Inversion structure and winter ozone distribution in the Uintah Basin, Utah, U.S.A.

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**Highlights**
- Multi-day winter inversion episodes lead to high ozone in eastern Utah.
- Inversion conditions are more frequent and long-lasting at lower elevations.
- Transport of ozone and precursors is limited during inversion episodes.
- Ozone is strongly influenced by elevation and proximity to sources.

**Abstract**
The Uintah Basin in Utah, U.S.A. experiences high concentrations of ozone during some winters due to strong, multi-day temperature inversions that facilitate the buildup of pollution from local sources, including the oil and gas industry. Together, elevation of monitoring sites and proximity to oil and gas wells explain as much as 90% of spatial variability in surface ozone concentrations during inversion episodes (i.e., $R^2 = 0.90$). Inversion conditions start earlier and last longer at lower elevations, at least in part because lower elevations are more insulated from winds aloft that degrade inversion conditions and dilute produced ozone. Surface air transport under inversions is dominated by light, diurnal upslope–downslope flow that limits net transport distances. Thus, different areas of the Basin are relatively isolated from each other, allowing spatial factors like elevation and proximity to sources to strongly influence ozone concentrations at individual sites.

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1. Introduction

A growing body of research has explored the air quality impacts of oil and gas development in the United States (Carter and Seinfeld, 2012; Colborn et al., 2014; Kemball-Cook et al., 2010; Oltmans et al., 2014). Oil and gas exploration and production is associated with emissions of greenhouse gases, ozone precursors, and particulate matter (Allen et al., 2013; Carter and Seinfeld, 2012; Edwards et al., 2014; Karion et al., 2013). Ozone precursors include oxides of nitrogen (NOx), non-methane hydrocarbons (NMHC), and other compounds. Ozone concentrations exceeding U.S. Environmental Protection Agency (EPA) standards (EPA, 2015a) have been observed in Wyoming’s Upper Green River Basin and Utah’s Uintah Basin during multi-day, wintertime temperature inversion episodes, and current inventories indicate that the majority of ozone precursor emissions in these areas are from the oil and gas sector (Stoeckenius and McNally, 2014). Significant wintertime ozone production was first observed in the Upper Green River Basin in 2005 (Schnell et al., 2009) and in the Uintah Basin in 2009 (Oltmans et al., 2014).

Persistent, multi-day temperature inversion episodes are common in basins and valleys in the montane western United States (Clements et al., 2003; Lareau et al., 2013; Whitman et al., 1999), and wintertime air quality (especially fine particulate matter) problems in this region are similarly common (Lareau et al., 2013; Malek et al., 2006). However, the Upper Green River Basin and Uintah Basin are the only two regions in North America known to experience wintertime ground-level ozone production significant enough to lead to exceedances of U.S. Environmental Protection Agency (EPA) health standards (High ozone during winter months has been observed in Asia, but only in the subtropics (Lin et al., 2004)). Poor air quality conditions in these basins develop when (1) sufficient snow cover is present to reflect most incoming solar...
radiation, promoting temperature inversions that trap emitted pollutants and increasing the amount of solar radiation available to drive photochemical reactions, and (2) a strong high pressure system exists to facilitate inversion formation and persistence (Oltmans et al., 2014).

Recent work has shown that during inversion episodes NMHC concentrations in these basins are much higher than the global background and higher than has been observed in urban areas (Helming et al. (2014); also see Results and Discussion section). NOx concentrations, on the other hand, tend to be similar to or lower than in urban areas, at least in the Uintah Basin (Edwards et al., 2013). Several recent papers provide insight into the details of wintertime photochemistry at the Horsepool site in the Uintah Basin (Edwards et al., 2013, 2014; Lee et al., 2014). Ahmadov et al. (2015) and Neemann et al. (2015) report on computer simulations of Uintah Basin wintertime ozone formation using Eulerian photochemical models. Both model studies involved significant changes to standard model parameterizations, allowing the models to produce daytime ozone concentrations that approximated measurements in some instances.

