Summary Information Page

I. Project Title: **The Red Butte Canyon Air Mass Exchange and Pollution Transport Study**

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IV. Funding Requested: **34,965**

V. Project Period: **7/1/2019-12/31/2020**

Scope of Work

Abstract

Every winter, particulate pollution (PM2.5) episodes under Persistent Cold Air Pool (PCAP) conditions impact the population centers located in northern Utah's topographic basins. Results from the Utah Winter Fine Particulate Study (UWFPS) conducted in early 2017 show that thermally driven air mass exchange through tributary canyons and inter-basin air mass exchange have a strong impact on the spatial and temporal variation of PM2.5 concentrations as well as the concentrations of precursor gases. This proposal directly addresses the needs of the RFP to evaluate "air exchange processes and pollutant transport" by quantifying the impact of a representative tributary canyon, Red Butte Canyon, on the Salt Lake Valley airshed. We will install and operate the University of Utah Doppler Wind LiDAR at the mouth of Red Butte Canyon to evaluate the thermally driven air mass exchange at the canyon/basin interface during the 2019/2020-winter pollution season. Combined with collocated PM2.5 and ozone (O3) observations, we will estimate the transport of PM2.5 and O3 through the canyon cross-section. Two ceilometers deployed in the vicinity of the canyon exit will be used to observe the changes in aerosol backscatter along the canyon flow axis. Additionally, the observations will be used to evaluate the skill of readily available forecast resources such at the High Resolution Rapid Refresh (HRRR) model in estimating the airmass exchange. In a future step, the findings for this representative "example" canyon flow case can be projected to other canyons to evaluate the overall influence of drainage flows on the entire Salt Lake Basin airshed.

Basis and Rationale

The results of the Utah Wintertime Fine Particulate Study (UWFPS, Baasandorj et al. 2017) indicate the need to further investigate the influence of thermally driven up- and down-canyon flows along the sidewalls of the large populated Utah basins that suffer from particulate pollution episodes.

Thermally driven nocturnal down-canyon and daytime up-canyon circulations are a well-known phenomenon in complex topography (Ekhard 1948, Zardi and Whiteman 2013). They develop most readily under clear skies and weak synoptic pressure gradients (Whiteman 2000). These are the same conditions leading to the development of persistent wintertime cold-air pools (PCAPs, Lareau et al. 2013,) that provide the meteorological conditions for the severe pollution episodes (Whiteman et al. 2014) resulting in the non-attainment of the PM2.5 standards in Utah's Salt Lake and Cache valleys.

During the night, the general effect is the transport (advection) of air with lower PM2.5 concentrations to the canyon exits (i.e. where the canyons open up and air is injected into the larger basin). This has been demonstrated in observations

conducted by the PIs during the January 2017 UWFPS (Fig. 1) and its preliminary study in the 2016-2017 pollution season, where observations were made at the mouth of Red Butte Canyon, and at the Parleys Canyon exit.

During the day, on the other hand, up-slope and up-canyon flows pump air with higher PM2.5 concentrations into the tributary canyons, especially those on the northeastern periphery of the larger basins (Salt Lake Basin, Cache Valley), as insolation and thus solar heating, which is driving these circulations, is strongest there (Whiteman and Hoch 2014). This phenomenon, often referred to as "sidewall ventilation", can modify PM2.5 concentrations (Bares et al. 2018) and is likely one the causes for elevated pollution layers within PCAPs (Hoch et al. 2017). The effect of this transport has been shown to impact the snowpack ion concentrations on the urban to montane gradient along the Wasatch Mountains (Hall et al. 2014).

