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METEOROLOGICAL CONTROLS ON O_3 AT MOUNT WASHINGTON, THE HIGHEST PEAK IN THE NORTHEASTERN UNITED STATES

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1.0 Introduction

Mount Washington (44.27°N, 71.30°W, ~1910 m) is the highest mountain in the northeastern United States, and it provides a unique opportunity to study meteorological constraints on the distribution of ozone (O_3) in the region. The co-location of an O_3 monitoring site near the base and at the summit yielded a rare dataset to explore the temporal behavior of the boundary layer, and gain insight on the vertical distribution of O_3 in mountainous terrain. The present study focused on identifying the differences in long-range transport and the associated source regions for enhanced and depleted O_3. Differences in the O_3 diurnal cycle between the base and summit will also be illustrated.

2.0 Methods

This study focused on recent summers 1998 to 2003. During this period, O_3 data was collected by two different organizations: the Atmospheric Investigation, Regional Modeling, Analysis and Prediction (AIRMAP) program, and the Appalachian Mountain Club (AMC). Ozone mixing ratios were measured at the summit of Mount Washington using unmodified Thermo Environmental Instruments, Model 49C UV photometric O_3 analyzers (Franklin, Massachusetts). Ozone data from the AIRMAP database (airmap.unh.edu/data/index.cfm) was used for summers 2001 to 2003. Ozone data collected by the AMC was used for summers 1998 to 2002 for both the summit of Mount Washington and a location near the base of the mountain. Hourly meteorological observations for the summit were provided by the Mount Washington Observatory.

Trajectories were calculated with the Hybrid Single Particle Lagrangian Integrated Trajectories (HY-SPLIT) model (Draxler, 1999; Draxler and Rolph, 2003) using meteorological data from the Eta Data Assimilation System (EDAS) Archive. Back trajectories from Mount Washington were initialized 4-times daily for summers (May – September) 1998-2003, and were calculated for 72 hours back in time. Trajectories were paired with a ~2-hour average O_3 mixing ratio surrounding their initialization time and then broken into two groups: 1) nighttime, trajectories initialized at 0200 and 0400 EST, and 2) afternoon, trajectories initialized at 1400 and 1600 EST. Trajectories were grouped with respect to enhanced ($O_3 \geq 90^{th}$ percentile) and depleted ($O_3 \leq 10^{th}$ percentile) O_3 mixing ratios. Enhanced and depleted afternoon and nighttime periods were identified separately. NOAA Daily Weather Maps (NOAA, 1998-2003) were used to examine meteorological features coincident with trajectory initialization.

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3.0 Ozone characteristics at Mount Washington

The summer mean and median hourly O_3 mixing ratios in recent years (1998-2003) ranged from 39 to 49 ppbv, with both the maximum median and mean occurring in 2003 (Table 1). The highest 1-hour maximum O_3 mixing ratio (128 ppbv) during this 6-summer period was measured in August 2002. The seasonal hourly average mean and median O_3 for the base of the mountain was normally ~15 ppbv lower than at the summit.

Table 1: Summer (May – September) O_3 statistics for the summit of Mount Washington based on all available hourly averaged data. AMC data was used for 1998-2000. AIRMAP data was used for 2001-2003.

Year	Mean	Median	Max	90th Percentile	10th Percentile
1998	45	43	86	63	29
1999	45	45	100	63	28
2000	40	39	85	56	27
2001	47	45	87	67	31
2002	47	45	128	69	34
2003	49	48	98	64	35

All values are given in ppbv.

The summit of Mount Washington generally received a greater O_3 exposure than the base (Figure 1). There was a low frequency of O_3 mixing ratios less than 30 ppbv at the summit, especially at night.

Mount Washington typically experienced a reversed diurnal cycle with O_3 mixing ratios peaking after midnight. This pattern is the reverse of lower elevation sites that peak in the afternoon (Hill and Allen, 1994). During afternoons with vigorous heating, vertical mixing promoted convergence of O_3 mixing ratios at the summit and base locations (Figure 2). A secondary nocturnal O_3 peak at the base appeared periodically in the O_3 record, and is hypothesized to be the result of O_3 transported to the base from layers aloft during periods of turbulence or during the development of a down slope wind system.