In this work we use an extensive measurement dataset from around the Uintah Basin to explore characteristics of winter ozone episodes, with particular emphasis on spatial features and relationships. We document consistent, predictable features of winter inversion episodes in the Uintah Basin and show how they impact ozone formation. The analysis relies mostly on data collected during the winter of 2012–13, but data from other years are used for comparison.

2. Methods

2.1. Methodological overview

This work analyzed measurement and model data generated by Utah State University (USU) and other entities. Correlation and multiple regression analyses were used, and Geographic Information Systems (GIS) analysis was used to manipulate spatial variables.

2.2. Measurement sites

Ten monitoring stations that measured ozone and meteorology in the Uintah Basin were operated by USU during winter 2012–13, and eleven more stations were operated by other entities, as shown in Table 1. Fig. 1 shows a map of these sites. Many of the sites also measured NOX, some measured NO2 (NOx + other reactive nitrogen compounds), and some measured a suite of non-methane hydrocarbons (NMHC). We obtained data for air quality monitoring stations operated by entities other than USU from EPA’s AQS database (EPA, 2015b).

2.3. Ozone

At stations operated by USU, we utilized 2B Technology Model 205 ozone analyzers, except at the Horsepool site, where we operated an Ecotech Model 9810 ozone analyzer. We performed calibration checks at all USU stations at least every other week using NIST-traceable ozone standards. Calibration checks passed if monitors reported in the range of ±5 ppb when exposed to 0 ppb ozone, and if monitors were within ±1% deviation from expected values when exposed to higher concentrations of ozone. We only included data bracketed by successful calibration checks in the final dataset. Ozone data obtained from EPA’s AQS database were collected by several different entities, and are assumed to have met EPA’s guidelines, including a maximum bias of ±7% (Regulations, 2015).

2.4. Reactive nitrogen

During the study period, NOx was measured with instruments utilizing molybdenum oxide-based NO2 converters and instruments utilizing photolytic converters. Molybdenum oxide NO2 converters are known to convert reactive nitrogen compounds other than NO2 to NO (Dunlea et al., 2007), and in environments with high reactive nitrogen (NOy). NO2 measurements made with molybdenum oxide converters will be biased high. Photolytic converters do not suffer from this bias (Sadanaga et al., 2010). In this text, we refer to NOx and NO2 measured with a photolytic converter as “true NOx” and “true NO2.”

We measured NO, true NOx (and true NO2 by difference), and NOy at Roosevelt with a Teledyne-API Model 200EU NOx analyzer modified with an Air Quality Design NOx analyzer inlet system that utilized an Air Quality Design photolytic NO2 converter. We measured NO and true NOx (and true NO2 by difference) at Horsepool with an Ecotech Model 9841 NOx analyzer modified with an Air Quality Design photolytic NO2 converter. We measured NOx at Horsepool with an Ecotech Model 9843 NOx analyzer. We calibrated these systems weekly with certified NO compressed gas standards and dynamic dilution calibrators, monthly with NO gas standard dilution and gas phase titration, and at the beginning and end of the campaign with nitric acid and n-butyl nitrate permeation tubes (for NOy). NOx measurements at all other sites listed in Table 1 were collected with instruments utilizing molybdenum oxide NO2 converters.

2.5. Nonmethane hydrocarbons

We measured 57 ozone-forming NMHC in 30-min and hourly samples at Horsepool and Roosevelt, respectively. Analyzed hydrocarbons were EPA PAMS compounds (EPA, 2015c). We analyzed NMHC at these sites by sample concentration on activated carbon traps followed by desorption into automated gas chromatography–flame ionization detection systems. We used a Perkin Elmer Clarus gas chromatograph with a TurboMatrix thermal desorber at Roosevelt and a Chromatotec AirMozeeze system at Horsepool. We calibrated these systems every other week with certified gas standards.

We also performed supplemental NMHC measurements at some sites from 1 February through 8 February 2013 using 6 L evacuated Summa canisters. Canisters were filled from 7 to 9 AM on 1, 3, 6, and 8 February. Some of these samples were analyzed with the Roosevelt Perkin Elmer automated gas chromatograph, but most were analyzed by AAC, Inc. (Ventura, California, U.S.A.) using gas chromatography and flame ionization detection, following EPA PAMS protocols (EPA, 2015c). Canister samples utilized automated sampling timers and critical orifice-based flow controllers. All wetted parts were either stainless steel or stainless steel coated with deactivated fused silica. All canister sampling components were cleaned between each use by repeatedly flushing with hot, humidified nitrogen. Canister NMHC samples were collected at Fruitland, Wells Draw, Seven Sisters, Horsepool, and Vernal. Total NMHC concentrations were calculated as the sum of the 57 individual compounds measured.

