model resolve local-scale wind patterns, wildfire plume rises, fire-atmosphere interactions as well as strong spatial gradients.

1.3. Project Schedule

Outlined below is the proposed project schedule that will be carried out by PI Kochanski and Co-PI Kelly and Mallia. The 4 phases listed in the chart below corresponds to the phases outlined in the project schematic diagram **(Figure 2).** These phases/tasks are also linked to the "budget summary" table in **Section 2.7.**



1.4. Expected Outputs and Outcomes

The proposed project will provide a comprehensive dataset that combines O_3 from multiple mobile and stationary networks, including the high-density AirU network. Based on this dataset events with enhanced O_3 as a result of wildfires will be identified. Simulations using WRF-SFIRE-CHEM will be used to determine the respective roles of smoke and urban emissions in elevating O_3 concentrations. This analysis will be carried out by running sensitivity tests with WRF-SFIRE-CHEM. Result from numerical analysis will be used in conjunction with observations to analyze key processes responsible for the formation of O_3 in urban environments as a result of wildfire smoke plumes. The synthesis of the model and observational data will provide insight on the mechanisms responsible for the formation of O_3 during both regional and local wildfire smoke events, which often impacts summertime air quality. With wildfires expected to increase in frequency over the couple of decades, the hope that the results from this project can be used by

UDAQ to pinpoint anthropogenic emission sources that can exacerbate air quality impacts from wildfires. This information can then be disseminated to Utah legislators by UDAQ so that Utah can implement more effective regulatory policies aimed at improving air quality. Results from this project can also inform DAQ on the potential pathways of O_3 formation as a result of wildfire smoke, which can be used to make more accurate air quality forecasts for wildfire smoke events.

1.5. Deliverables

The proposed project will provide a comprehensive dataset that combines O_3 from multiple mobile and stationary networks, including the high-density AirU network. Results from our model-based sensitivity tests will summarized in a spreadsheet, with O_3 contributions from different sources (fires, background chemical species, specific anthropogenic sources, ect.). Raw WRF-SFIRE-CHEM outputs will be archived as Network Common Data Form (NetCDF) files, while meteorological and chemical fields of interest will be visualized and displayed on our interactive web portal to allow for easy access to animated simulations at http://demo.openwfm.org (Figure 9). Results from this study will be submitted to a peer-reviewed journal at the conclusion of this study, in addition to providing UDAQ with the required quarterly and the final report(s). Results from this study will be presented at several conferences, including UDAQ's annual Science for Solutions workshop. All data and code generated from project will be made available to UDAQ within 8 months of project completion. Data and code will be publicly available on our Research Group's webpage, which is hosted by the University of Utah's Center for High Performance Computing (CHPC).

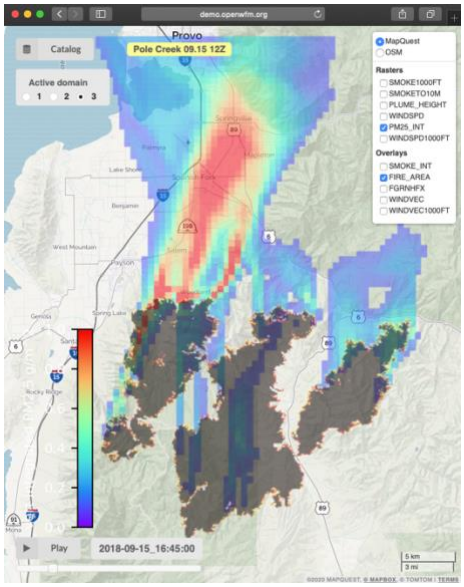


Figure 9. WRF-SFIRE simulations of smoke (colored) and fire area (black area) displayed on our interactive web portal.

2. Project Budget

2.1. Key personnel

Salary support is requested for PI Kochanski for 1 summer month during the 1st year of the project and 1 summer months in year 2. The principal investigator's time includes both scientific and project management functions. Salary estimates are based on the PI's 2020 salary rate of $12,264 per month with 3% inflation adjustment in year 2. 6-month salary support is requested for the Co-PI Derek Mallia (3 months in year 1, and 3 months in year 2). He is a postdoctoral scholar working within the Fire Modeling and Land-Atmosphere Interactions groups. His salary estimate is based on his average monthly rate of $3889. 1/8 of a month salary support is requested for Co-PI Kerry Kelly at her current monthly rate of $10901. Additional 2.5 months of support is requested for a Chemical Engineering student at $2600 per month.

Total salaries: $56,562.

2.2. Fringe benefits

The actual benefit rates for PI Kochanski (9.6% year 1, 10.6% year 2) for Co-PI Mallia (39%), Co-PI Kelly (36%) and 14% for a student are used for budgeting purposes.

Total benefits: $13,201

2.3. Supplies

Funds are requested for storage to accommodate the output from generic atmospheric simulations, STILT simulations as well as chemical simulations performed using WRF-SFIRE-CHEM.

