Anthropology to atmospheric dynamics at altitude: Celebrating 75 years of multidisciplinary research at the UCLA White Mountain Research Center in eastern California

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High-elevation air pollution research at the White Mountain Research Center: Recent results for surface-level ozone

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ABSTRACT Air pollution research has been conducted intermittently at the White Mountain Research Center since its founding, and efforts since 2009 have focused primarily upon continuous, long-term measurements of surface-level ozone (O_3), which is present at elevated concentrations due to the high elevation and transport from upwind source regions.

INTRODUCTION

Overview

The high-elevation WMRC sites – Crooked Creek, Barcroft Station and the Summit Hut – are unique because of both their altitude and their location downwind of major population centers and the industrial agriculture of the California Central Valley. (See Table 1 for detailed WMRC site information, including latitude / longitude / elevation values.) Air quality measurements at these locations can provide insight into important topics such as the long-range transport of pollutants from urban areas and the Central Valley to remote receptor sites, or the vertical mixing between the stratosphere and the troposphere. This paper will commence with a brief overview of the atmospheric sampling that has taken place over the past 75 years and will then focus upon the ongoing efforts to monitor ozone (O_3), which started in 2009.

History

Most of the atmospheric science carried out at the WMRC over the past 75 years has addressed either the suitability of the high-elevation WMRC sites for large astronomical telescopes (Zwickey, 1950), or the concentrations of trace pollutants in remote air samples. In the latter case a frequently used technique has been to collect a sample of WMRC air into an evacuated flask, which is then taken back to a laboratory for analysis. Recent decades have seen an increase in *"in-situ"* (in place) monitoring efforts where pollutant concentration data are recorded directly by on-site instrumentation.

Scientists have long recognized that the remoteness and high elevation of the WMRC – combined with the (relative) ease of access – make the WMRC an outstanding choice for assessing background atmospheric conditions. These unique features were enthusiastically publicized by Nello Pace, who promoted Barcroft Station throughout the 1950's as the highest altitude weather

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Table 1. WMRC sampling locations for permanent, continuous, long-term monitoring of ozone (and other pollutants). SMC = operated by Saint Mary's College of California; GBUAPCD = operated by the Great Basin Unified Air Pollution Control District.

Site	Lat.	Long.	Elev.	Pollutants	Start Year	End Year
White Mtn.	37.6342	-118.2556	4346 m	O_3	2009	ongoing
Summit Hut				PM	2019	ongoing
Barcroft Station	37.5827	-118.2364	3778 m	O_3	2009	2014
Barcroft Observatory	37.5902	-118.2387	3879 m	O_3	2013	ongoing
				PM	2019	2024
Crooked Creek Station	37.4990	-118.1719	3088 m	O_3	2009	2011
Crooked Creek Ridge	37.5001	-118.1672	3231 m	O_3	2012	2024
Owens Valley (SMC)	37.3602	-118.3297	1237 m	O_3	2009	2014
Owens Valley (GBUAPCD)	37.3608	-118.3308	1238 m	O_3, PM, CO, SO_2	2015	ongoing

station in the continental U.S. (pers. comm., Pritchett, 2025). One of the first scientists to conduct atmospheric sampling at the WMRC was a young Caltech geochemist named Charles David Keeling, who made very precise measurements of carbon dioxide (CO_2) at Barcroft and the Summit in July of 1955 (Keeling, 1958). The sampling techniques that Keeling utilized at the WMRC were soon extended to other remote sites across the planet, including the Mauna Loa Observatory in Hawaii. Keeling's Mauna Loa CO_2 data, which began in 1958, are now recognized as a seminal accomplishment in environmental science, and the "Keeling Curve" has become an iconic image in popular culture.

Criteria Pollutants

The Clean Air Act, initially passed by Congress in 1963, and significantly revised in 1970, 1977, and 1990, requires that the EPA monitor and control air pollution throughout the United States. To achieve this objective, the EPA has identified six "criteria pollutants" – ground-level ozone

(O_3), particulate matter (PM), carbon monoxide (CO), lead (Pb), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). Ozone and particulate matter are the most important criteria pollutants because of their significant impacts on public health (EPA, 2025). Because of space constraints, the present report will focus only upon O_3. Readers who are interested in the particulate matter data collected at the WMRC since 2019 are encouraged to contact the author.