2.6. Meteorological parameters

We measured wind speed, wind direction, temperature, humidity, and barometric pressure at all sites operated by USU. In addition to utilizing available meteorological data from the EPA AQS database (EPA, 2015b) for sites listed in Table 1, we utilized
meteorological data from regional National Weather Service and Remote Automated Weather Station network sites. We obtained these data from the University of Utah’s Mesowest website (Mesowest, 2015). We used the following sites from Mesowest:

- Blacktail (BLAU1)
- Diamond Rim (DIAU1)
- Five Mile (FIVU1)
- Fort Duchesne (UINU1)
- Roosevelt (K74V)
- Upper PR Canyon (UPRU1)
- Upper Sand Wash (USWU1)
- Vernal (KVEL)
- Wild Horse (WHBU1)
- Winter Ridge (WNTU1)
- Yampa Plateau (SFLU1)

Table 1

<table>
<thead>
<tr>
<th>Site name</th>
<th>Operator</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elev. (m asl)</th>
<th>Other Meas.</th>
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</table>

Fig. 1. Map of ozone measurement sites and oil and gas facilities around the Uintah Basin, Utah, U.S.A. during winter 2012–13. Only wells that reported oil or gas production during February 2013 are shown.
2.7. Ballon-borne sondes

We operated a balloon-borne meteorology and ozone measurement system at Parriette Draw (latitude = 40.035, longitude = −109.830) periodically during winter 2012–13. The system consisted of an Anasphere SmartTether to measure temperature, humidity, barometric pressure, wind speed, and wind direction and a 2B Model 205 to measure ozone. The 2B analyzer was modified to include GPS location and altitude and contained a serial-to-radio converter to relay ozone results to the ground in real time. The outer housing of the 2B was removed to reduce weight. The SmartTether and 2B Model 205 were lifted simultaneously by a 3 m diameter tethered balloon filled with helium, and the balloon’s height was controlled by an electric winch.

Balloon-borne sonde measurements at Ouray and Horsepool were operated by the National Oceanic and Atmospheric Administration’s Global Monitoring Division (Schnell et al., 2013). They utilized a chemometric (based on reaction of ozone with I2) instrument to measure ozone, and an Imet radiosonde to measure temperature, pressure, temperature, relative humidity, and altitude.

2.8. Spatial and statistical analyses

We used ArcGIS 10.1 to analyze and interpolate spatial data from all measurement sites. We determined correlation and multiple regression relationships among measured parameters and a variety of spatial variables using ArcGIS 10.1 and SPSS Version 22. We obtained spatial data from the Utah Division of Oil, Gas and Mining (DOGM, 2015), the Colorado Oil and Gas Conservation Commission (COGCC, 2015), and the Utah Automated Geographic Reference Center (AGRC, 2015). We used the following variables in the spatial analysis:

- Number of producing wells (oil, gas, both);
- Volume of oil and gas production at each well during the month of February 2013;
- Number of natural gas compressor stations;
- Number of natural gas processing plants;
- Number of water surface acres at produced water evaporative disposal facilities;
- Human population; and
- Elevation.

Fig. 1 shows a map of many of these oil and gas-related parameters and the location of the largest populated areas in the Basin. We considered wells to be producing if they reported production during February 2013 to the Utah Division of Oil, Gas, and Mining or the Colorado Oil and Gas Conservation Commission. If the ratio of production of gas (in thousand cubic feet per day) to oil (in barrels per day) was greater than or equal to 15, we considered the well to be a gas well. Otherwise we considered it to be an oil well. Locations of some produced water ponds in Colorado are not known with certainty, so produced water ponds in Colorado were excluded from the analysis.