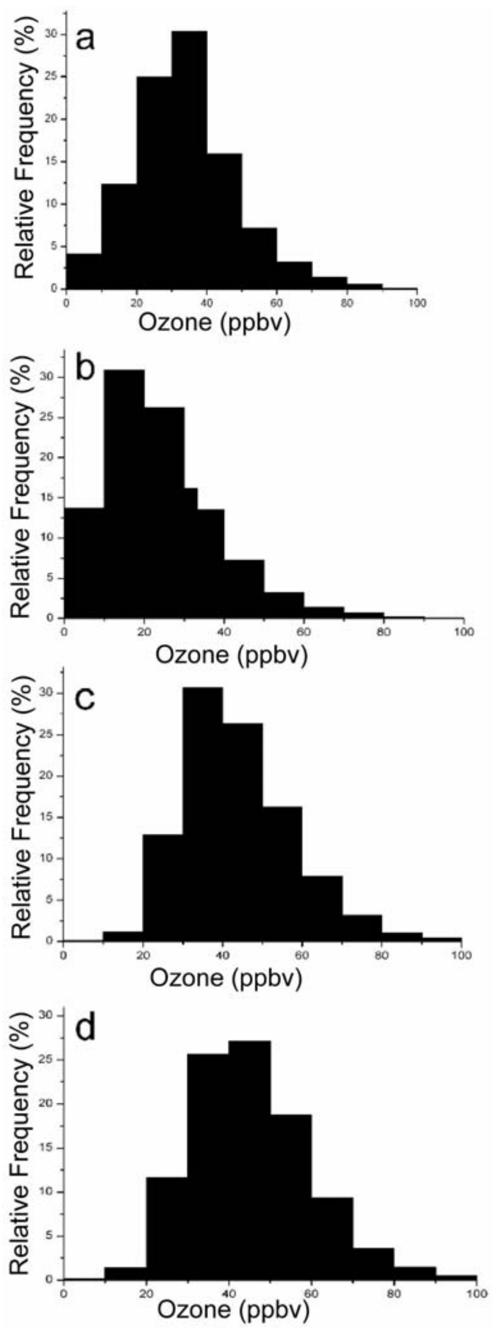

Figure 1: Cumulative frequency distributions and histograms of hourly O_3 at the base of Mount Washington for a) daytime hours, 6am – 6pm and b) nighttime hours, 6pm-6am. Cumulative frequency distributions and histograms of hourly O_3 at the summit of Mount Washington for c) daytime hours, 6am – 6 pm and d) nighttime hours, 6pm - 6am.

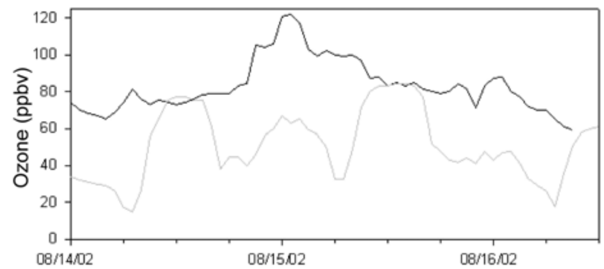

Figure 2: Ozone time series based on hourly data provided by the AMC for the summit (black) and base (gray) of Mount Washington for 00 UTC 14 August 2002 to 12 UTC 16 August 2002. The summit peaked at approximately 2 AM EST.

4.0 Enhanced and depleted ozone events on the summit

Most high and low O_3 periods at Mount Washington during the 6 summers were spread out across the season and were not part of a small number of several-day events. Enhanced O_3 events at Mount Washington were generally associated with westerly transport, while depleted O_3 events corresponded to northwesterly transport (Figure 3).

