Snow Shadow, Data Sparsity, and AI Forecast of Winter Ozone

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Background

The Uinta Basin (Utah) is a high-elevation mountain basis. It is elevated enough to support cold, snowy winters; yet southerly enough to receive ample sunshine on clear days [1]. Given emissions from oil/gas industry, high ozone can occur when:

- Snow is at least 50–75 mm (2–3 in)
- Surface pressure rises and wind calms
- Cold air sinks to the Basin floor and sunlight reacts with these pollution precursors to form ozone: dangerous to our lungs.

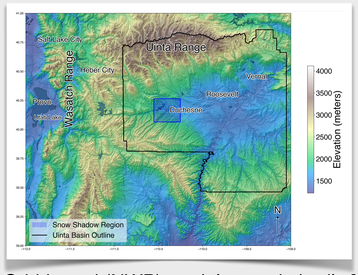


Fig. 1: Topographical map showing the Uinta Basin and snow shadow region near Duchesne.

Grid-based (NWP) models can do badly [2, 3]. Development and evaluation of models (like CLYFAR, our in-house AI model [3]) is difficult due to data sparsity (Fig. 1), especially **training and testing**. Also hard to monitor in real time - snow depth and coverage obscured by clouds in satellite imagery, on not high resolution in time.

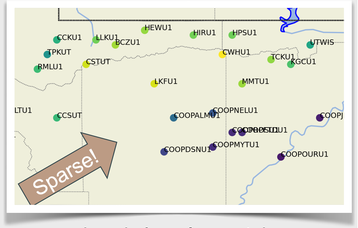


Fig. 2: Low-level sites reporting once a day (blue); subhourly mountain stations in green.

- Snow and rain shadows are regions in lee of mountains where moist air rises, precipitates, and descends drier.
- It is *received wisdom* the Uinta Basin has a snow shadow.
- This project will formally document & diagnose the snow shadow in the Basin, given its important to ozone production and impacts on oil and gas industry regulation.
- The **Wasatch Range** acts as primary barrier to westerlies
  - We look for a west-to east precipitation gradient
  - Observations show high-elevation, windward Alta averages 250–300 cm (98–118 in) more snow than Duchesne (lee side)

Data sources

- Vertical profiles from radiosonde at Salt Lake Airport (KSLC)
- Surface observations from the Synoptic Weather repository span four sites 1463–2945 m: snow depth, temperature, wind.
- GEFS model output at time zero (analysis) serves as proxy for sparse observations (used here for cloud cover)

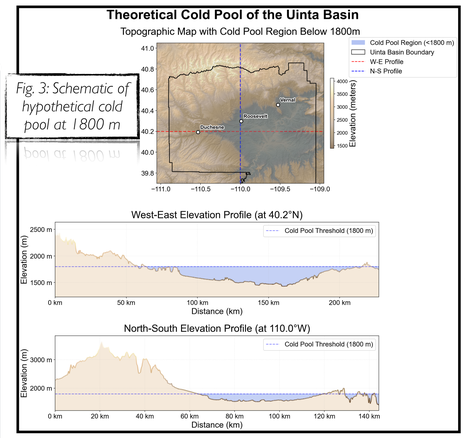


Fig. 3: Schematic of hypothetical cold pool at 1800 m

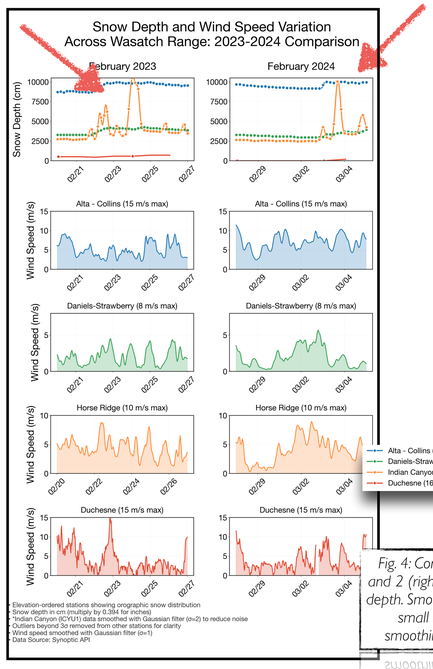


Fig. 4: Comparison of cases 1 (left) and 2 (right) through reports of snow-depth. Smoothing done as described in small print. Note artifacts of smoothing marked by red arrow.

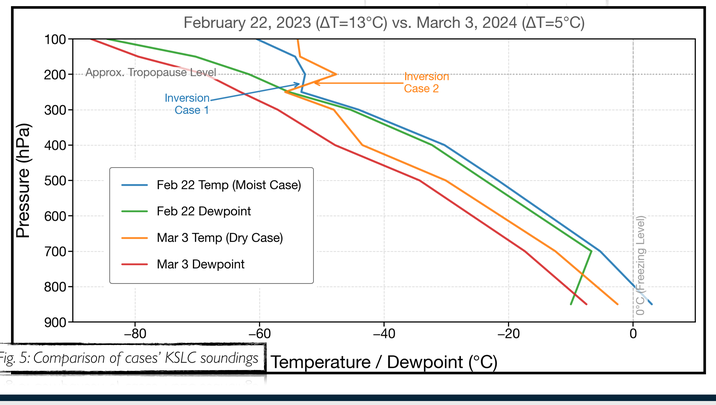


Fig. 5: Comparison of cases' KSLC soundings

Exploratory Results

Cross-sections of an example cold pool (Fig. 3) show the basin's bowl-like shape with steeper gradients on western edge near the Wasatch versus gentler eastern slopes. [4]