We calculated the sum of each of the listed spatial variables (except elevation) in radii around the air quality measurement sites from Table 1. Radii of 5, 10, 15, 20, 25, and 50 km were used. We then used these values in correlation and multiple linear regression analyses as predictors of ozone concentrations. For elevation, we used the actual elevation of each site and the elevation averaged over horizontal radii of 5, 10, 15, 20, 25, and 50 km around each site as predictors of ozone concentrations. Also, we used the difference between site elevation and average elevation in radii around each site as a predictor. We also used these predictors in correlation and multiple regression analyses with NMHC concentrations at measurement sites as a predictor and the predictand.

We used the 4th highest 8-h average daily maximum ozone concentration (the EPA regulatory metric) for the entire winter season, daily maximum 8-h average ozone concentrations on specific days, and average NMHC measured from 1 to 8 February 2013 at each measurement site as predictors in the correlation and multiple regression analyses. We used adjusted R2 values to determine the relative value of different multiple regression models, and predictor variables were considered significant at α = 0.05. We employed an iterative process of including and excluding predictors to determine whether each variable at each radius was significant and, if so, whether it added additional predictive power to the multiple regression model.

3. Results and discussion

3.1. Influence of elevation

Concentrations of ozone during winter 2012–13 in the Uintah Basin exceeded EPA standards during several distinct inversion episodes (Fig. 2). Day-upon-day buildup of ozone concentrations was observed during each episode, with ozone returning to background values during high wind events associated with storm front passage (Oltmans et al., 2014). The most consistent spatial feature of these episodes was that the highest ozone concentrations were observed at sites at lowest elevations, and sites at elevations above 2000 m tended not to experience ozone exceedances (Figs. 3 and 4). Silcox et al. (2012) observed a similar relationship between site elevation and particulate matter concentrations during winter inversions in Salt Lake Valley, Utah. We explore possible causes of the correlation between ozone and elevation, including:

1. More ozone precursor sources at lower elevations (as hypothesized by Silcox et al. (2012));
2. More negative lapse rates at lower elevations during inversions, which would limit vertical transport more effectively and thus trap pollutants more tightly;
3. “Pooling” of cold air at the lowest elevations, as suggested by Clements et al. (2003). In other words, this would be the tendency of low-temperature air to drain towards and pool in the low-elevation center of the Basin. This would lead to high ozone at low elevations if air that drained to lower elevations was rich in ozone and/or its precursors;
4. Longer lasting or more frequent inversion conditions at lower elevations, which could involve (a) earlier formation of inversion conditions and/or (b) later breakup of inversion conditions; and/or
5. Stronger winds aloft that allow for greater ventilation of higher elevation sites.

The sections below explore each of these possibilities, clarifying the roles of precursor sources and several meteorological phenomena in determining when and where elevated ozone concentrations occur.

3.2. Precursor sources

The number of oil and gas-related precursor sources in the Uintah Basin increases with decreasing elevation (R2 = 0.45 for correlation between number of producing wells and elevation), and this is likely one reason for the negative relationship between ozone and elevation. Indeed, some measurement sites with dense
oil and gas production nearby tended to have higher ozone than could be explained based on a linear relationship between ozone and elevation. The Seven Sisters site (elevation = 1618 m), for example, is near the center of natural gas production in the Uintah Basin, and tended to have similar daily maximum 8-h average ozone concentrations to Ouray (elevation = 1464 m) during the 2012–13 winter (percent difference between the sites was 0 ± 19% for days with ozone exceeding 75 ppb, mean ± standard deviation), even though Seven Sisters is more than 150 m higher in elevation. Seven Sisters had much higher ozone than Vernal (elevation = 1606 m), a site at very similar elevation but without any nearby oil and gas wells (percent difference was 35 ± 26% for days with ozone exceeding 75 ppb).

We performed correlation and multiple regression analyses in an attempt to disentangle the effects of elevation and proximity to sources on ozone spatial distribution. Strong correlations were observed between the 4th highest 8-h average daily maximum ozone for winter 2012–13 at each measurement site and a number of chemical and spatial variables, a subset of which is shown in Table 2 (see Methods for a full set of variables used). Table 2 uses r values, rather than R², to show whether correlations were positive or negative. For ozone, the strongest correlations were with elevation, followed by proximity to oil and gas facilities. NMHC concentrations were, in contrast, most strongly correlated with proximity to oil and gas facilities, followed by elevation. Also, ozone and NMHC were correlated with each other (R² = 0.57, p = 0.08 for 6 February total NMHC and 6 February daily maximum ozone), showing the importance of NMHC as a precursor to ozone.