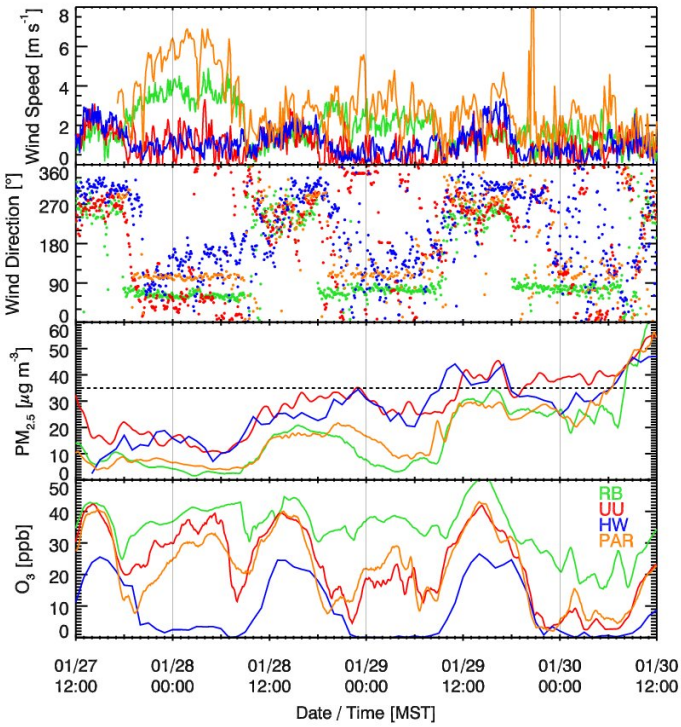

Fig. 1: Time series of near-surface wind speed, wind direction, PM2.5, and ozone concentration, at the months of Red Butte Canyon (green) and Parleys Canyon (orange) as well as at the University of Utah (red) and at Hawthorne Elementary (blue) during the onset of a pollution episode at the end of January 2017. The *qualitative* effect of thermally driven nighttime down-canyon flows is seen, as down-canyon wind speeds increase, PM2.5 concentrations decrease and ozone concentrations increase at the mouths of Red Butte and Parleys Canyon.

Besides the nighttime down-canyon transport of "cleaner" air (i.e. lower PM2.5 concentrations) the PIs further reported in increase ozone concentrations associated with these circulations (Baasandorj et al. 2017a, Baasandorj et al. 2017b). These findings suggest the transport of background ozone into the PCAP, and thus potentially influencing the chemical mechanism of PM2.5 formation by providing an oxidant necessary for the oxidation of NO_2 to nitric acid, thus potentially affecting concentrations of a direct precursor for the dominating PM2.5 aerosol species, ammonium nitrate.

While these studies were qualitative and more focused on the dependence of these circulations on the evolutionary stage of the PCAP, the depth and strength of the inversion layer, and cloud conditions, **this proposed study will aim at quantifying the air mass exchange** at the interface of a representative canyon, Red Butte Canyon. The choice of this example drainage is obvious: It is a drainage where

the *qualitative effects* have been previously documented, its cross section is of a shape and size that makes it easy to instrument, and it is affecting an area at the canyon-basin interface that is already heavily instrumented (ceilometer (aerosol backscatter), surface winds, PM2.5, and ozone).

The key instrument for this research effort is the University of Utah Doppler Wind LiDAR. It will be strategically positioned near the mouth of Red Butte Canyon, and scanning strategies will be designed based on RHI (range-height indicator) and PPI (plane position Indicator) scan patterns to evaluate the full structure of the nocturnal down- and daytime up-canyon flow fields. The instrument will either be operated from the roof of the Mountain Met Laboratory or from an area in Red Butte Gardens, whose management has previously accommodated the PIs placement of research equipment.

While the selected canyon is not one of the largest tributaries to the Salt Lake Basin, its accessibility and average size make easy to instrument. It is important to emphasize that the finding from this study of the influence of this example canyon will facilitate a future projection of the influence of the entirety of tributaries entering the Salt Lake (or Cache) Valley. Part of the proposed effort is a comparison of the observed air mass exchange at the mouth of Red Butte Canyon with the exchange processes resolved by the readily available High Resolution Rapid Refresh (HRRR) model. This evaluation will guide future observational and modeling efforts to **calculate basin-wide pollution and precursor budgets**.

This proposal directly addresses the priority to investigate "Air Exchange Processes and Pollution Transport" defined in the RFP by investigating the air mass exchange at the interface of a tributary canyon with a basin atmosphere which also affects the "Oxidants exchange between he cold air pool and the free atmosphere" through sidewall ventilation.

Note: This proposal is independent of, but synergistic with, the proposal "The Red Butte Canyon Ozone Network" submitted by PI Mitchell that will focus on observing detailed ozone concentrations along the Red Butte Canyon drainage. The work proposed here only requires the ozone and PM2.5 observations at the Department of Atmospheric Sciences' Mountain Meteorology Laboratory, which are maintained by Co-PI Dr. Crosman. Additional ozone measurements along the Red Butte Canyon drainage would provide very interesting additional information, but are not required for the successful completion of this project. Similarly, the proposed detailed wind observations at the mouth of Red Butte Canyon would be an additional asset that could be utilized by PI Mitchell in their proposed project.