External Hard Drive	$481
Total supplies :	**$481**

2.4. Indirect Costs

The negotiated DAQ rate of 10% is used for the estimate of indirect cost. The indirect cost is also charged from the first $25k of the subcontract to the University of Utah. The indirect charges charged by the San Jose State University are $5289, the indirect cost charged by the University of Utah is $4235. The overall indirect charges for the whole project are $9524

2.5. Total Budget:

$56,562 + $13,201 + $481+ $9254 = **$79768**

2.6. Budget summary:

The tasks listed in the budget summary above correspond to the tasks outlined in project schedule diagram listed in **Section 1.3**.

	Task 1	Task 2	Task 3	Task 4	Total	Grand Total
PERSONNEL						
PI Adam Kochanski @ $12448/month x 2 months	$7,469	$7,469	$7,469	$2,490	$24,896	
Co-Pi Derek Mallia @ $3889/month x 6 months	$7,142	$7,142	$7,142	$2,380	$23,804	
Co-Pi Kerry Kelly @ $10901/month x 1/8 month	$1,227			$136	$1,363	
Ch. Eng. student @ $2600/month x 2.5 months	$5,850			$650	$6,500	
FRINGE BENEFITS @ 10.1% for PI Kochanski	$755	$755	$755	$252	$2,516	
FRINGE BENEFITS @39% for Co-Pi Mallia	$2,786	$2,786	$2,786	$928	$9,285	
FRINGE BENEFITS @36% for Co-Pi Kelly	$442			$49	$491	
FRINGE BENEFITS @14% for Ch.Eng. student	$819			$91	$910	
SUPPLIES						
5TB storage expansion		$481			$481	
EQUIPMENT						
Instrument 1 @ $/unit x X units	$ -	$ -	$ -		$ -	
TRAVEL						
Travel @ x$/mi x X miles x miles/trip x X trips	$ -	$ -	$ -		$ -	
CONTRACTUAL						
Consultant A	$ -	$ -	$ -		$ -	
OTHER						
Publication fee, etc.	$ -	$ -	$ -		$ -	
TOTAL DIRECT COSTS	$28,314	$19,624	$19,143	$7,399	$74,480	
TOTAL INDIRECT COSTS @ 10%	$2,010	$1,393	$1,359	$525	$5,288	
TOTAL PROJECT COST	$30,325	$21,017	$20,502	$7,924	$79,768	**$79,768**

2.7. Leveraging of other resources

The project will take advantage of the 196-core computing cluster available for the Kochanski research group, as well as the data storage and computing infrastructure available from the University of Utah Center for High Performance computing. The project will also leverage the multiyear effort that resulted in the developments of the coupled fir-atmosphere-chemistry framework WRF-SFIRE-CHEM, as well as data from the University of Utah's Atmospheric Trace gas and Air Quality (U-ATAQ) lab and the AirU network. All the team members will contribute to the reporting requirements. The list below outlines the research-related responsibilities.

3. Personal Roles and Responsibilities

The proposed project will leverage the collaboration between three research groups: the Interdisciplinary Wildfire Modeling Center at SJSI, the fire modeling group at the Atmospheric Sciences Department led by Co-PI Mallia, and the Chemical Engineering group led by professor Kerry Kelly.

3.1. PI Adam Kochanski

PI Adam Kochanski is an Assistant Professor at the San Jose State University Department of Meteorology and Climate Science with over 15 years of experience with atmospheric modeling. Responsibilities of PI Kochanski include both scientific and project management functions. He will oversee the whole project; and coordinate with the DAQ. He will be in charge of meeting project objectives as well as specific DAQ requirements. He will be responsible for the setup and configuration of WRF-SFIRE-CHEM, collecting and processing fire observations and fuel data for WRF-SFIRE-CHEM, integrating fire emission data into the model and optimization of the model configuration. He will perform and assist with analyzing simulations of selected wildfire events performed using WRF-SFIRE-CHEM. He will also collect and pre-process fuel data to streamline static data processing for model initialization.

3.2. Co-PI Derek Mallia

Co-PI Derek Mallia is a Postdoctoral Research Associate at the University of Utah's Department of Atmospheric Science. Co-PI Derek Mallia will assist PI Kochanski with configuring and running WRF-SFIRE-CHEM, along with collecting and processing fire perimeter data, and obtaining and processing chemical boundary conditions and anthropogenic emissions. He will be responsible for compiling air quality data for northern Utah, along with identifying potential events with enhanced O_3 concentrations as a result of wildfires. He will also lead the effort towards analyzing the model data and validating it against air quality measurement. Derek Mallia will assist Adam Kochanski with disseminating research results, preparing presentations, quarterly reports and the final report, and writing up results in a manuscript to be submitted at the conclusion of this project. He will collaborate with UDAQ personnel on proper utilization and interpretation of the model data.

3.3. Co-PI Kerry Kelly

Co-PI Kerry Kelly is an Assistant Professor at the University of Utah's Chemical Engineering Department. She and her student will be responsible for the acquisition, processing and quality control of the ozone and PM2.5 data form the AirU network. They will develop and deploy data processing techniques allowing for estimation of ozone concentrations based on the measured concentrations of oxidizing and reducing species. The team of Kerry Kelly will be also responsible for calibration of the AirU sensors.

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