Ozone and NOx spatial distributions were weakly correlated (R² = 0.27). However, as explained in Methods, NOx measurements at most sites were made with molybdenum oxide NO2 converters, which are subject to a high bias when NOy concentrations are high...
relative to $\text{NO}_x$ (Dunlea et al., 2007). $\text{NO}_x$ concentrations were much higher than true $\text{NO}_2$ concentrations during winter 2012–13 (Fig. 2). During inversion conditions at Horsepool, $\text{NO}_x$ was seven times greater than true $\text{NO}_2$ (23.2 ± 7.7 ppb $\text{NO}_x$ vs. 3.3 ± 3.2 ppb true $\text{NO}_2$ for the average of 24–26 January, 4–6 February, and 1–3 March 2013). Only $\text{NO}_x$ measurements at Horsepool and Roosevelt, which were made with photolytic $\text{NO}_2$ converters, provide an accurate measure of true $\text{NO}_2$ during winter inversions, and these two sites do not provide enough spatial variability for a meaningful correlation analysis.

Elevation variables were consistently better predictors of 4th highest 8-h average ozone and daily maximum ozone at surface sites than were oil and gas-related variables. The average elevation in a 10 km radius of measurement sites was the strongest predictor of ozone ($R^2 = 0.80$ for 4th highest 8-h average ozone), and when the number of producing oil and gas wells within a 10 km radius of measurement sites was added as an additional independent variable in a multiple regression model, it increased the predictive value of the model significantly (adjusted $R^2 = 0.90$). This resulted in the following equation:

$$O_3 = 0.0165w - 0.0783e + 232.8,$$

where $O_3$ is the 4th highest 8-h average daily maximum ozone, $w$ is the number of producing oil and gas wells within 10 km, and $e$ is the average elevation in a 10 km radius.

The other oil and gas-related variables (including number of compressors, number of gas plants, number of produced water facilities, and oil and gas production levels) were correlated with the number of producing wells, and they either were not significant or had less predictive power for ozone than the number of producing wells within 10 km when added or substituted as predictors in the multiple regression analysis. The number of producing wells within other radii of measurement sites had less predictive power than the 10 km radius. Proximity to human population was not a significant predictor of ozone or NMHC. Also, the difference between site elevation and average elevation in a radius around sites was not a significant predictor of ozone or NMHC, showing that locations in canyons or on hilltops have ozone concentrations that are similar to the area that surrounds them.

Using the number of natural gas wells within 10 km along with average elevation within 10 km, rather than using the number of oil and gas wells, was as useful as using the number of oil and gas wells at predicting ozone (adjusted $R^2 = 0.90$), but using the number of oil wells within 10 km was not (adjusted $R^2 = 0.81$; proximity to oil wells variable was not significant, $p = 0.45$). This finding could indicate that emissions associated with gas production are more important to ozone formation than emissions associated with oil production, either because natural gas-related emissions are more reactive, or because they are more abundant on a per-well basis. Indeed, Warneke et al. (2014) showed that, while organic compound emissions from oil wells and ordinary gas wells were similar, emissions from gas wells with on-site glycol dehydrators were much higher, especially emissions of highly reactive aromatics. Since some natural gas wells—but no oil wells—in the Uintah Basin use on-site glycol dehydration, it is possible that the better correlation with gas wells is driven by higher emissions at a subset of gas wells which utilize on-site glycol dehydration. The average elevation of oil wells is greater than gas wells (1712 ± 195 m vs. 1650 ± 223 m), which adds complexity that may not be fully accounted for in this analysis. Also, as discussed by Neemann et al. (2015), in the western Uintah Basin (which has mostly oil wells) intrusions of clean air from the west more frequently displace polluted air and weaken inversions, leading to lower ozone.

