Inter-basin Airmass Exchange Estimates for Air Quality Applications using Doppler Wind LiDAR

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ICAM2019 35th International Conference on Alpine Meteorology
2 – 6 Sep. 2019
Riva del Garda, Italy

Introduction

The Salt Lake Valley (SLV, Fig. 1) and other densely populated topographic basins in northern Utah and throughout the world suffer from prolonged pollution episodes during wintertime that are associated with Persistent Cold Air Pools (PCAPs). PCAPs develop when high pressure systems and subsidence temperature inversions trap colder air and anthropogenic emissions in topographic basins.

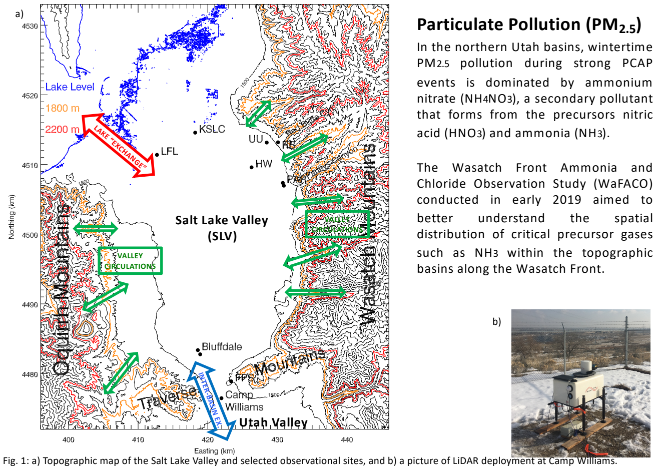

Fig. 1: a) Topographic map of the Salt Lake Valley and selected observational sites, and b) a picture of LiDAR deployment at Camp Williams.

Particulate Pollution ($PM_{2.5}$)

In the northern Utah basins, wintertime PM2.5 pollution during strong PCAP events is dominated by ammonium nitrate (NH_4NO_3), a secondary pollutant that forms from the precursors nitric acid (HNO_3) and ammonia (NH_3).

The Wasatch Front Ammonia and Chloride Observation Study (WaFACO) conducted in early 2019 aimed to better understand the spatial distribution of critical precursor gases such as NH_3 within the topographic basins along the Wasatch Front.

Cold-Air Pool Exchange Processes

While atmospheric mixing and transport processes are generally suppressed under the statically stable atmospheric conditions of PCAPs, some thermally and synoptically driven processes still work to modulate particulate pollutant ($PM_{2.5}$, NH_4NO_3) and pollutant precursor (NH_3, NO_x, etc.) concentrations within and along the edges of the PCAPs.

For the SLV, these processes include (1) **canyon circulations** through tributaries, (2) **lake breeze circulations** from the Great Salt Lake (GSL), (3) **synoptically forced airmass exchanges** with the atmosphere over the GSL, and (4) **inter-basin exchanges** between the Utah Valley and Salt Lake Valley.

Inter-Basin Transport Estimates

In January and February 2019, the Jordan Narrows Ammonia Transport Study investigated inter-basin atmospheric transport between the SLV and Utah Valley, using a Doppler wind LiDAR, automatic weather stations, and the WaFACO ammonia (NH_3) observations.

The Valley Heat Deficit

The Valley Heat Deficit *H* (Whiteman et al. 2014) is a thermodynamic measure of the intensity or strength of a cold-air pool, corresponding to the amount of energy that would be needed to bring a valley or basin atmosphere to a neutral stratification.

$$\boxed{H_h = c_p \int_{1288\ \mathrm{m}}^{h} \rho(z)[\theta_h - \theta(z)]\mathrm{d}z \quad [\mathrm{J\,m^{-2}}]}$$

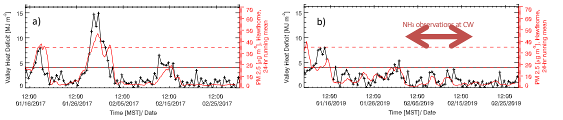

Fig. 2: Time series of the Valley Heat Deficit for the SLV and $PM_{2.5}$ concentrations for a) early 2017 and b) early 2019.

The Valley Heat Deficit *H* for the SLV can be calculated from twice-daily radiosonde ascents at KSLC, the Salt Lake International Airport. Fig. 2 indicates that the 2018-2019 cold season was dominated by a progressive synoptic pattern that prevented persistent cold air pools from forming during the course of the 2018-2019 study.

Topographic calculations

A digital elevation model (DEM) and the dominant wind direction within the Jordan Narrows was used to calculate the cross section of the topographic gap between the Salt Lake Valley and Utah Valley basins (Fig. 3 a-e).

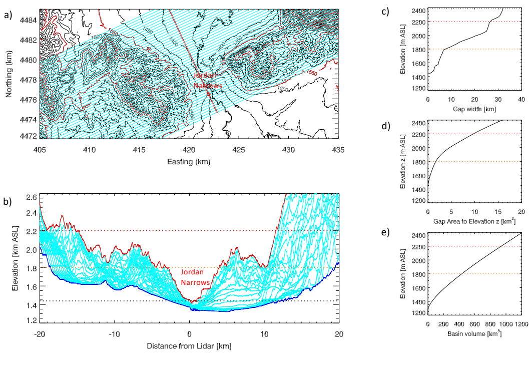

Fig. 3: Topographic analysis of the Jordan Narrows Gap and the Salt Lake Valley to calculate the gap cross section and basin volume.