METHODS

Ambient ozone concentrations are measured by 2B Technologies Model 202 or Model 205 Ozone Monitors. These monitors determine the O_3 concentration via a direct, Beer's Law measurement at $\lambda = 254$ nm. Ozone concentrations (ppb by volume) are measured every ten seconds and then signal averaged, typically into hourly values. These values are then recorded into internal monitor memory or broadcast to a data website, in real time, using satellite telemetry. All O_3 monitors are calibrated against ozone calibration sources both before and after ~12-month-long deployment periods that typically start mid-summer, in July or August. The objective is to obtain permanent / long-term / continuous O_3 data at multiple WMRC locations, but because of the extremely harsh conditions and lack of access during the winter months, there are periods when O_3 data are not collected because of snow-covered solar panels, loss of satellite telemetry, or failure of the O_3 monitors. The hourly ozone values obtained in this manner are estimated to be accurate to ±5 ppb or better. Detailed descriptions of the experimental method outlined here can be found in Burley and Ray (2007) and Burley and Bytnerowicz (2011).

RESULTS

There have been continuous, long-term air quality measurements that have taken place at the WMRC since 2009 (Table 1). The measurements for Barcroft ("Barcroft Station") and Crooked Creek ("Crooked Creek Station") were initially located adjacent to the respective parking lots for these two facilities, but both were subsequently moved to higher elevations. The current Barcroft measurement ("Barcroft Observatory") is housed in the ruins of what used to be a dome for an optical telescope, while the "Crooked Creek Ridge" site that operated from 2012 to 2024 was located on the ridgetop behind the current Crooked Creek facility.

Hourly average ozone concentrations for summer (May-June-July) of 2021 vary by location and day of year (Fig. 1). The Summit, Barcroft and Crooked Creek data are very similar to one another and show an irregular pattern that rarely dips below a value of ~40 ppb or exceeds a value of ~75 ppb. The Owens Valley data, in contrast, show a pronounced diurnal pattern in which ozone concentrations reach a minimum just before sunrise, followed by a rapid rise, and then maximum values in the afternoon and a steady decline after sunset.

To remove the impact of day-to-day variability, the hourly data from Figure 1 are converted into diurnal averages that span the entire sampling window of May 1 to July 31, 2021 (Fig. 2). Averaging the data in this fashion is useful because it can reveal the hour-by-hour variation (or lack thereof) across a "typical" 24-hour cycle that might otherwise be obscured by large day-to-day fluctuations. In Figure 1, for example, even a skilled observer would be unlikely to recognize

that the three high-elevation sites (Summit Hut, Barcroft Observatory, Crooked Creek Ridge) all have essentially flat diurnal cycles, with minimal hour-to-hour variability (on average). This behavior, however, is readily apparent in Figure 2.

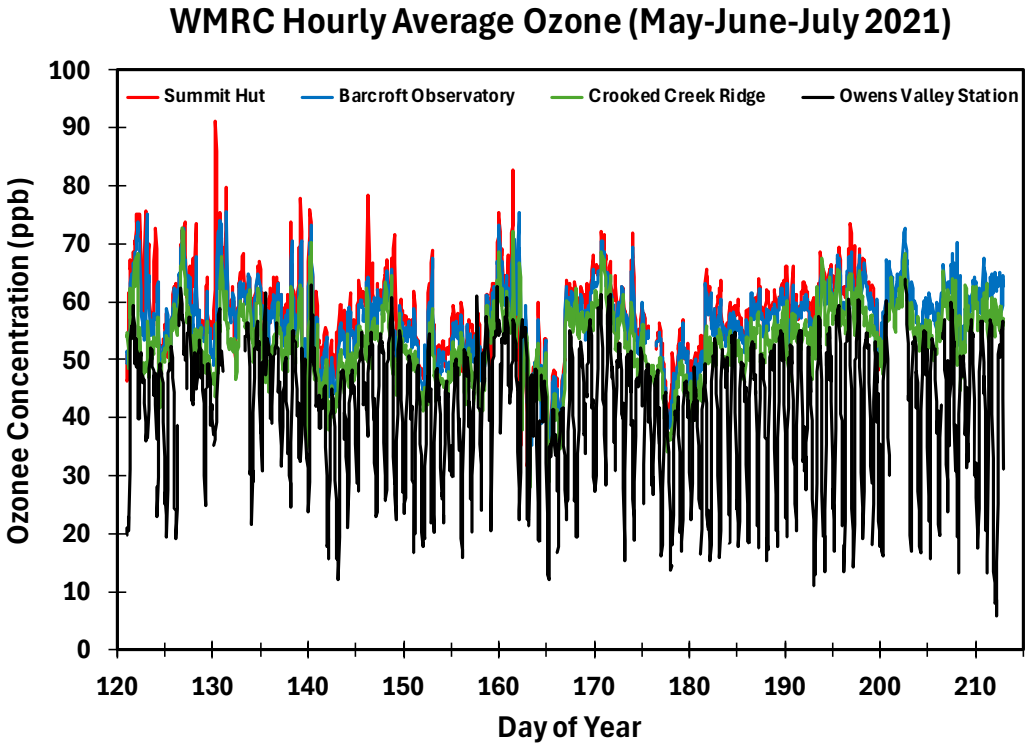

Fig. 1. Hourly ozone concentrations (in units of ppb by volume) measured at the Summit Hut, Barcroft Observatory, Crooked Creek Ridge, and Owens Valley Station for May 1 (day of year = 121) through July 31 (day of year = 212) of 2021. The Owens Valley data were recorded by the Great Basin Unified Air Pollution Control District.