Ahmadov et al. (2015) allocated oil and gas emissions in their top-down inventory equally to all wells, regardless of whether they were oil, gas, or gas with well-site glycol dehydration units. This simplification could lead to an overestimate of ozone in the western Uintah Basin where oil production is dominant.

Like winter 2012–13, strong temperature inversions and ozone production prevailed during winter 2010–11 (Martin et al., 2011). Using 10 km average elevation and the number of wells within 10 km as predictors of 4th highest 8-h average daily maximum ozone, the multiple regression coefficients and intercept for winter 2010–11 were not statistically significantly different from the slopes and intercept for winter 2012–13 ($p = 0.75, 0.96$, and 0.95, for the elevation coefficient, the number of wells coefficient, and the intercept). The slopes and intercepts were also not statistically significantly different when daily maximum 8-h average ozone on 1 March 2013 (a high ozone day) was used, but the 10 km average

| Table 2 | Pearson correlation coefficients (r) for relationships between selected air quality and spatial parameters during winter 2012–13. N.S. means not significant at $\alpha = 0.05$. "# Days Exceed. EPA Std." means the number of days a site exceeded the EPA ozone standard of 75 ppb as an 8 h average. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | 4th high 8-h avg. ozone | # days exceed. EPA Std. | 26 Jan. max. 8-h ozone | 6 Feb. max. 8-h ozone | 1 Mar. max. 8-h ozone | 1–8 Feb avg. total NHMIC |
| Site elevation | –0.76 | –0.75 | –0.84 | N.S. | –0.61 | N.S. |
| 10 km average elevation | –0.90 | –0.90 | –0.93 | –0.50 | –0.76 | N.S. |
| 25 km average elevation | –0.71 | –0.71 | –0.69 | N.S. | –0.68 | –0.83 |
| # oil and gas wells in 10 km | 0.59 | N.S. | N.S. | N.S. | 0.71 | 0.93 |
| # oil and gas wells in 25 km | 0.73 | 0.64 | N.S. | N.S. | 0.82 | 0.91 |
| # oil wells in 10 km | N.S. | N.S. | N.S. | N.S. | N.S. | N.S. |
| # gas wells in 10 km | 0.59 | N.S. | N.S. | N.S. | 0.77 | 0.85 |
| Population in 10 km | N.S. | N.S. | N.S. | N.S. | N.S. | N.S. |
elevation slope (−0.122) and the intercept (314.4) were significantly different when daily maximum 8-h average ozone on 26 January (another high ozone day) was used.

Adjusted R² values were lower for each of these cases than for the original case, ranging from 0.75 to 0.86. Variable meteorological conditions on individual inversion days and years likely confounded the relationship of ozone with elevation and proximity to oil and gas wells. Also, winter 2012–13 had more days with strong inversions, with 39 days that exceeded the EPA ozone standard of 75 ppb at the Ouray monitoring station (which tends to have the most exceedances per year of any station), while winter 2010–11 had only 24 exceedances at the Ouray station. With more inversion days, it is likely that the relationship between ozone and spatial variables was more detectable during winter 2012–13.

### 3.3. Lapse rate

If lapse rates (the negative of the rate of temperature change with increasing altitude) are more strongly negative (i.e., temperature increases more rapidly with altitude) at lower elevations, this could limit vertical transport more strongly, trapping pollutants at the surface better at lower elevations and leading to higher ozone.

Though balloon-borne sonde data that provide vertical measurements of the Basin atmosphere were spatially and temporally limited during winter 2012–13, extant data show that the depth of the inversion (i.e., the distance from ground level to the height at which the lapse rate is no longer negative) was greater for lower elevation sites (Fig. 5; also see Ahmadov et al. (2015)). In other words, the inversion top appears to be somewhat level across the Basin, regardless of surface elevation, making lower elevation sites more distant from the inversion top. This actually leads to a less negative lapse rate at lower elevations, at least in a technical sense.

For example, balloon measurements at Ouray (1464 m) showed the temperature to be 1.3 °C lower at the surface than at 250 m above the surface during an inversion episode that occurred during 2–8 February. At Horsepool (1569 m), the surface temperature was 5.2 °C lower than at 250 m above the surface. This was due to a neutral lapse rate that was typically observed near the surface and a capping negative lapse rate that occurred at a uniform elevation above sea level (Fig. 5A).