Doppler wind LiDAR observations

A Doppler wind LiDAR and an automatic weather station were deployed at Camp Williams (CW) within the Jordan Narrows. Vertical profiles of the wind speed and direction via VAD retrievals (Fig. 4a) were combined with the results from topographic calculations to estimate the height-dependent volume flux (Fig. 4b), which can be integrated to different levels (Fig. 5).

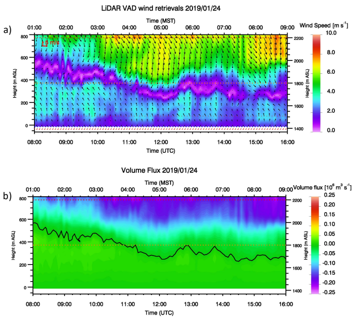

Fig. 4: Examples from 24 January 2019 of a) Doppler wind LiDAR retrievals of the wind field in the Jordan Narrows and b) volume flux calculation based on these retrievals and topographic conditions.

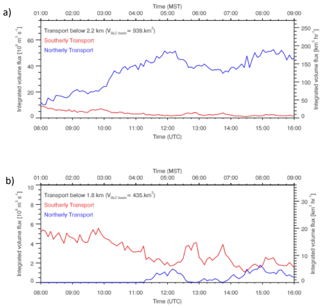

Fig. 5: Integrated volume flux calculations through the Jordan Narrows to heights of a) 2200 m ASL and b) 1800 m ASL.

Ammonia Transport through the Jordan Narrows

For two weeks in February 2019, high-frequency observations of ammonia (NH3) and carbon dioxide (CO2) concentrations are available in the Jordan Narrows. During this period, large scale synoptic conditions were not conducive for the development of PCAP conditions. Nevertheless, elevated ammonia (and carbon dioxide) concentrations correlated well with meteorological conditions (Fig. 6).

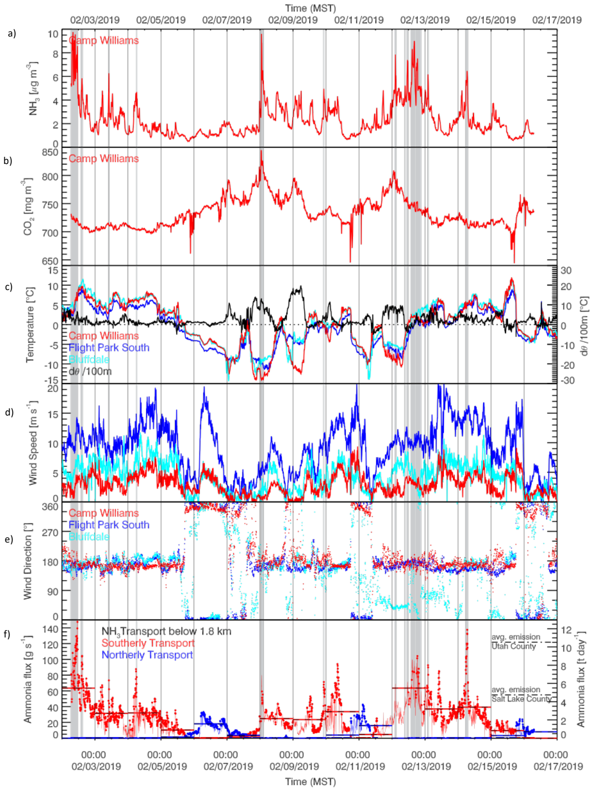

Fig. 6: Time series of a) ammonia (NH3) and b) carbon dioxide (CO2) concentration at Camp Williams (CW) in the Jordan Narrows, and c) temperatures, d) wind speeds and e) wind directions at CW, Bluffdale (BD), and Flight Park South (FPS) for 2-17 February 2019. Static stability is indicated in c) as the potential temperature gradient between CW and FPS. Times with NH3 concentrations above 8 ppb are highlighted. The bottom panel (f) shows successful (thick symbols) NH3 transport estimates through the gap up to 1800 m ASL. Horizontal lines indicate daily NH3 transport averages.

Results

We used the combination of Doppler Wind LiDAR-derived wind profiles, topographic calculations, and surface-based measurements of ammonia (NH3) concentrations to estimate the transport of ammonia through the Jordan Narrows, the topographic gap between the Salt Lake Valley and Utah Valley basins.

- During the limited (14-day) period for which surface NH3 concentrations were available, southerly flow and transport through the Jordan Narrows dominated.
- Or estimated show that the transport through the Jordan Narrows is significant when compared to average daily wintertime average emissions estimated by the Utah Department of Environmental Quality (personal communication). On average, Utah Valley exported about 20% of its daily emission into the Salt Lake Basin, which in turn imported about 45% of its own emission.
- Some assumptions used in the methodology, such as the representativeness of surface concentrations when estimating concentrations of the flow layer, should be evaluated in future experiments.

Acknowledgments: Funding for this study was provided by the Utah Department of Environmental Quality (UDEQ).

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