DISCUSSION

The remote, high-elevation WMRC sites (e.g., Fig. 3) have elevated background concentrations of surface O_3 (Figs. 1, 2), a finding that is fully consistent with previous WMRC air quality investigations from Burley and Bytnerowicz (2011) and Bytnerowicz et al. (2019). In addition, all four WMRC sites experience the same multi-day trends because they are sampling the same regional air masses (Fig. 1). Days 161-165, for example, display a pronounced, simultaneous decrease in ozone at all four locations. The average diurnal patterns, however, show significant, elevation-dependent differences that reflect the different ozone sources and transport / mixing dynamics that predominate at each location (Fig. 2). The factors that influence the shapes of the diurnal curves – discussed in detail below for all four sampling sites – are not unique to the White Mountains, and similar elevation-dependent behavior has been observed at other California locations, including Lake Tahoe (Burley et al., 2015), Devils Postpile National Monument (Burley et al., 2016), and Yosemite National Park (Burley and Ray, 2007).

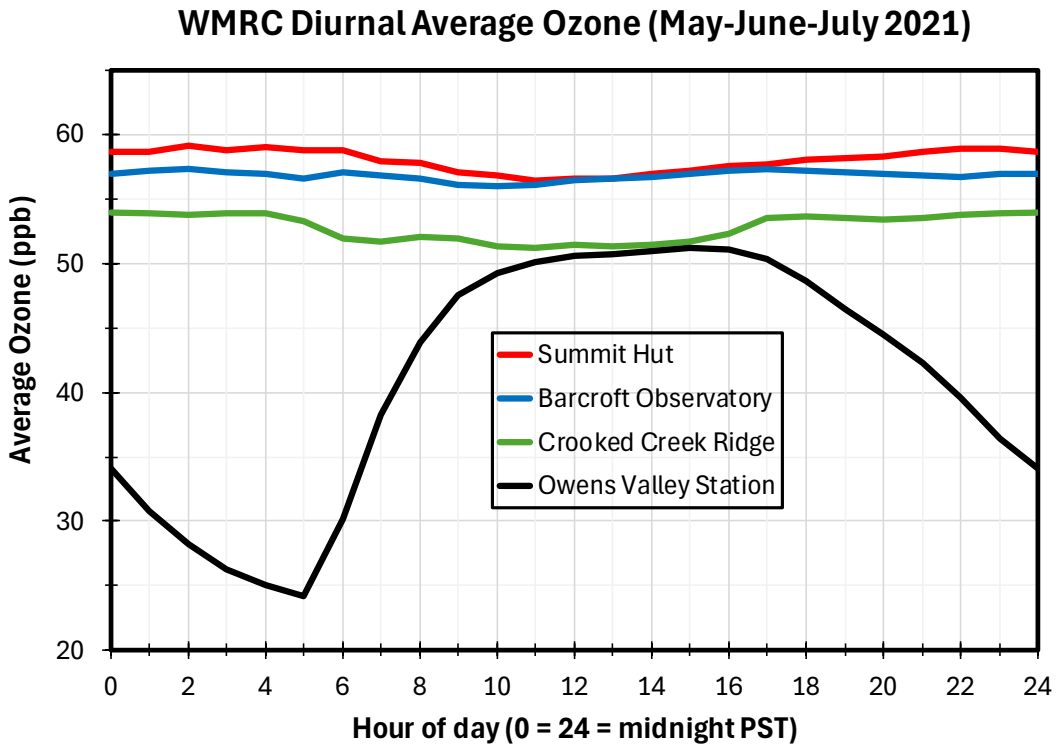

Fig. 2. Diurnal average ozone concentrations (in units of ppb by volume) measured at the Summit Hut, Barcroft Observatory, Crooked Creek Ridge, and Owens Valley Station for May 1 through July 31 of 2021. The Owens Valley data were recorded by the Great Basin Unified Air Pollution Control District. Each hourly data value corresponds to the average of approximately 92 individual measurements at that particular hour (PST) across the window of May 1 – July 31.

At Owens Valley Station, ozone concentrations decline at night because ozone near the surface chemically reacts with surface vegetation or NO emitted from local combustion sources. The ozone removed in this manner is not replaced by local photochemical production because there is no sunlight (photons) to drive the photochemical reactions that produce ozone from volatile organic compounds (VOCs) and NO_x. In addition, downward mixing of ozone-rich air from aloft is greatly diminished at nighttime (especially on flat terrain) because there is no solar heating of the surface. Thus, O_3 concentrations decline steadily during the evening hours. When sunrise arrives, solar heating of the surface resumes, and there is a rapid downward mixing of ozone-rich air from above. Local photochemical production of O_3 also commences, reaching a peak in the mid-afternoon.