Technical Approach

This proposed work is mainly an observational study focusing on the detailed airmass exchange processes through thermally-driven circulations at the Red Butte Canyon - Salt Lake Valley basin interface. This effort is motivated, however, by

allowing the evaluation of the skill of available high-resolution meteorological model products in estimating the effect of tributary canyons.

a) Observations

The proposed work combines observations at the Red Butte Canyon Exit to evaluate the airmass and pollution exchange at this representative Canyon-Basin interface during the 2019-2020 wintertime particulate pollution season. It requires **(1) wind profile** observations that can be correlated with **(2)** changes in **PM2.5 and ozone concentrations** as well as with **(3)** changes in the **spatial patterns of aerosol backscatter.** These observations will be put in context with observations of the strength and evolution of the PCAP forms the meteorological boundary condition for the evolution episode.

1) The **wind profile** will be measured with the University of Utah's Halo Photonics scanning Doppler Wind LiDAR. It will be strategically positioned near the mouth of Red Butte Canyon, and scanning strategies will be designed based on RHI (range-height indicator) and PPI (plane position Indicator) scan patterns to evaluate the full structure of the nocturnal down-, and daytime up-canyon flow fields. The instrument will either be operated from the roof of the Mountain Meteorology Laboratory or from an area in Red Butte Gardens, whose management has previously accommodated the PIs' placement of research equipment. VAD (Vertical Azimuth Display) based wind retrievals in the center of the canyon flow axis will be combined with multi-sector RHI and low-angle PPI scans to evaluate flow transitions at the canyon mouth ("valley exit jets"; Chrust et al 2014). This will allow the calculation of the volume flux through the canyon cross section. PI Hoch has extensive experience in Doppler LiDAR observations and will lead this effort.
2) **Ozone and PM2.5 concentrations** will be measured via the infrastructure and instrumentation at the Department of Atmospheric Sciences' Mountain Meteorology Laboratory, using Model 205 Dual Beam Ozone Monitor (2B Technologies) and an ES-642 E-Sampler (MetOne). CoPI Dr. Crosman has extensive experience in running, calibrating, and maintaining these instruments and will be responsible for these observations.
3) The **spatial variation of aerosol backscatter at the canyon-basin interface** will be resolved using 3 Vaisala CL31 laser ceilometers. These have been successfully used in past experiments to characterize aerosol loading, layering, and injection of clearer air through tributaries (Fig. 2). One existing ceilometer is positioned at the Mountain Meteorology Laboratory. Two others will be deployed between the canyon exit and the bottom of the Salt Lake Basin. PI Hoch has used ceilometers for many years and will lead this effort.

The general meteorological conditions and the evolution of PCAP and pollution episodes will be compiled from data available from MesoWest (Horel et al. 2002) and based on calculations of the Valley Heat Deficit (Whiteman et al. 2014) using