Though more negative lapse rates were not observed at lower elevations, the structure that was observed may nevertheless lead to higher ozone values at lower elevations because low-elevation locations were more distant from the inversion top and thus may be further removed from turbulent conditions above the inversion (see discussion in subsequent sections).

During inversion episodes, ozone showed a more linear vertical structure with respect to elevation than did temperature, whether balloon or surface measurements are considered (Figs. 4 and 5B). This could occur because ozone precursors were mostly emitted at or near the surface, and limited vertical transport under the inversion kept ozone and precursors there. Still, ozone was negatively correlated with temperature during inversion episodes (e.g., R² ranged from 0.14 to 0.84 for balloon data shown in Fig. 5, R² = 0.81 for surface site data shown in Fig. 5).

### 3.4. Drainage of pollutant-laden air to lower elevations

Fig. 6 shows surface wind vectors for an inversion episode that occurred in late January 2013. The observed wind speed at sites lower than 1700 m during winter 2012–13 inversion episodes was 0.9 ± 0.5 m s⁻¹ (no difference between day and night wind speeds was observed; p = 0.34), which was less than sites above 1700 m (2.5 ± 1.5 m s⁻¹). The inversion insulates the Basin from stronger aloft flows, as observed in the greater Colorado Plateau by Whiteman et al. (1999). Many sites within the Basin exhibited a near 180° wind direction change between day and night, usually with daytime winds moving upslope and nighttime winds moving downslope along local topographic features (Neemann et al., 2015; Reeves et al., 2011) (Fig. 6). The Basin is topographically complex, and local surface wind directions are shown in Fig. 6 to be similarly complex.

The diurnal upslope-downslope flow observed at surface sites during inversion episodes (1) limits the effective distance emitted pollutants can travel and (2) may allow emitted and photochemically-derived pollutants to return to their origin, which would tend to result in pollutant concentrations that build day-upon-day, as observed in Fig. 2 and first postulated to occur in Wyoming’s Upper Green River Basin (ENVIRON, 2008).

The fact that day and night wind speeds during inversion episodes were not different and were usually in opposite directions at low-elevation sites provides evidence against a persistent downslope flow that brings cold air to the lowest elevations of the Basin, at least during the strong inversion conditions presented here. Persistent downslope flow could occur either (1) at the beginning or end of inversion episodes or (2) at elevations above or on the

![Fig. 5. A: Average 12:00–14:00 temperatures from balloon-borne sondes operated at Ouray, Horsepool and Pariette on 6 February 2013, along with average 12:00–14:00 temperature for the same day at surface sites. The lowermost point for balloon data signifies the elevation of that site. B: Average 12:00–14:00 ozone from the same balloon-borne sondes and from surface sites on the same day.](image-url)
margins of the inversion. Either of these cases could help build and maintain the inversion, but would not lead to a buildup of pollutants at lower elevations. As noted above, locations of oil and gas wells were negatively correlated with elevation, so intrusion of surface air from higher elevations would likely tend to dilute pollutant concentrations at the lowest elevations, rather than enrich the air with ozone-forming pollutants, so even if persistent downslope drainage did occur during temperature inversions it would not, in and of itself, lead to higher ozone at lower elevations. Indeed, Neemann et al. (2015) showed that downslope flow of air from outside the inversion can weaken inversion conditions and lower ozone concentrations on the west side of the Basin, and that downslope flow that does not penetrate the inversion layer can strengthen inversion conditions.

### 3.5. Inversion formation, vertical structure, and breakup

Fig. 7 shows a representative example of an inversion episode that occurred in the second half of January 2013. Ozone was uniformly low on 13 January 2013, and all elevations of the Basin were well ventilated. By 16 January, a strong temperature inversion had formed. This allowed ozone to begin to build up in the stagnant air under the inversion. The temperature inversion continued through 22 January, but wind increased at the highest elevation sites by that time, and ozone continued to increase at the lowest elevations and become more linear with respect to site elevation. By 27 January high wind at elevations higher than 1800 m brought ozone concentrations down, but sites at the lowest elevations still had consistently low wind and higher ozone until 28 January, when windier conditions descended to the lowest elevation sites, the temperature inversion was eliminated, and ozone was again uniformly low.