At Barcroft and the Summit there are no local sources of ozone precursors (VOCs and NO_x) and thus no local photochemical production of O_3. Instead, essentially all the ozone that is measured is produced elsewhere and transported in. The transport dynamics that bring ozone to these remote, high-elevation sites are irregular and do not show a recurring diurnal pattern, and the resulting diurnal plots (Fig. 2) are flat across the 24-hour cycle. The mixing at these two sites remains pronounced even during nighttime hours because of the mountainous topography and extremely high elevation, which combine to yield good exposure to ozone-rich air from the free troposphere.

Fig. 3. Joel Burley with the initial installation of the Summit Hut ozone experiment, in August of 2009. The sampling inlet is protected by the inverted Teflon beaker, which acts as a rain shield. The camouflage-painted shipping case contains the 2B ozone monitor, a 12-volt battery, and a solar charge controller.

Ozone concentrations decrease somewhat as one descends from the Summit to Barcroft because the Summit is slightly closer to the "ozone layer" that exists in the lower and middle stratosphere, where ozone concentrations are much higher – typically in the range of 2-8 ppm (2000-8000 ppb). Differences in surface vegetation, which can act as an ozone sink, may also contribute to this trend, since the extent of plant matter increases as one descends from the vegetation-free Summit to the grassy plateau of Barcroft Observatory. Both Barcroft and the Summit can experience "stratospheric intrusions" when there is a sudden downward transport of ozone-rich air from the upper troposphere or lower stratosphere. When this happens (Fig. 1, Day = 130.33), observed ozone values tend to spike upwards (sometimes above 100 ppb), with a simultaneous drop in both ambient temperature and relative humidity.

The diurnal cycle for Crooked Creek (Fig. 2) is similar to the cycles measured at Barcroft and the Summit, but the average O_3 concentrations are lower (~50-55 ppb rather than ~55-60 ppb), and there is a pronounced dip in the midday O_3 values. The lower magnitude reflects the same elevation- and vegetation-based trends noted above, while the midday dip results from enhanced vertical mixing that occurs during daylight hours. This mixing process moves ozone-depleted air

from lower elevations (e.g. the Owens Valley) upwards to the high-elevation WMRC sites, where it partially dilutes ozone-rich air from aloft. The same midday dilution process also occurs at Barcroft and the Summit, but to a lesser extent given the elevation differences between Crooked Creek (3231 m), Barcroft (3879 m), and the Summit (4346 m).

One way to look at the Figure 1 and 2 ozone data for Barcroft and the Summit is that it represents the "polluted background" level of O_3 that is transported eastward from California into Nevada. The air masses that are measured at these two sites typically originate in eastern Asia and then transit across the Pacific Ocean in approximately 4 to 10 days. The air that comes ashore along the California coast has ozone concentrations in the range of 10 – 40 ppb at the surface, and values approaching or exceeding 50 ppb at altitudes of 4000-5000 meters (Jaffe et al., 2018). Over the past 50 years, long-range transport of ozone and other pollutants has increased (due to increasing industrialization in eastern Asia) and it is estimated that strong Asian transport episodes are increasing observed ozone concentrations in the western U.S. by as much as 8-15 ppb (Lin et al., 2012).

After an airmass from Asia reaches the California coast it usually requires another day or two of additional transit time to travel to the high-elevation WMRC sites. Along the way can pick up additional ozone (and/or VOC and NO_x ozone precursors) from population centers like the San Francisco Bay Area or greater Los Angeles, or the industrial agriculture regions of the California Central Valley. Slower-moving airmasses tend to accumulate (and photochemically create) higher concentrations of ozone, while faster-moving airmasses tend to contain much lower concentrations of O_3 upon their arrival at Barcroft or the Summit. The net result can be counter-intuitive because most people who vacation or conduct research at remote, high-elevation sites (like the White Mountains) assume – sometimes incorrectly – that the air quality will be better compared to what they experience at home. The net result is also challenging from a regulatory standpoint because the observed average O_3 values (usually in the range of 50-60 ppb) are only slightly lower than the National Ambient Air Quality Standard (NAAQS) established by the EPA for ozone, which is 70 ppb (for an 8-hour average). An air quality district in Nevada might exceed the NAAQS threshold for ozone because of upwind pollution being transported in from Asia or California, even though its local emissions of ozone precursors are very low. It will be difficult for that air quality district to formulate a plan – which the EPA will require if there are repeated violations – to establish compliance with the NAAQS.

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