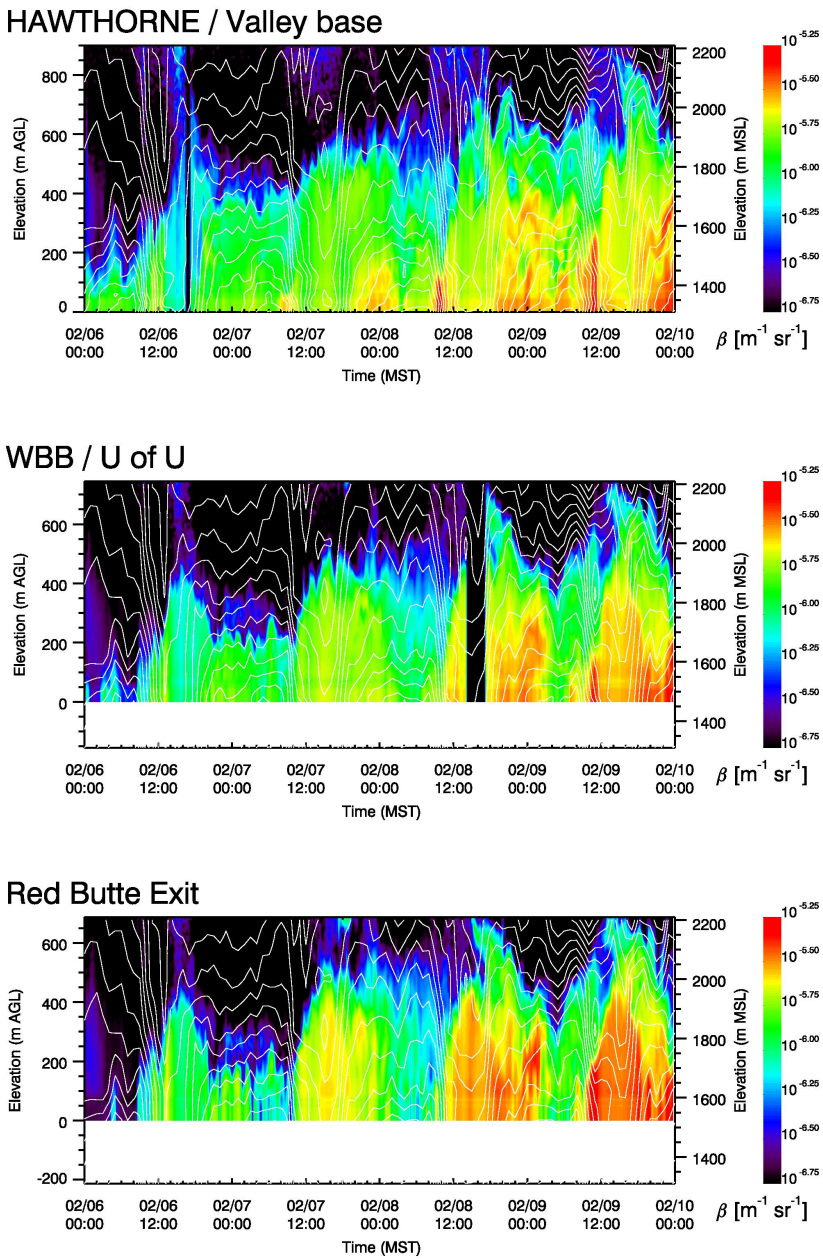

Fig. 2: Time-height cross sections of aerosol backscatter during the onset of a pollution episode in the Salt Lake Basin in February 2016 from three CL-31 ceilometers positioned near the valley bottom (Hawthorne Elementary, HW, top panel), at the University of Utah (UU, center panel), and at the mouth of Red Butte Canyon (RB, bottom panel). The nighttime advection of aerosol-scarce air to the canyon exit is seen as well as the daytime transport of aerosols up the valley sidewall (sidewall ventilation). Note missing data in the afternoon of 2/8 at UU and a short outage at HW on 2/6).

twice-daily radiosoundings from the Salt Lake City International Airport. This dataset will be crucial to evaluate the air mass exchange along the canyon-basin interface as a function of different meteorological conditions and PCAP developmental stages.

b) Model evaluation

Air mass transport (volume flux) derived from the observations will be compared to estimates based on meteorological wind fields for canyon flows simulated by the High-Resolution Rapid Refresh (HRRR) model. The HRRR operational model (https://rapidrefresh.noaa.gov/) is run over the contiguous U.S. at 3 km resolution (Benjamin et al. 2016). HRRR incorporates sophisticated data assimilation and has been shown to adequately capture complex local terrain flows in northern Utah. The HRRR model data is archived at the University of Utah (Blaylock et al. 2017). This evaluation will guide future observational and modeling studies. This effort will be led by CoPI Dr. Crosman who has extensive experience in evaluating high-resolution model output in complex terrain under PCAP conditions.

Expected Outputs and Outcomes

1) **Evaluation of volume flux or airmass exchange:** The wind LiDAR observations are expected to lead to a better understanding of the nocturnal down- and daytime up-canyon flow field. Once the characteristics of the flow field (depth of flow, canyon center speed-ups, edge slow-downs, jet heights, jet depth, etc.) are determined, we expect to use a single wind profile retrieval (via VAD technique) to estimate the volume flux out of (or into) the canyon. We expect to estimate the volume flux on 10 to 15-min time steps and will be able to evaluate changes of the volume flux based on meteorological conditions and the evolutionary stage of the PCAP.

2) **Estimate of transport (PM2.5 and Ozone mass flux):** By combining the volume flux from (1) with surface observations of PM2.5 and ozone concentrations, (and reasonable assumptions of vertical gradients thereof) we expect to provide reasonably constrained estimates of PM2.5 and ozone mass fluxes. While the mass flux will be only determined through one tributary, we expect this study will provide guidance on how to project these findings to the entirety of tributaries, thus making an important step towards understanding and constraining the pollution budget of an entire basin airshed.

3) **Guidance for future model studies:** The initial comparison of the observational findings to readily available high-resolution model products will guide future efforts to evaluate basin-wide pollution budgets. If the comparison shows reasonable agreement, confidence is gained in using the evaluated model to evaluate transport through the entirety of tributaries. Discrepancies between observed and model-based transport are expected to highlight model deficiencies (resolution, stability regimes, etc.) and to guide future modeling approaches.