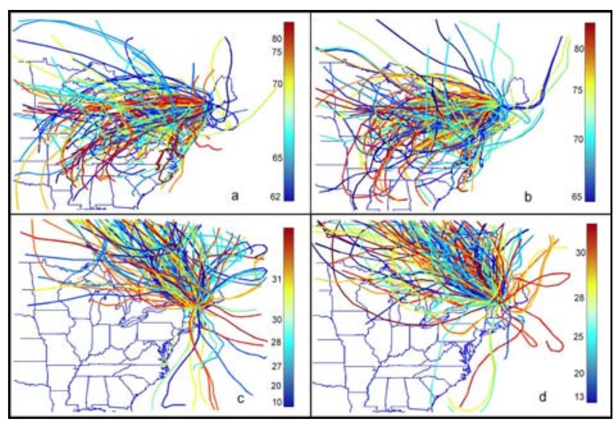

Figure 3: Back trajectories from Mount Washington (1998-2003) corresponding to a) afternoon enhanced ($\geq$ 62 ppbv), b) night enhanced ($\geq$ 65 ppbv), c) afternoon depleted ($\leq$ 31 ppbv) and d) night depleted ($\leq$ 30 ppbv) O_3 periods. The color scales indicate the average O_3 mixing ratio upon arrival at Mount Washington. Note that the color scale is different for each map, to reflect the different range of O_3 mixing ratios in each category.

Nighttime periods of O_3 greater than 80 ppbv were associated with trajectories following two main paths: westerly or southwesterly, and local winds in a small range from 225-300° (Figure 4).

Periods of enhanced O_3 occurred when New Hampshire was located on the backside of an anticyclone or in the warm sector of an approaching surface cyclone (Table 2). This synoptic situation generated a condition where major pollution sources most likely originated along the eastern seaboard or in the Midwest. Vertical transport also differed for enhanced and depleted trajectories, with enhanced trajectories having a higher average altitude than their depleted counterparts for both afternoon and nighttime periods. Our analysis indicates that enhanced O_3 at the summit is influenced by the higher O_3 levels characteristic of the free troposphere (Logan et al., 1999), and Mount Washington may be impacted by lofted pollution from the urban/industrial regions of the Midwest surrounding the Great Lakes.

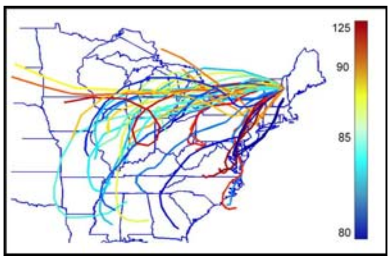

Figure 4: Nighttime backward trajectories corresponding to O_3 mixing ratios $\geq$ 80 ppbv at Mount Washington.

5.0 Conclusions

This study identified both the major transport pathways and synoptic conditions coincident with enhanced and depleted O_3 at Mount Washington. Enhanced O_3 events at Mount Washington were generally associated with westerly flow, while their depleted counterparts were associated with northwesterly flow. The rapid westerly and southwesterly transport channels identified during periods of O_3 greater than 80 ppbv indicate that there is a broad sphere of influence contributing to periods of enhanced O_3 at Mount Washington. The diurnal cycle of O_3 at Mount Washington is consistent with other mountain sites, with the summit receiving a greater O_3 exposure than the base. Factors such as mixed layer depth and vertical mixing play a role in determining the relationship between O_3 at the summit and base of the mountain.

6.0 References

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Table 2: Percentage of trajectories in enhanced and depleted groups associated with a particular synoptic feature coincident with the initialization time.

	Ozone $\leq$ 10th Percentile		Ozone $\geq$ 90th Percentile	
	Night	Afternoon	Night	Afternoon
Descending from above 700 hPa	11	18	29	43
Ascending / predominantly below 850 hPa	49	36	40	33
Surface Anticyclone centered over New England	16	26	7	9
New Hampshire in Warm Sector	2	5	62	57
Concurrent surface Anticyclone over Mid-Atlantic states or Carolinas	8	7	26	32
Regional-scale precipitation on arrival	72	74	32	26

The number of cases in each group were as follows: $O_3 \leq 10^{th}$ percentile: 177 night, 174 afternoon; $O_3 \geq 90^{th}$ percentile: 170 night, 152 afternoon.