Case 1: Feb 20–27 2023

- KSLC soundings show:
  - strong inversion (ΔT=13°C/23.4°F)
  - moist profile below 700 hPa
- **Snowfall** demonstrated the snow shadow effect:
  - Alta-Collins had large accumulation (250–300 cm / 98–118 in)
  - However, Duchesne saw minimal snowfall (Fig. 4; bottom row, red).
- **Favorable conditions for cold pool formation** (cf. Fig. 3, 5).
- Global Forecast Ensemble System (GEFS) analysis showed:
  - high cloud cover (60-80%) across the Wasatch Range
  - distinct clearing in the basin (Fig. 6, left panel).
- Following light snow in the lee (Uinta Basin), **ozone concentrations peaked at 80—90 ppb: above the EPA's 70 ppb standard** (Fig. 8).
- Wind showed strong elevation dependence, with mountain stations recording 10–15 ms^{-1} while basin locations were below 5 ms^{-1} (Fig. 4).

Case 2: Feb 28–March 5 2024

- In contrast, the March 3 case showed a weaker inversion (ΔT=5°C/9°F) and drier profile (Fig. 5).
- Despite similar cloud patterns across the Wasatch Range (Fig. 6, right panel), no significant snow accumulated in the basin while Alta-Collins maintained deep snowpack (Fig. 3).
- Wind change with height showed less variability than the 2023 case (Fig. 4).
- Few wind observations (Fig. 7) highlight the challenge in basin monitoring:
  - Substantial data gaps at Duchesne and Roosevelt stations.
  - These gaps are particularly evident in COOP sites (manually reported in the Basin only once a day)
  - Vernal Airport data (KVEL) was excluded to show data coverage issues.
- Without snow cover, **ozone levels remained below 45 ppb across the basin sites** (Fig. 8).

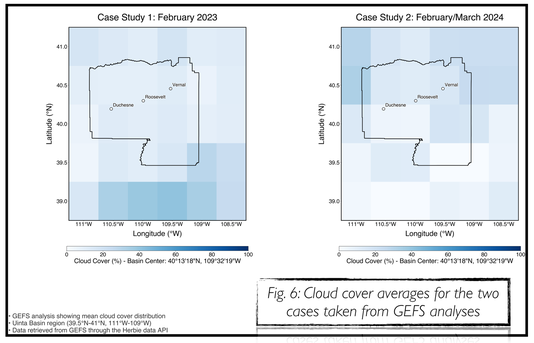


Fig. 6: Cloud cover averages for the two cases taken from GEFS analyses

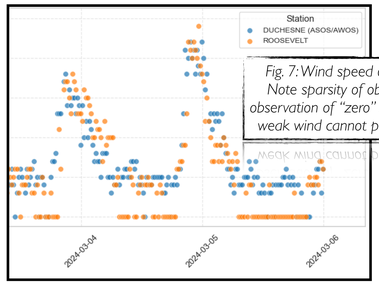
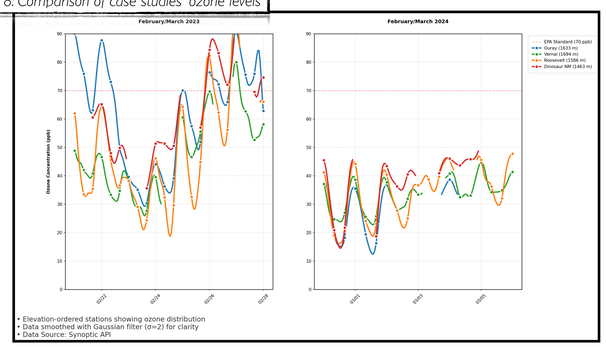


Fig. 7: Wind speed obs at two Basin sites. Note sparsity of observations in time; an observation of "zero" suggests stall speed (i.e., weak wind cannot push anemometer cups)

Fig. 8: Comparison of case studies' ozone levels



Conclusions

- Snow shadow appears in two case studies
  - Substantial spatial variability in snow accumulation patterns.
- Data sparsity, especially Duchesne and Roosevelt stations
  - Difficult real-time monitoring
  - Hard to calibrate and evaluate ozone forecasts
  - Subject to unforeseen "black swans" using trained AI model
- Preliminary case studies suggest strong relationships between cold pool strength, snow cover, and ozone levels, as in [4]
- Wind direction w.r.t. height may impact variables discussed.

Future Work

- Hydrology
  - Snow accumulation and the watersheds of Uinta Basin (*Green* and *Duchesne* Rivers)
  - Impact on wildlife, vegetation, human populations
  - Compare hydrology with/without snow-shadow influence
- Using 3D NWP model output
  - Create 3D basin visualizations
  - Identify terrain-induced circulation patterns
- AI/ML Development
  - Optimizing ozone-prediction system with deep learning
  - See poster 687 (Lawson) regarding CLYFAR system [5]
- Addressing lack of data
  - Proposals to work with high schools to install stations
  - Algorithms to determine snow yes/no from webcams
- **Paper in preparation for 2025**

References

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3. Lyman, S., C. Jones, J. R. Lawson, M. Mansfield, L. David, T. O'Neil, and B. Holmes, 2023: *Bingham Center 2023 Annual Report.*
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Generative AI used for brainstorming

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