Deliverables

Deliverables include **quarterly progress reports** and a **final report** to be submitted by the end of the project.

A presentation of the project findings will be given at the "Air Quality: Science for solutions" conference.

Quicklooks of LiDAR-retrieved wind profiles and of the ceilometer backscatter profiles will be made available near real time, PM2.5 and ozone concentrations will be available at real time via MesoWest. (https://mesowest.utah.edu/).

Data sharing: To preserve the observational data for future use, all project data will be placed in the University of Utah Research data repository (https://hive.utah.edu/). "The Hive" is a publicly accessible repository for research data generated by University of Utah researchers, students, and staff.

Schedule

The project is planned over a 18 month period. Observations will be made during the 2019-2020 winter season.

Timeline	Task
Jul 2019-Oct 2019	Site access agreements, equipment preparation, calibration and maintenance Design of LiDAR scanning strategies
Sep 30 2019	Quarterly report
Nov 2019	Deployment of LiDAR and ceilometers, testing of communication, fine tuning of LiDAR scans
Dec 2019 - Feb 2020	Observation phase. Compiling of daily data quicklooks. Close monitoring of instrument performance. Daily equipment maintenance. Documentation of PCAP and pollution episodes and potential case studies
Dec 31 2019	Quarterly report
Mar 2020	Equipment take-down. Archiving of all raw data. Presentation of initial results at Science for Solutions Conference
Mar 31 2020	Quarterly report
Apr -Jun 2020	Data quality control. LiDAR scan analysis, flow characteristics evaluation, air mass volume flux estimate
Jun 30 2020	Quarterly report
Jul-Sep 2020	Estimates of PM2.5, aerosol, and ozone mass transport, evaluation of HRRR with observed volume fluxes.
Sep 30 2020	Quarterly report
Oct-Dec 2020	Compile final report, submit data to repository, publication in scientific journal
Dec 31 2020	Submission of Final Report

Budget

Budget item		**Cost UDAQ** (# months or hours covered)	**University of Utah** (cost share via **matching funds**) (#months covered)	Total
Personnel costs (hourly rates)				
Senior Personnel:				
PI Hoch (@ 36 USD/hr)		15443 (2.5 mo)	3089 (0.5 mo)	18531
CoPi Crosman (@ 34 USD/hr)		5855 (1 mo)	0	5855
Fringe benefits (37%)		7880	1143	9023
Other personnel (@ 13 USD/hr)		749 (57.6 hr)	291 (22.4 hr)	1040
Fringe benefits (8 %)		60	23	83
Lab and Technical Supplies		1080	0	1080
Other expenses (truck use, power, modem fees)		720	0	720
Total direct costs		31786	4546	36332
Indirect cost (10%)		3179	455	3633
Project total		**34965**	5000	39965

Budget justification:

PI Hoch is requesting 3 months of his salary, CoPI Crosman 1 month of salary, to cover the tasks specified in the next section. Personnel costs are requested covering a total of 80 hours of undergraduate student help during the equipment deployment and for maintenance tasks. Lab and technical supplies are budgeted to USD 1080, covering the cost of a replacement pump for the ozone sensor, one weatherproof data logger enclosure, and other small items.
Other expenses (USD 720 total) include the use of the Department truck for deployment and maintenance trips (USD 36/day and USD 0.31/mile; on ~11 days (12 miles/day on average), modem charges for the experiment period (USD 65/month, 4 months), and potential charges for power costs for ceilometer deployments (~USD 50) outside of University of Utah property.

Matching funds of USD 5000 will be provided by the Department Of Atmospheric science, covering 0.5 months of PI Hoch's time and ~22 hours of undergraduate student help.

Personnel Roles and Responsibilities

PI Dr. Hoch is responsible for the overall project management and project coordination. He is responsible for negotiating site access agreements, siting of equipment, equipment deployment, LiDAR programming and wind retrieval calculations, ceilometer data processing and analysis, and volume and pollution transport estimates. Dr. Hoch is responsible for the submission of quarterly and final reports.
CoPI Dr. Crosman is responsible for maintaining the PM2.5 and ozone measurements at the Department of Atmospheric Sciences Mountain Meteorology Laboratory located at the mouth of Red Butte Canyon, and for quantifying transport terms at the Red Butte Canyon - Salt Lake Basin interface based on available HRRR model datasets.
Both PIs will contribute to the final Report and to scientific publication of the results.

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