Throughout winter 2012–13, the lowest elevations routinely developed temperature inversions, along with lower surface winds, before other sites and maintained those conditions longer. This likely leads to higher ozone at lower elevations by increasing the time available for ozone and its precursors to build up under the inversion (Fig. 7). Although some horizontal transport does occur under inversions, it is limited (Fig. 6). Vertical transport under the inversion is limited by definition, since warm air aloft restricts vertical motion. Thus, chemical conditions at a given surface location can be expected to be relatively isolated, both horizontally and vertically. Fig. 8 shows that daytime and nighttime ozone both build with each 24 h period during inversions, so the final ozone concentration reached depends on the number of inversion days experienced. Thus, low elevation sites have more days for ozone to build up, and dispersion of that ozone to other areas of the Basin is limited.

Fig. 6 shows ozone concentrations at Mountain Home (elevation = 2234 m), Seep Ridge (elevation = 1975 m), and Sand Wash (elevation = 1416 m) during the late January inversion episode shown in Fig. 7. All three of these sites are distant from dense oil and gas activity (5, 7, and 16 wells within a 10 km radius, respectively). Before the inversion episode began, daytime ozone at all three sites was similar. Daily ozone production began increasing at Sand Wash at least one day before Seep Ridge and Mountain Home. Daily maximum ozone at Mountain Home peaked on 20 January and then began to decline. Ozone at Seep Ridge plateaued around the same time, and then began an unsteady decline a few days later. Sand Wash ozone, on the other hand, continued to increase until 24 January, and didn’t return to what might be considered baseline values until a day after the two higher elevation sites.

### 3.6. Aloft winds

Figs. 6 and 7 show that sites at elevations above temperature inversions tend to maintain relatively strong winds during inversion episodes. As inversion conditions deteriorated at the end of an episode, high winds descended lower, ventilating mid-elevation sites and allowing ozone concentrations at these sites to decrease (e.g., Fig. 7). Lower elevation sites are further from the inversion top and the high winds that accompany it, and so are likely to experience less dilution of polluted air during inversions.
Edwards et al. (2014) point out that, while ozone concentrations build day-upon-day during inversion episodes, organic compounds, including methane, often increase for a few days after inversions form and then level off. They also point out that concentrations of organics are lowest during the day when boundary layer heights are highest. They postulate that the leveling off of some compounds is due to loss at the top of the boundary layer that becomes equal to the compounds’ emission rates. This hypothesis is supported by this work, which shows clear evidence that aloft winds limit the vertical extent of inversions and lower pollutant concentrations near the inversion top. Ozone would also be lost by this mechanism, but ozone production under inversion conditions must be greater than the loss rate, since ozone concentrations continue to increase during each day of inversion episodes. Fig. 2 shows that NMHC concentrations do not always show a clear leveling off during inversion episodes, providing evidence that the strength of this loss mechanism may vary.

4. Conclusions

While each inversion episode in the Uintah Basin is unique, sites at lower elevations consistently have higher ozone. This is due, in
part, to the fact that more precursor sources exist at lower elevations, but proximity of measurement sites to oil and gas precursor sources explains only some of the spatial variability in ozone measurements. Obviously, adequate precursor emissions are required to produce ozone, but areas with the highest density of precursor sources and areas with highest ozone are decoupled in many regions (Beaver et al., 2012), not just in the Uintah Basin. In the Uintah Basin, elevation is the most important predictor of ozone because (1) inversions start earlier and end later at the lowest elevations, allowing ozone and precursors more time to build up day-upon-day, (2) Lower elevations are less impacted by high altitude winds that allow ozone and precursors to mix out of the Basin, and (3) effective air transport distances are relatively low during inversions because of low surface wind speed and consistent diurnal upslope-downslope wind patterns, which tend to keep produced ozone near its point of origin. Ozone spatial distribution appears to be driven more by proximity to natural gas production than oil production. This may be due to more abundant or more reactive emissions from natural gas wells and infrastructure, but confounding factors exist and more study is needed to confirm this.

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